# A Novel Readout Scheme for Muon Tomography Application in Material Identification

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## Abstract

This work reports on the development of a cost-effective, multiparameter readout and data acquisition system for a muon scattering tomography system constructed with Resistive Plate Chambers. Initial test measurements of the proposed readout scheme based on the NINO ASIC in the front-end with a low-cost FPGA at the back-end have been performed using a prototype Resistive Plate Chamber to study its event selection and data handling capabilities. The time-over-threshold property of NINO ASICs has been used to obtain position information from the detector. In our test setup, we studied absorption radiography images of a lead block using the hit information acquired with our novel readout scheme. The experimental data have been compared to numerical simulations to investigate the efficacy of the proposed readout system.

*Keywords:* muon tomography, data acquisition system, resistive plate chamber, NINO, FPGA
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## 1. INTRODUCTION

Muon tomography can be used for material identification utilizing multiple Coulomb scattering suffered by cosmic ray muons while passing through a matter [1, 2]. The resultant deflection of a muon from its original trajectory can be represented by a Gaussian distribution in a given plane [3, 4] which is dependent on several physical properties like density ($\rho$), atomic number $(Z)$, and atomic mass $(A)$ of the matter and the momentum of the muon. Thus, a measurement of the scattering angle by tracking the pre- and post-interaction muon trajectories enables one to identify the material of the test object for a given muon energy.

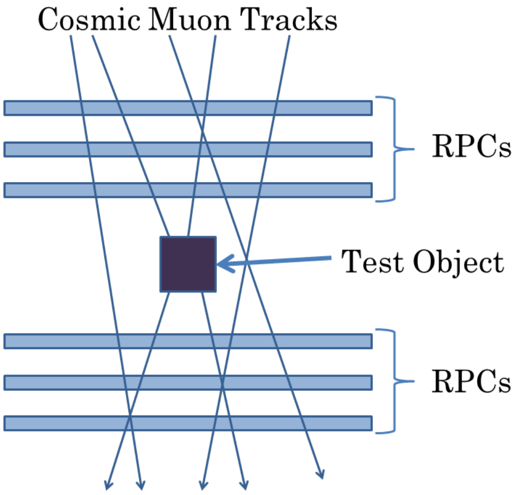

FIGURE 1: Schematic diagram of muon scattering tomography (MST) setup.

We plan to construct our muon scattering tomography (MST) setup using two sets of Resistive Plate Chambers (RPCs) to track muons before and after their interaction with a test object, as shown in Figure 1. The RPC is preferred due to its simple design,

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ease of construction, cost-effective production of the large detection area, along with very good temporal, spatial resolutions, and detection efficiency. An FPGA-based multiparameter data acquisition system (DAQ) has been developed in this context for the collection of position information from the tracking RPCs and subsequent track reconstruction. It offers a simple, low-cost, scalable readout solution for the present MST setup. The proposed scheme has been tested for its performance using the absorption radiography technique where the image of a lead block has been produced by a single RPC. The experimental result has been compared to a simulation of this setup for validation.

## 2. READOUT SCHEME

A complete scheme of the proposed DAQ is shown in Figure 2 where the front-end part consists of an ASIC followed by an FPGA-based back-end. These components are briefly described below.

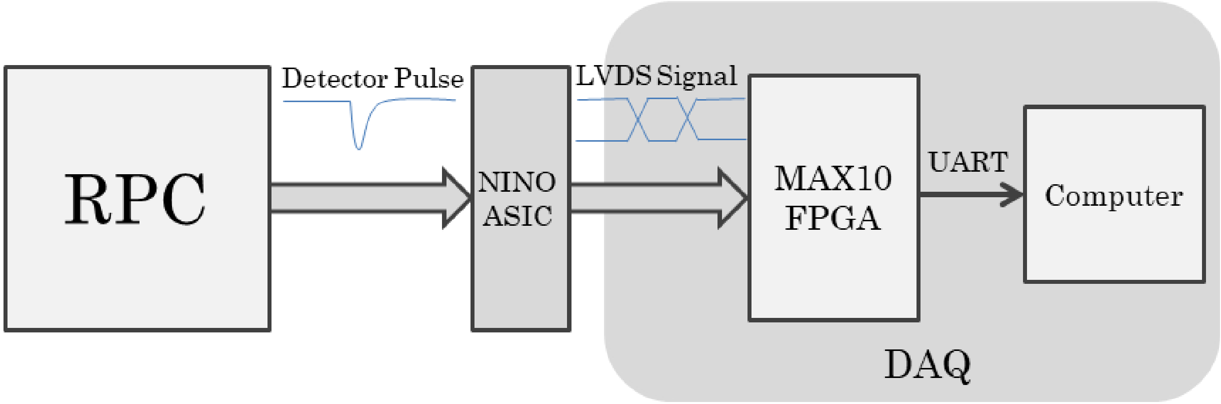

FIGURE 2: Scheme of the Data Acquisition System (DAQ).

