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Ignacio Lázaro Roche, J.B. Decitre, S. Gaffet. MUon Survey Tomography based on Micromegas detectors for Unreachable Sites Technology (MUST2): overview and outlook.. 6th International Conference on Micro Pattern Gaseous Detectors, May 2019, La Rochelle, France. pp.012048, 10.1088/1742-6596/1498/1/012048 . hal-02893006

HAL Id: hal-02893006

<https://hal.science/hal-02893006>

Submitted on 8 Jul 2020

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To cite this article: Ignacio Lázaro Roche *et al* 2020 *J. Phys.: Conf. Ser.* **1498** 012048

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MUon Survey Tomography based on Micromegas detectors for Unreachable Sites Technology (MUST²): overview and outlook.

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Abstract. The use of Micro-Pattern Gaseous Detectors in geophysics and civil engineering applications has experienced an increase related to the incorporation of muon tomography in these fields. The Temporal Tomography of Density by the Measurement of Muons project has developed a new direction-sensitive tool for muon flux measurement based on a thin time projection chamber with a bulk-Micromegas readout and SRS electronics. This configuration presents interesting distinctive features, allowing a wide angular acceptance of the detector with a low weight and compact volume. The functioning principle of the device, the results of the characterisation tests, the ongoing work to improve its performance and the next phase to scale up the existing muon camera network at the Low Background Noise Laboratory of Rustrel are presented.

1. Introduction

Gaseous detectors are widely used a century after the discovery of the charge amplification basic principle. They stand out in applications where a large coverage area is required with a relatively low material budget. The progress of photolithography and microprocessor production techniques in the circuit board industry have led to a transition in the field of gaseous detectors during the last decades from wire structures to Micro-Pattern Gas Detectors (MPGDs). The development and combination of new MPGDs families and the improvement of the production techniques allow the creation of application-oriented detectors in order to enhance their performance and robustness [1]. Moreover, the intrinsically good temporal and spatial resolution of this kind of detectors motivated their incorporation into nontraditional fields, such as geophysics, to build muon tracking devices.

Cosmic muons are a natural passive source capable of penetrating up to several hundred meters underground. There are two main techniques for muon tomography: transmission and scattering. Both of them rely on the direction-sensitive measurement of the cosmic muon flux. Due to the intrinsic limitations of each technique, only transmission appears suitable to image large volumes [2]. The measurement of the muon flux attenuation caused by the medium's opacity (density integrated over the distance travelled by the particle), allows obtaining in situ the density distribution of the targeted volume. This technique provides reliable, original and independent information relative to the physics of the measures produced by the seismic, gravimetry or resistivity soundings of the Earth for instance. It is thus as a complementary method in several disciplines and eases the inverse problem resolution [3].



2. Technology description

The Temporal Tomography of Density by the Measurement of Muons (T2DM2) project was originally created to conceive a muon detector to help elucidate the dynamics of the water transfer process through the non-saturated zone of the Albion plateau (South-East of France). The main motivation was to conceive a detector capable to fill the technological gap for applications with compactness and transportability constraints. The Micromegas-like detectors [4] have proven to be a sturdy versatile tool for temporal monitoring of large volumes with 2D submillimeter resolution, compact size, light weight, relative low cost and ground and underground operation capabilities. There are currently different setups based on Micromegas readout planes conceived for performing muon tomography measurements with distinctive features aiming different objectives [5-6].

2.1. Micromegas within a time projection chamber

The MUon Survey Tomography based on Micromegas detectors for Unreachable Sites Technology (MUST²) consists on a thin time projection chamber (TPC) with a bulk-Micromegas readout, as shown in figure 1. When a muon enters the conversion and drift volume of the TPC, it ionizes the gas and produces clusters of electron-ion pairs along its path. These primary electrons are driven by an electric field to the position-sensitive amplification structure, i.e. the Micromegas detector, where the electric field strength reaches significantly higher values. The movement of charges and avalanche amplification in this zone, collected by the resistive layer and the micromesh, induces a measurable signal in the readout structure.

