PROCEEDINGS OF SCIENCE

A new muon tomography detector for glaciers melting monitoring

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Muon Tomography is a widely used technique, employed to perform imaging of the inner structure of large objects such as volcanoes, containers and pyramids. This technique takes advantages of the muon flux that reaches the surface of the Earth ($\sim 70 m^{-2} s^{-1} sr^{-1}$), produced by the interaction between Cosmic Rays and the atmosphere. The difference between the measured muon flux, with and without a certain object in the field of view, allows to infer the thickness of material traversed by the muons. In case of glaciers, thanks to the different density of ice and rock, a directional flux measurement provides information on both the glacier thickness and the bedrock-ice interface depth. The goal of our project is the development of a detector able to measure the glacier thickness with a real time data taking and processing, in order to perform studies of the seasonal behavior and the glacier melting trend through the years. The detector goal is to be able to reconstruct the trajectory of muons with an angular resolution of order of 5 milliradians to obtain a precision on the target object thickness of the order of few meters. The detector is designed to be operable in open-sky and scalable. In this contribution, we will show the results of a set of simulations aimed to optimize the detector design and the foreseen performances of the designed detector. The results are obtained through a detector simulation and a track finding algorithm. The angular resolution of the reconstructed muon tracks will be shown considering different configurations of the triggering system and the quality of the tracks, together with a study of the dependence of the angular resolution on the direction of the incoming particle.

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1. Introduction

The interaction between primary Cosmic Rays and the atmosphere produces a large amount of muons in their decay showers, which reach the Earth surface, with a flux of $\sim 70m^{-2}s^{-1}sr^{-1}$, thanks to their long decay time. The muon flux is well know in terms of momentum and angular distribution, and it can be measured with good precision. The low interaction rate of muons with matter allows them to pass through large volumes of materials, allowing to investigate the internal structure of objects placed between the cosmic ray source and the detector. In the last decades, thanks to the technological improvement in particle detectors, Muon Tomography has become a widely used technique in a large number of research fields, as geology [1], archeology [2], and vulcanology [3].

Absorption-based muography (AM) investigates the internal structure of a target by inferring the thickness and density of the object of interest by measuring the absorption of muons by the target itself. This probability can be measured calculating the difference of the directional muon flux measured with and without ("open-sky" flux) the target object in the field of view. In case of a target composed by two volumes (i.e. bedrock and ice), an average density can be calculated by the measurement, and with information about the density of the different volumes traversed by the muons, the depth of the interface between the two different volumes can be inferred. Assuming the total traversed thickness (T) to be known and that muon flux decrease exponentially with the thickness of the traversed material and its radiation length, the thickness of the two volumes can be computed solving the following equations:

$$\Phi(p,\theta,T) = \Phi_0 \cdot e^{-(L_1/X_1+L_2/X_2)} \tag{1}$$

$$T = L_1 + L_2 \tag{2}$$

where X_1 and X_2 are the radiation lengths of the two volumes, Φ is the measured flux, Φ_0 is the open-sky muon flux and L_1 and L_2 are thicknesses of the two volumes (the two unknown variables). AM offers only the possibility for 2-dimensional imaging of the target.

The detected muon tracks are used to reconstruct the trajectory of the incoming muons, and in particular, to determine their angles of impact in the detector (zenithal and azimuthal, θ and Φ). The open-sky flux is measured in regions away from the target within the same field of view, that is a good approximation assuming the muon flux constant along the azimuthal angle. In AM, the main source of uncertainty comes from the multiple scattering of muons inside the target object that can result in a wrong reconstruction of the muon direction. The multiple scattering can be taken under control considering that is random effect without a privileged direction, and averaging on the muon arrival directions. Another source of uncertainties is represented by the muon flux not traversing the target, that can produce spurious events that affect the muon flux measurement.

The most recent muon tomography detectors operated in open-sky for volcanoes and pyramids were based on scintillating bars [4] and gaseous detector [3], reaching angular resolution of the O(10-15 mrad). Measurement on glacier thickness was performed using detectors based on emulsion [5], that despite the great resolutions achieved, are not able to work in an high flux environment or for extended periods of data taking in open-sky conditions. Moreover, emulsion can not acquire data in real time, hindering the possibility to continuously monitor the muon flux and perform seasonal studies. This emulsion based measurement was performed installing the detector under the glacier, exploiting the artificial tunnel under the mountain, and reducing the possibility to extend the use of this detector for other glaciers.

2. Detector

The goal of our project is to develop a detector that reaches an angular resolution on the reconstructed track of O(5 mrad), to have an error on the ice thickness of ~5 m and to investigate inner structures inside glaciers. The detector should be able to operate in open-sky, for long periods of time, with a low power consumption, and in adverse weather in order to perform studies on seasonal and annual behavior of the ice thickness. The detector has to have a trigger system to reject the background in data acquisition phase, a fast response (>1 kHz) to cut the background in analysis phase. The background is mainly due to muons that not traverse the target and secondaries particles produced by the interactions between muons and the rocks.