### 2.1. *Front-End Electronics*

The NINO ASIC [5], an ultra-fast front-end preamplifier discriminator chip developed for the ALICE TOF detector, has been used as the readout chip. It has eight channels with an input dynamic range from 100 fC to 2 pC. The output pulse width varies from 13 to 20 ns and is proportional to the input signal charge. Each channel accepts signals from the detector and provides LVDS (Low Voltage Differential Signal) output, which is suitable for low-power, high-speed transmission with better noise immunity compared to single-ended connections. The output pulse width is dependent on the time the input signal stays over a preset threshold value which is defined as the time-over-threshold (TOT) value. A readout board made with a single NINO ASIC and an adjustable threshold regulator, developed by the INO Collaboration [6] as shown in Figure 3, has been procured and used in our setup.

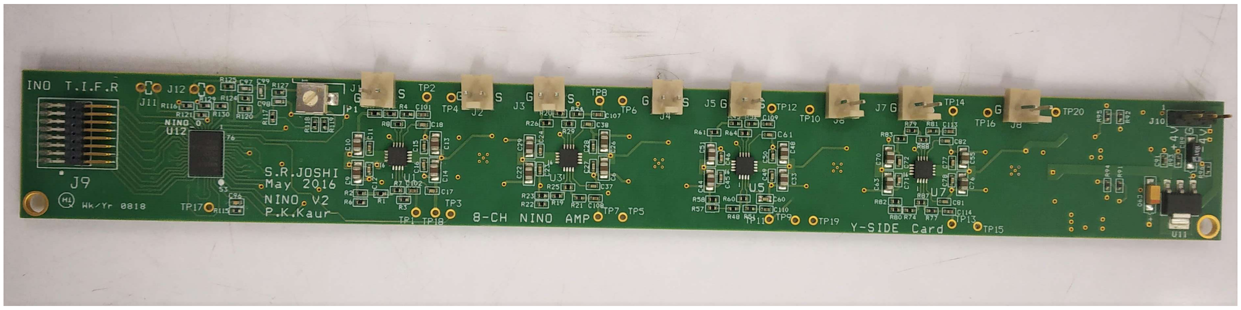

FIGURE 3: A NINO readout board.

### 2.2. *Back-End Electronics*

An Intel MAX 10 FPGA has been used in the back-end due to its capability of accepting LVDS signals as input and high bandwidth. The MAX 10 board [7] is a compact FPGA development platform developed by INO, which contains the Intel MAX 10 FPGA with 2000 Logic Elements (LEs), 108 memory blocks, 101 I/O pins, and a 50 MHz on-board clock. A connector board has been designed by us to map the LVDS connections between the NINO readout and FPGA board with the required 100 Ω termination resistance. The FPGA board along with the connector board is depicted in Figure 4.

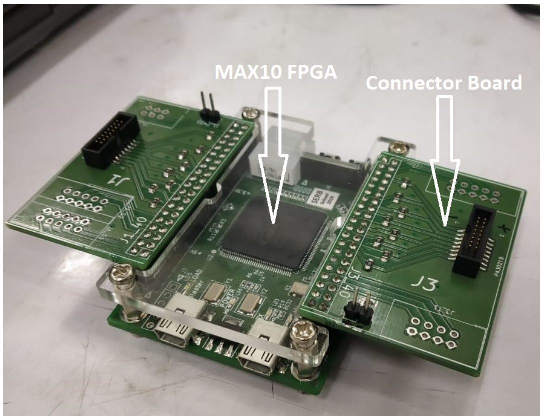

FIGURE 4: The FPGA board equipped with connector boards.