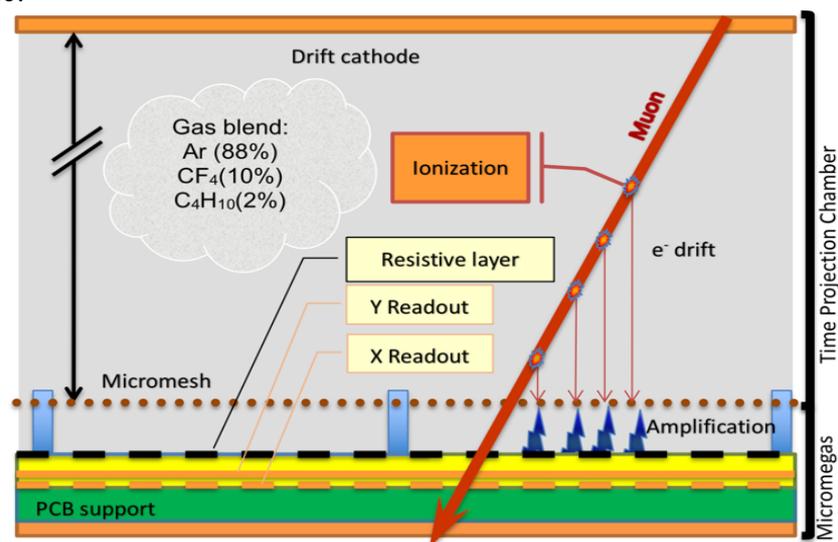


Figure 1. Schematic cross-section of the MUST² to illustrate its components and functioning principle.

Theoretically, all primary electrons created stochastically during the primary ionization should contribute to the signal strength. However, several processes such as: recombination of electron-ion pairs (weak electric field), attachment to gas constituents during scattering (presence of gas contaminants) and neutralization of the electrons (low mesh transparency) contribute to a loss of information and should be taken into account in the detector design and operation. Electric field homogeneity is of major importance in obtaining a straight projection of the particle path during TPC operation and avoids artifacts. The uniformity of the electric field inside the drift region has been improved by means of a field cage.

Design of the detector and choice of operational parameters play a major role in the charge transport and multiplication, a proper balance between these elements is therefore required in order to meet a set of physical and technical constraints. A detailed description of the different elements and parameters can be found in [7].

2.2. Gas choice and management

The choice of gas is a key parameter for the detector's performance. The goal while running a TPC is: (i) to maximize the production of primary electrons, (ii) to obtain an electron drift velocity compatible with the data acquisition time window, (iii) to minimize the fluorescent photon emission and expulsion of Auger electrons and (iv) to achieve a high ion mobility to rapidly flush out the ions and minimize the deformation of the electric field and discharge probability.

Unfortunately, a long mean free path and ease of ionization are frequently conflicting features for a simple gas, therefore mixtures are frequently used. The number, type and proportion of its components will influence the response of the detector during the entire signal formation process from the primary electron yield to the gain. The most common choice is a gas mixture based on a noble gas with addition of a quencher gas. The gas blend chosen for the current experiment is Ar:CF₄:iC₄H₁₀ (88:10:2)[7].

The performance of the detector is related to the quality of the gas and its homogeneous distribution inside the detection volume. Gas parameters (e.g., fine composition, flow, contaminants, temperature, pressure, etc.) affect directly the physical processes that lead to the signal creation. More specifically, the presence of contaminants such as O₂ and H₂O produce an attenuation of the signal strength.

To minimize the undesirable effects associated with the gas deterioration, an auxiliary system coupled to the detector has been designed and patented along with the detector [8]. The piping of the gas circuit has been done with Teflon-PFA (material with low diffusion permeability) and connectors with negligible spillage to minimize the presence of contaminants. The gas conditioner system (GC), shown in figure 2, consists of an adjustable system of gas filtering and recirculation; it also keeps the pressure inside the detection volume steady in order to compensate for possible gas leaks along the system, or the gas expansion/contraction due to temperature changes.