To fulfill all these requirement, we propose a detector based on scintillating fibers and Silicon PhotoMultipliers (SiPMs) as light detectors, with a low number of channels (~ 2000) to reduce the cost, and employing commercial powering and read-out to make it easy replicable. The detector conceptual design foresees a structure of 5 modules (Fig. 1) each composed by two layers of scintillating fiber bundles embedded in a plastic cladding to provide mechanical stability. The layers (h = 0.9 cm l = 99 cm d = 99 cm, see Fig. 1) are composed of 110 bundles of scintillating fibers running along orthogonal directions with respect to each other, to provide at each module the three coordinates (x, y, z) of an hit. Bundles (2R = 2.7 cm) are composed by 7 fibers disposed as show in figure 1, and each of them represents a single read-out element and it is read independently by a SiPM array. For the presented study, the light is considered to be integrated over the whole fiber bundle, with a binary response; while in the future, information on the number of fired SiPM in the array will be used to provide additional tracking information through the building of tracklets inside the bundle.

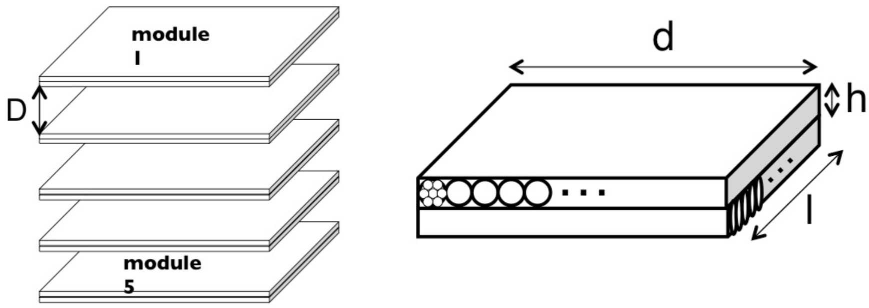

Figure 1: Sketch of the detector design: on left the whole detector composed by 5 module; on the right one module composed by 2 layers each of that made by 110 bundle of 7 scintillating fibers.

The distance between each module (D) was optimized, by studying three different configuration through simulations, D = 18 cm , 27 cm, 36 cm, corresponding to a total detector length of 99 cm (basic), 144 cm (medium) and 189 cm (long). As light detectors, different geometries and array arrangements were tested for SiPM matching to fibers. The actual best solution is an array composed by 16 SiPm of 1 mm × 1 mm. For the prototype different commercial solution for read-out and power supply were evaluated.

3. Results

We present here the optimization and feasibility studies for the detector for glacier muon tomography. The results shown were obtained using a GEANT4 [7] simulation of the full detector. In the presented results, we assumed a 100% detection efficiency for muons and no further information on deposited energy was used for tracking or efficiency purposes.

The angular resolution of the detector was measured in the three studied configurations (basic, medium, long) using a particle gun with muons impinging the detector from different directions. The detected hits were used to reconstruct the directions (reco direction) of the incoming muons, and were compared with the real direction, as generated by the simulation, to measure the residual between the true and reconstructed direction. The results showed a resolution on the track direction ranging from 10 mrad for basic configuration, to 5 mrad for long one. Angular resolutions (zenithal and azimuthal) for the long configuration are showed in Fig. 2. The same simulation was used to

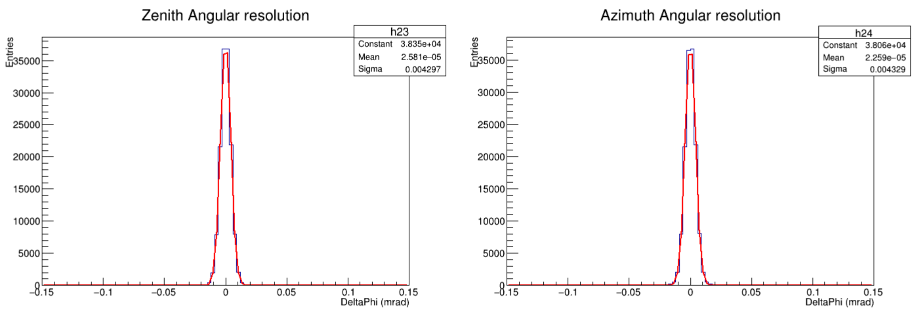

Figure 2: Uniformity on the detector reconstruction capabilities as function of the impinging polar impinging angle (θ), from top left and clockwise: spatial resolution on x coordinates, spatial resolution on y coordinates, angular resolution on phi, angular resolution on theta.

evaluate the uniformity of the response over the field of view, studying the variation of the angular resolution as a function of the impinging angle. Disuniformity effects account for less than 3% variation for high impinging angles, as shown in Fig. 3.