### 2.3. *Software Implementation*

Programming the FPGA is an important task for this project. VHDL and Verilog are two hardware description languages that can be used to program FPGA. Here, we have used VHDL in combination with Quartus prime software [8] to compile and upload code into the FPGA. The UART (Universal Asynchronous Receiver/Transmitter) protocol has been used to transfer data from FPGA to the computer, which has been implemented on the FPGA. To measure the TOT output of NINO, a 500 MHz clock has been generated using a Phase-Locked Loop (PLL) [9]. This clock helps to measure the TOT with a maximum probable inaccuracy of 2 ns. The MAX 10 FPGA board has been programmed to store NINO outputs of 128 events in a temporary FIFO memory. A controller has been designed to send a trigger signal for each muon event to transmit the NINO data to the computer storage through the UART module. This data flow algorithm has been implemented for all input channels inside the FPGA, as illustrated in Figure 5. Python programming language has been used to acquire data on a PC using a COM port where the data contain the TOT value of each channel of each NINO.

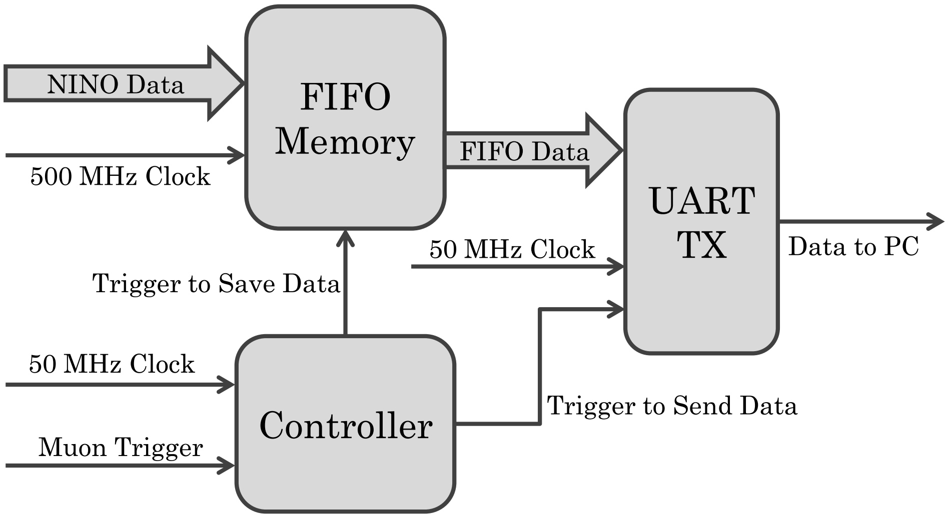

FIGURE 5: Schematic diagram of the operation inside the FPGA.

## 3. TEST OF THE READOUT SYSTEM

To study the performance of the readout scheme, a test bench has been set up using one RPC detector, two NINO boards as the readouts for two orthogonal panels ($X$, $Y$) of the readout strips of the RPC, and one MAX 10 FPGA board for receiving front-end data from 16 channels. The response of the detector for cosmic muons has been recorded with and without a lead block placed in front of it as the test object. The details of the setup and the results are discussed below.

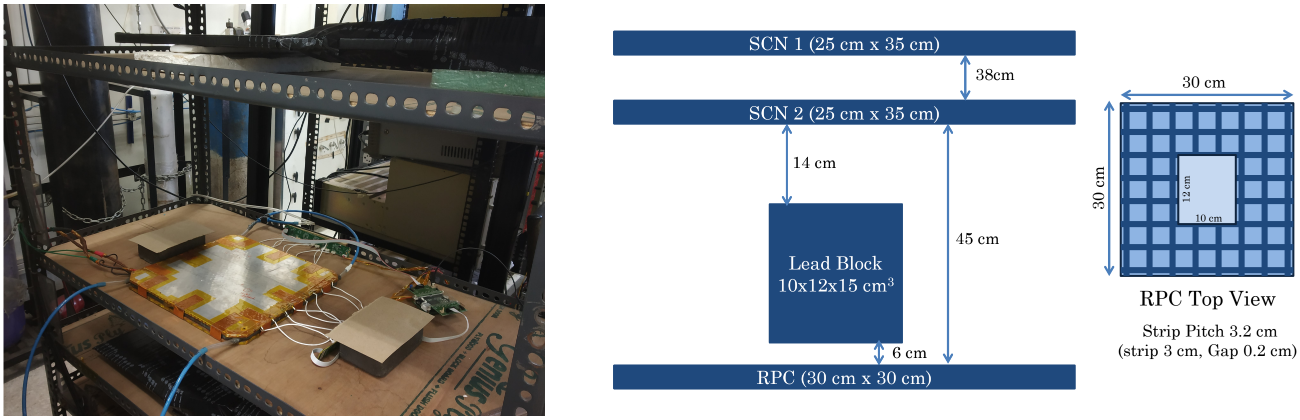

FIGURE 6: Image and the scheme of the experimental setup.