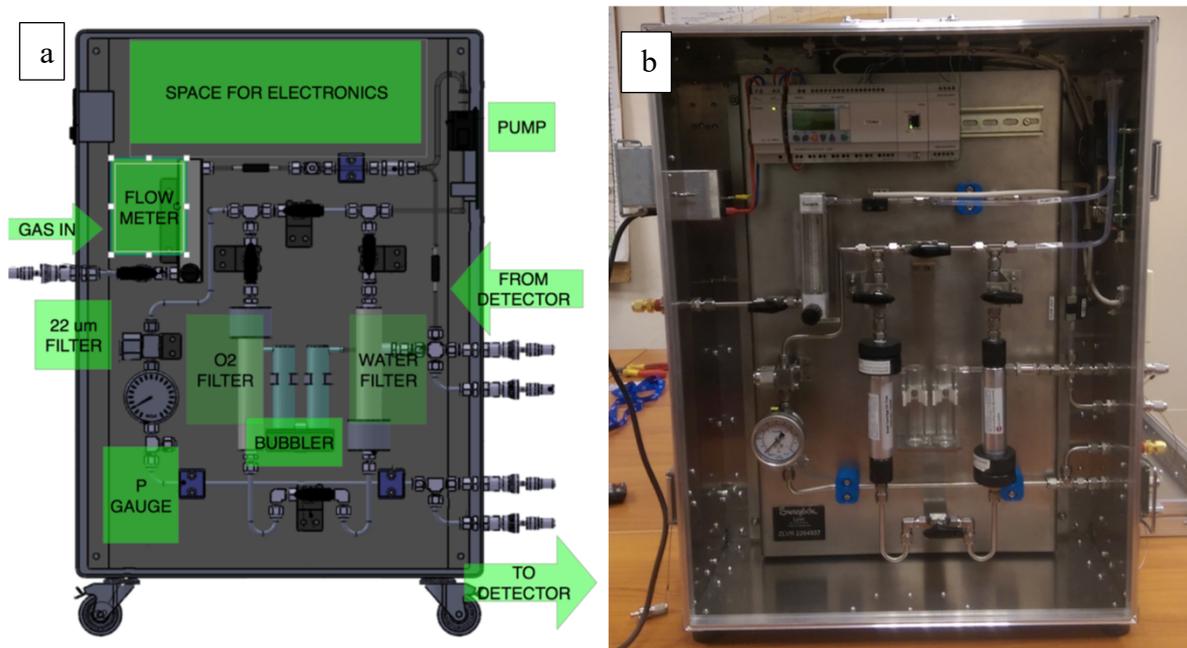


Figure 2. (a) 3D model of the GC with its components identified. (b) View of the GC trolley without the cover.

2.3. Data acquisition trigger

The creation of a reliable trigger signal associated with the muon passage through the detector plays a major role in the electronics performance to retrieve the particle's information. The versatility of the MUST² detector allows three different kinds of trigger as seen in figure 3.

