GEM Detectors for Muon Tomography of Nuclear Contraband

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Abstract

The design and construction of a Muon Tomography station is presented. Muon Tomography (MT), based on scattering of cosmic ray muons, is an improvement to the actual portal monitors at borders, since the current techniques use regular radiation detection that are not very sensitive to nuclear contraband (U, Pu) if these materials are well shielded to absorb emanating radiation. We propose to use low mass, high spatial resolution (~50 μm) large area Gas Electron Multiplier (GEM) detectors for the tracking of the cosmic muons MT to overcome the intrinsic limitations. The prototype MT station employs 6 tracking stations based on 30 cm × 30 cm triple-GEM detectors with 2D readout. The detectors are arranged into tracking superlayers at the top and bottom of the probed volume. Due to the excellent spatial resolution of GEMs it is sufficient to use a gap of only a few cm between tracking stations. We present details of the production and assembly of the GEM-based tracking stations in collaboration with CERN and the RD51 collaboration as well as the design of the corresponding front-end electronics and readout system. Discussion about GEM detectors in two sides of the probed volume for a complete muon tracking, and building a large-area (1m × 1m) GEM-based MT station prototype to be tested under realistic conditions for vehicle or container scanning are made.

MT Principle and GEM detector

Muons are created in the upper atmosphere by cosmic rays. A muon is a charged elementary particle with mass 105.7 MeV/c^2; μ-flux at sea level is 10^4 min^{-1} m^{-2} at an average energy of 4 GeV. Multiple Coulomb scattering depends on density and atomic number Z of the material traversed. Due to their penetrating nature, muons are good candidates for detecting shielded high-Z materials. The GEM detector is a micro pattern gaseous detector for charged particles. It uses a thin sheet of Kapton coated with metal on both sides and chemically pierced by a regular array of holes a fraction of a millimetre across and apart. A voltage is applied across the GEM foils and the resulting high electric field in the holes makes an avalanche of ions and electrons pour through each hole. The electrons are collected by a suitable device; here a readout plane with x-y strips.

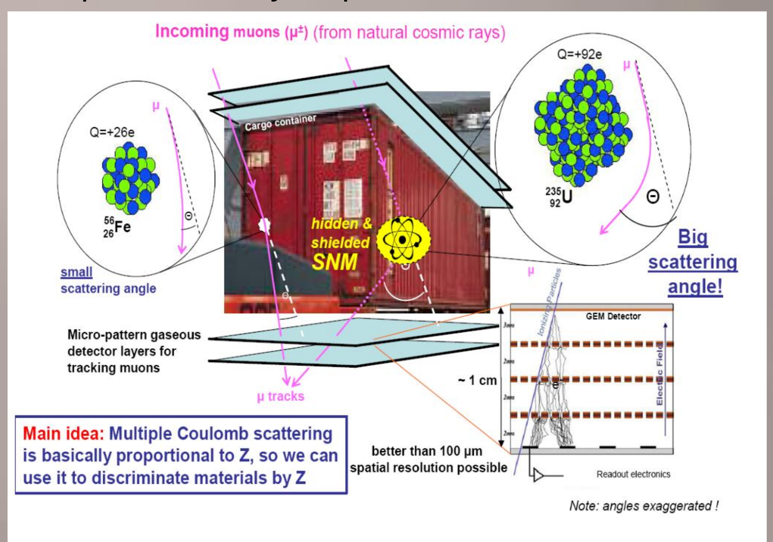

Fig. 1. Principle of Muon Tomography using cosmic rays and GEM detector transversal layout.

Muon Tomography Simulations

We have used Monte Carlo simulations to model the effectiveness of various MT station configurations, which is primarily determined by the time required to produce an accurate and precise Point-Of-Closest-Approach (POCA) reconstruction. POCA reconstructions provide the locations and by how much muons have been scattered. Computer simulation data are used to choose practical and effective detector configurations and the data from real-world detectors will be used to validate these simulations.

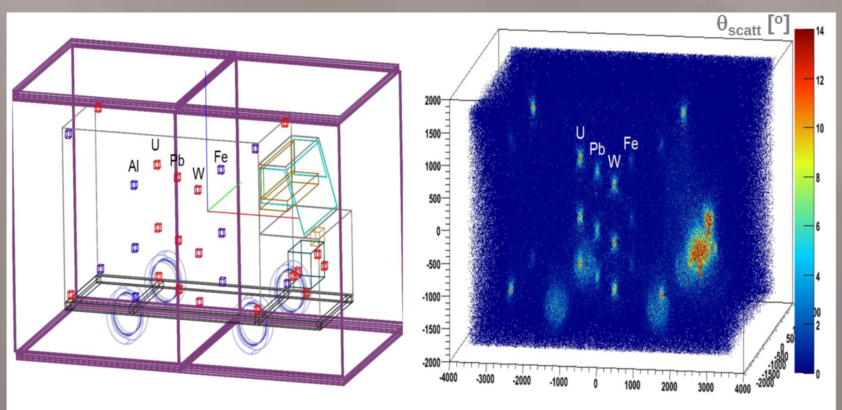

Fig. 2. Simulated cargo van scenario with Al, Fe, W, U, Pu targets (*left*). Mean angle reconstruction with POCA (*right*).