### 3.1. *Description of Test Setup*

In our test setup, a glass-RPC of dimension 30 cm × 30 cm, filled with a gas mixture of 95% Freon and 5% Isobutane, has been operated in a vertical cosmic ray hodoscope. It was equipped with two orthogonal panels ($X$, $Y$) of readout strips with a width of 3 cm and a pitch of 3.2 cm. A NINO board has been used in each readout panel containing 8 strips to obtain time-over-threshold outputs corresponding to the current signals induced on the readout strips of the RPC due to a muon event. A coincidence of two plastic scintillators with an area of nearly 25 cm × 35 cm has been used as a muon trigger. A lead block of dimension 12 cm × 10 cm × 15 cm has been placed 6 cm above the center of the RPC. The image and the schematic diagram of the experimental setup are shown in Figure 6.

### 3.2. *Test Results*

In our experiment, the RPC has been placed in a vertical cosmic ray hodoscope for 12 hours. For each event, data from the two NINOs have been used to get hit information along $X$ and $Y$ directions. The TOT weighted mean position has been used for the multiple hit events. For simplicity, only avalanche events have been considered. The streamer signals have a larger spread than the avalanche signals which can worsen the position resolution. The event with greater than four strip hits has been treated as a streamer event. Events that have fired only one readout panel have been excluded. Nearly 14000 valid hits have been put into a 2D histogram with 8 × 8 bins according to its hit position. The absorption radiographic image of the hit points for 8 × 8 pixels has been shown in Figure 7 for two positions of the lead block, one at the middle and the other at an edge. The images have been obtained by subtracting the data taken in presence of lead block from that taken without it.

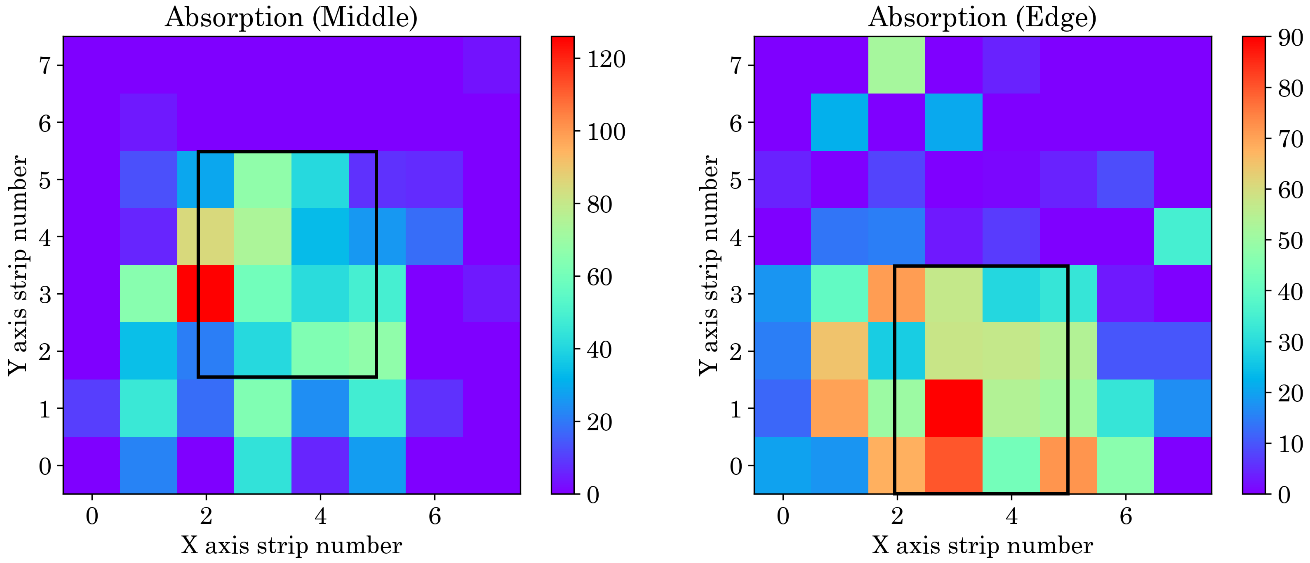

FIGURE 7: Experimental muon absorption images (the black line indicates the boundary of the lead block).