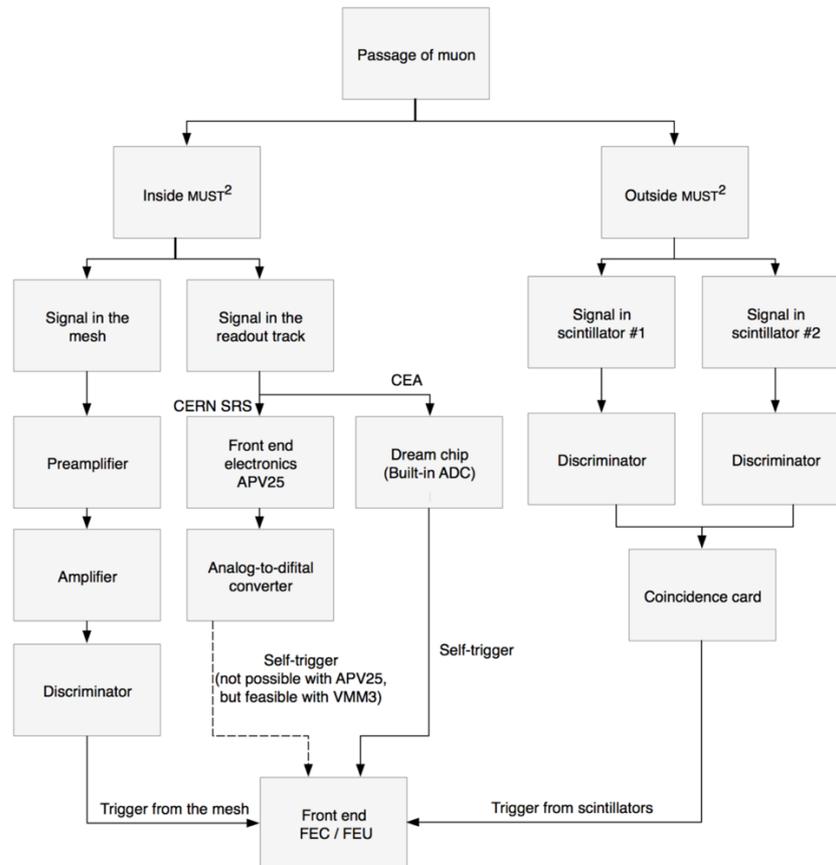


Figure 3. Flow chart of data triggering.

2.3.1 External trigger. Consists of creating a standardized signal pulse to prompt the FPGA to perform the data logging by means of two auxiliary scintillators aligned with the MUST² detector operating in coincidence mode. The scintillators used during the tests have roughly the same surface as the detector (100 x 50 x 1 cm) and they are made of polystyrene-based plastic, covered with light reflecting film and black vinyl. Each one is encased by a protection box and placed analogously to the detector to ease the material stacking. Two different data acquisition electronic systems have been tested: CERN's SRS [9] and CEA's FEU [10]. The standard of pulse might vary depending on the instrumentation equipped; NIM in case of the SRS FEC, TTL for the CEA's FEU.

2.3.2 Internal trigger from micromesh. This configuration enables the standalone acquisition capability, which doesn't require auxiliary detectors. The signal, from the floating micromesh, is recovered by a tool specifically designed by CERN to trigger the SRS readout with MPGD detectors called "trigger pickup box" [11]. The measured signal-to-noise ratio related to the passage of muons has validated the feasibility of this self-trigger operation mode.

2.3.3. Internal trigger from electronics. CEA's FEU electronics and more recent SRS VMM3, allow to program a custom trigger configuration with no auxiliary detectors. The filtered signal of each readout channel is compared to a programmable threshold value. The outputs are summed to obtain multiplicity information: if the multiplicity exceeds a programmable threshold, the differential output for data acquisition is triggered.

While internal triggers don't rely upon auxiliary detectors (with the subsequent saving in volume, weight and cost); are more sensitive to random coincidences from simultaneous events, instrumental noise and gain fluctuations and require a fine tuning prior to operation.

3. Characterisation tests

A series of experiments have been carried out with the MUST² in order to find the best operational parameters, characterize the detector performance and to validate the technology.

3.1. Gain measurement

The membership of T2DM2 in RD51 collaboration has allowed the project to carry out characterization tests at CERN's Super Proton Synchrotron (SPS). This particle accelerator provides mono-energetic beams of muons or pions in their test-beam facilities. The gain of the detector has been calculated as the ratio of (charge originated into the amplification zone) to the (primary charge generated by the incoming muons) according to equation (1):

$$Gain = \frac{\Delta I}{N_T \cdot d \cdot \mu / s \cdot q} \quad (1)$$

where ΔI is the average variation of the current measured between beam's spills and breaks, $N_T \cdot d$ is the number of primary electron-ion pairs induced within the TPC per muon, μ / s is the number of muons per second during the spill measurement and q is the charge of the electron.