To evaluate the detector physics reach a conical target (height = 1560 m and radius = 520 m) was introduced in the simulation, as a first simulation of the mountain. The target was placed at 1 km distance from the detector, it was made by standard rocks [6] and was simulated both with and without an ice cap of 200 m over it. The muon flux was simulated according to the present knowledge of its behavior as function of zenithal and azimuthal angle and energy, to ensure a good statistics without a large computing time consumption only muons with at least 400 GeV of momentum were generated. The results of the simulation show a sensible differences in the fluxes of muons measured with and without ice in the target, as shown in Fig. 4, where each pixel in the plot represents a square surface of ~5 × 5 m. This result was obtained with an equivalent exposure time of O(10^6)s, satisfying the goal of a seasonal monitoring of glacier thickness. The results show that the detector is able to investigate the presence of ice-bedrock interface with an exposure time

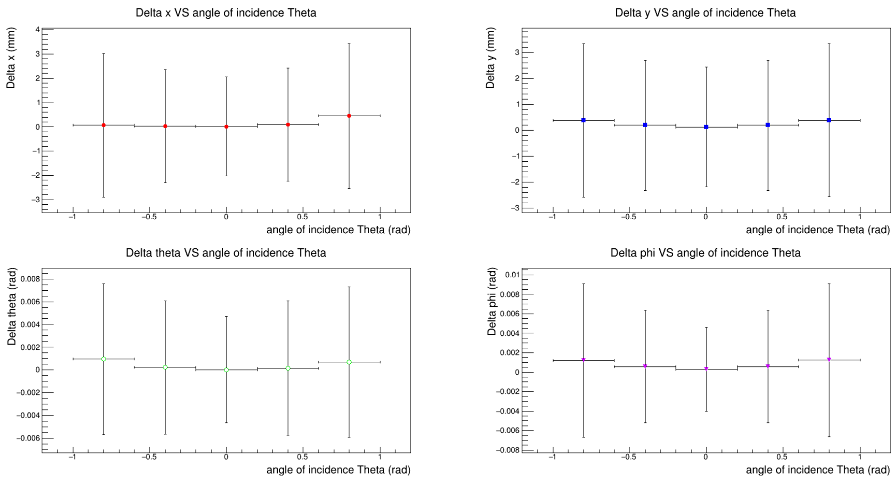

Figure 3: Resolution on track direction for the long-configuration detector, Zenith angle on the left, Azimuth angle on the right.

that allows seasonal measurement of thickness of the glacier, and the presence of glacier internal structures, highlighting the feasibility of the project.

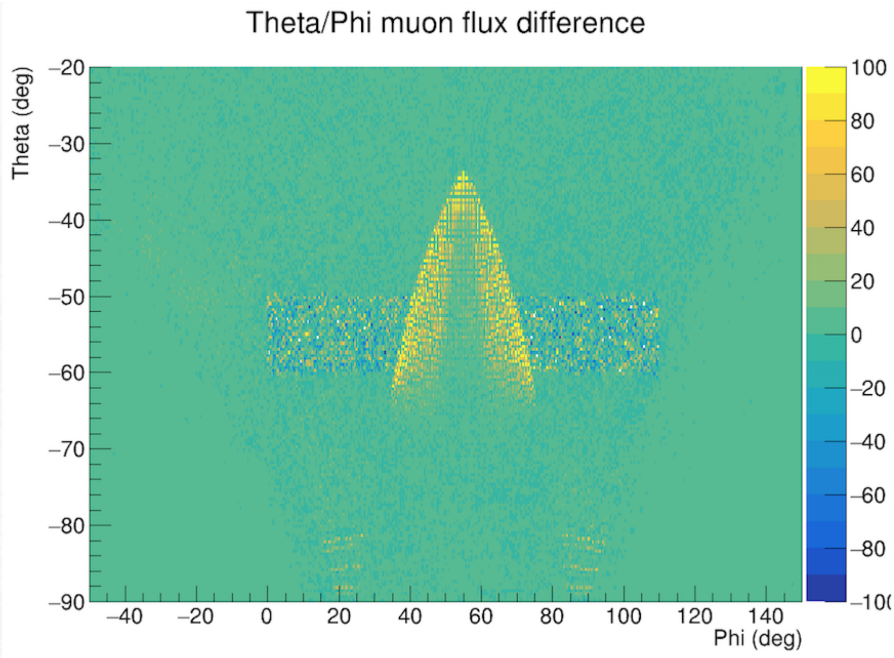

Figure 4: Difference of muon flux with and without the ice in the target. Each pixel represent a square of ~5×5 m.

4. Outlook

We presented the first results for a feasibility study of a dedicated detector for in-situ glacier monitoring able to operate in open-sky conditions, low maintenance and long duration data taking.

Previous glacier monitoring projects were based on emulsions that are not able to operate on-line and in open-sky condition, and on technologies - such as gas detectors - more demanding in terms of maintenance. Our preliminary results based on GEANT4 simulation show promising prospect for the design, with expected resolution <10 mrad for tracking reconstruction, high background rejection, and good stability over the field of view. Results on flux reconstruction show that a good resolution on ice-bedrock interface depth can be obtained with 1 month integrated flux, allowing seasonal variation studies.

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