## 4. COMPARISON WITH GEANT4 SIMULATION

In order to verify our experimental absorption radiography images of the lead block, a simulation study has been carried out using Geant4 [10]. A model, similar to our experimental setup, containing one gas volume of 2 mm thickness and a cross section of 30 cm × 30 cm has been constructed. A lead block of a dimension of $10 \times 12 \times 15\,\text{cm}^3$ has been considered at a distance of 6 cm away from the gas volume as was done in the experiment. The setup has been subjected to a 12-hour exposure of the cosmic muon flux received at the sea level using Cosmic Ray Library (CRY) [11] to get an equal muon event to match with an experimental scenario. The FTFP_BERT physics list has been used to propagate the particles throughout the lead and detector. It takes care of all the electromagnetic and weak interactions of the charged particles like muons.

### 4.1. Simulation Result

The muon hits obtained over the detector cross section have been segmented into 8 × 8 pixels, each having an area of $3.2 \times 3.2\,\text{cm}^2$ to make it similar to the experimental readout granularity. The absorption images for two positions of the lead block have been obtained following the same procedure, i.e., by subtracting the hit map obtained with the lead block from that produced without it. The simulation results show a 5% absorption of incident muons by the lead block. The simulated absorption pattern shown in Figure 8 exhibits close agreement with the experimental absorption percentage of 5.9% depicted in Figure 7.

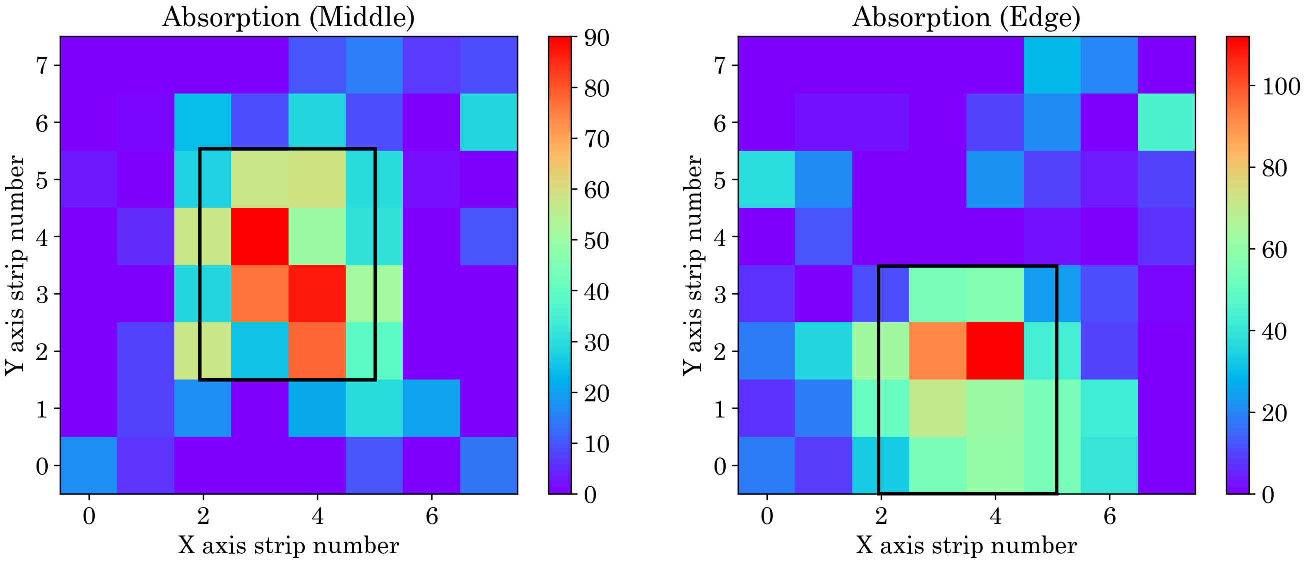

FIGURE 8: Simulated muon absorption images (the black line indicates the boundary of the lead block).

## 5. CONCLUSIONS

An FPGA-based DAQ prototype has been tested with a NINO ASIC readout and an RPC detector measuring cosmic muons. The muon absorption radiography images of a lead block have been produced experimentally and later compared to simulated results with a satisfactory agreement. The authors plan to increase the granularity by using a finer readout strip of pitch 1 cm to improve the position resolution and hence the clarity of the image.

## CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

## ACKNOWLEDGMENTS

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