The results of the calculated gain are shown in figure 4 (a) as a function of the resistive layer voltage, which controls the detector signal amplification. The gain calculated during the two tests with different beam incidental angles shows a good consistency and is in good agreement with other experiments using resistive Micromegas [12].

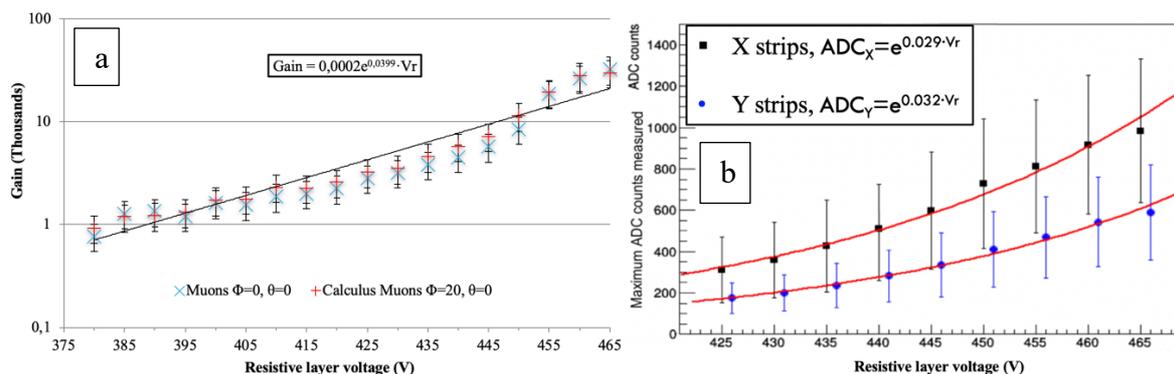


Figure 4. (a) Calculated gain of the detector as a function of the resistive layer voltage for two different measurements. (b) Signal amplitude measured by the electronics in the two readout planes as a function of the resistive layer voltage.

The gain influences the measured signal amplitude. Figure 4 (b) shows the maximum measured ADC counts voltage in in the X and Y readout strips, (the Y results are shifted 1 V for better visualization). The figure shows a good correlation between the exponential regression slopes of the calculated detector gain and the amplitude of the signal measured in the readout tracks. It is also possible to see an amplitude offset in the induced charge on the two readout planes due to the screening effect of the superimposed levels. A good gain value should provide a compromise between a strong enough signal in the lower readout plane with less induced charge, and a signal without saturation on the X readout tracks.

3.2. Interdependence of TPC and electronics

A good synchronization between the signal generated by the passage of the muon and the signal acquired by the electronics is essential to enhance the efficiency of trajectory reconstruction. The signal synchronization is driven by two parameters, the system's latency and the signal length.

The system's latency can be defined as the time interval between the passage of the muon (stimulus) and the signal detection by the electronics (response). This parameter depends on physical factors during the signal formation processes, as well as on the delay inherent to the electronic components and the

signal transmission through the wires. Therefore, the latency value is a function of the experimental setup. The data acquisition electronics used during the tests, CERN's SRS APV25, does not record data continuously, instead it is possible to sample a time window of 675 ns from a 4 μ s time buffer after every triggered event. The slow control of the electronics permits customizing the offset of the data logging within the buffer time. A scan of offsets has been done to determine the acquisition chain latency with the best value for operation.

In parallel, ideally the whole signal should fall within the data logging time window. The process that controls is the electrons' drift velocity within the TPC. This value has been estimated to 467 ns by running MAGBOLTZ [13] simulations taking into consideration the gas blend, the detector's geometry (drift height of 5 cm) and a constant electric field of 600 V/cm. To illustrate the actual length of the signal generated in the TPC, figure 5 shows the distribution of times with signal over the established threshold in the X and Y coordinates during an acquisition.

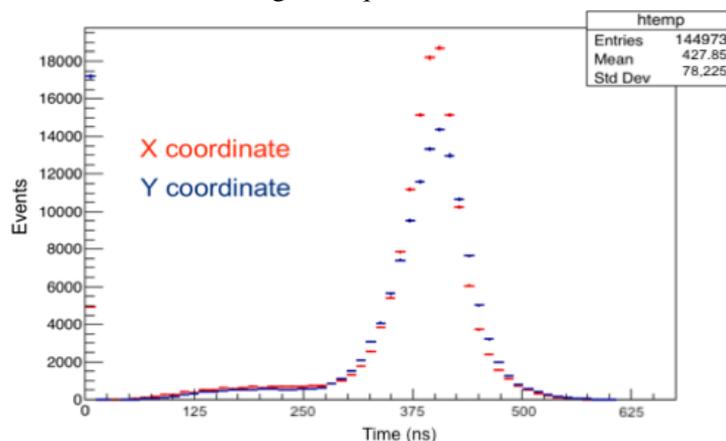


Figure 5. Time over threshold.

The signal length duration is homogeneous in the two coordinates, the amplitude in the Y coordinate is however lower due to the induced charge difference between the readout planes. The average signal length for the tested configuration is $427,85 \pm 78,22$ ns. Both experimental and theoretical values are in good agreement.

4. Next phase

4.1. Challenges

A field campaign has allowed to validate the field transportability and the capability to perform long-term out-of-lab measurements [14]. During the data acquisition, temperature fluctuations had a non-neglectable influence in the signal amplitude of the MUST² detector, inducing variations of the reconstructed muon flux of the same order as the natural variations of the muon flux. A system for adapting the amplification voltage as a function of the environmental temperature, to keep the detector gain constant, is under development for experimental sites with variable temperatures.

The first version of the muon trajectory reconstruction algorithm presents some limitations for particles with incident with angles close to the orthogonal axis of the detection plane or with trajectories superimposed to the micromegas readout tracks (see figure 6 (a)). This bias is caused by the strict requirement of simultaneous adjacent hit tracks on both planes to minimize false positive events. A new version of this algorithm, which features different point reconstruction techniques with individual fit quality scores, has been developed and is currently under testing. Figure 6 (b) shows the analysis of the same dataset, corresponding to an open sky measurement of 200 minutes. Preliminary results indicate a global improvement of efficacy of reconstruction, with emphasis in the former blind spots, in addition to a reduction of artifacts. Further data analysis and more experimental data is required to fully validate the sensitivity of the detector to small opacity variations coming from the aforementioned directions.

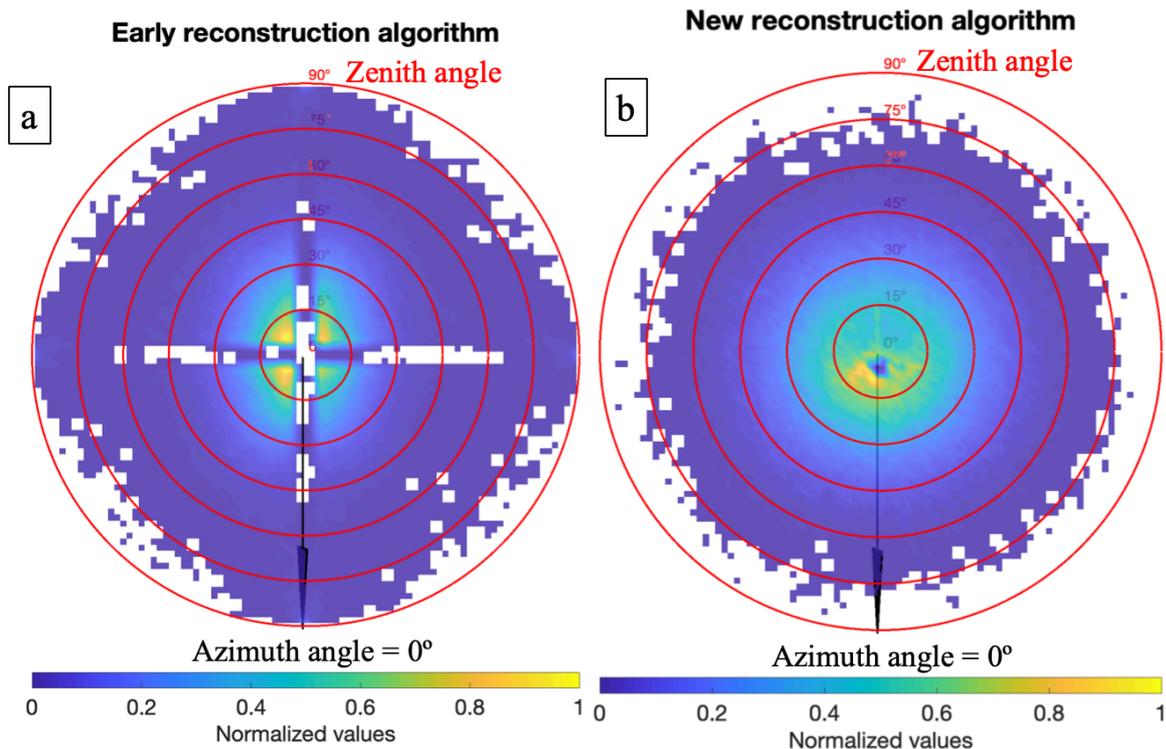


Figure 6. Polar chart of the angular distribution of reconstructed events from the same dataset with (a) the early reconstruction algorithm and (b) the new reconstruction algorithm.

4.2. Short-term plans

The Low Background Noise Laboratory at Rustrel (LSBB) has obtained funds (FEDER LSBB2020) for the construction and deployment of 20 autonomous MUST² detectors. This new generation of muon camera will integrate slight design improvements and a major electronics update. The new components are expected to be delivered by the end of 2019.

The network of standalone detectors allows versatile setup configurations: (i) simultaneous multiple point-of-view measurements towards 3D tomography, (ii) clusters of detectors to increase the active detection surface in deep measurements to minimize the integration time, (iii) scatter measurements with MUST² detectors as trackers upstream/downstream the target volume and (iv) aligned detectors in multilayer configuration to improve angular resolution.

5. Conclusion

Transmission muography is an expanding non-destructive technique based on the attenuation of the natural-occurring cosmic-muon flux due to the opacity of the material they traverse. The MUST² detector is a useful tool with distinctive features for the direction-sensitive measurement of the muon flux towards muographic applications in different fields.

The characterization tests performed, both in a controlled environment and under field conditions, allowed and (i) the validation of the multiphysics simulations performed to design the detector, (ii) the fine tuning of the operational parameters and (iii) the assessment of the performance limits inherent to the hardware design and data analysis.

The current main challenges are to improve gain stability and the efficiency of the reconstruction algorithm.

The network of autonomous cameras, soon to be deployed at the LSBB, will allow versatile configurations to enhance the cosmic muon absorption/scattering measurements.

Acknowledgments

The authors would like to thank the invaluable support of the CERN's RD51 collaboration for the development of micro-pattern gas detectors technologies for all the assistance provided since the beginning of the project. We would like to acknowledge the *mairie* of Saint-Saturnin-les-Apt for giving us access to the dam site as well as the city archives. Part of this research was performed within the framework of a CIFRE grant attributed to I. Lázaro whilst he worked for IRIS Instruments (ANRT contract #2015/0325) and supported by the European Fund for Regional Development (FEDER).

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