High Voltage Test of GEM Foils

The acceptance criterion for a GEM foil requires the foil to hold 500 V under nitrogen gas with a leakage current less than 5nA in each of the 12 HV sectors. These tests are made in a class 1000 clean room and are performed before and after framing the foils.

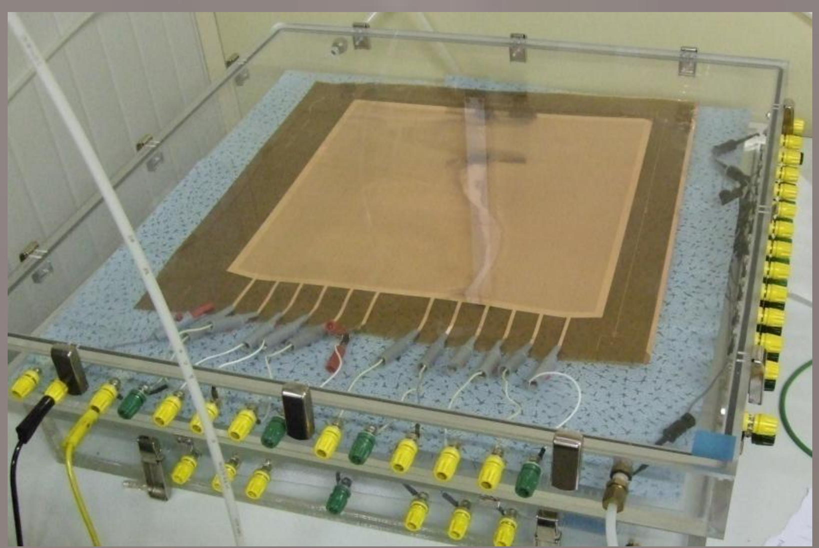

Fig. 3. GEM foil under HV test in an air-tight Plexiglas box under Nitrogen at GDD-CERN lab.

GEM Detector Assembly

We use a thermal method for tensioning GEM foils. The foils are placed on a Plexiglass frame and put into an oven at 45º C, which stretches the foil. We glue an FR4 frame onto the tensioned foil to maintain the tension. These frames are carefully cleaned and coated beforehand.

Fig. 4. Foil in stretching device ready to go into oven.

The drift cathode foil and the readout foil are glued onto honeycomb support structures. In the final stage of detector assembly, the drift honeycomb is glued to the stack of 3 framed foils and this assembly is glued onto the readout honeycomb. The gas connectors are then glued in and the small sides of the detector stack are coated to minimize gas leaks between frames.

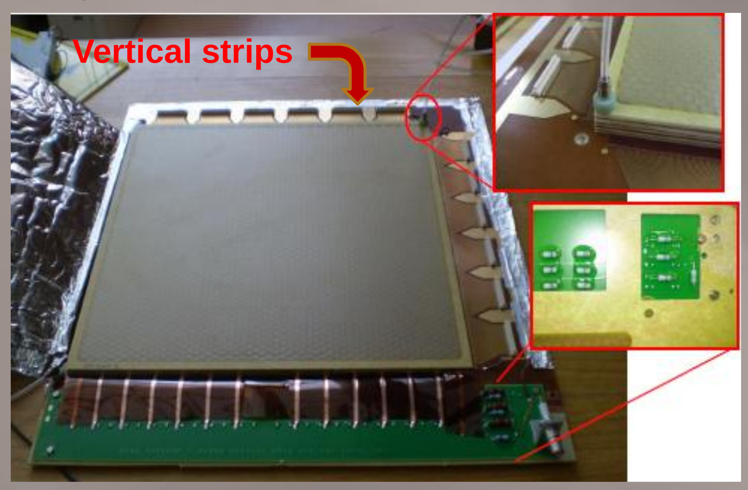

Fig. 5. Triple-GEM detector (30cm × 30cm), x-y strip readout, with HV board connected.

Since our GEM foils are based on an upgraded version of the original COMPASS GEMs (without beam killer), they have 12 separate sectors, so in case of a short one loses only one sector instead of the whole foil. For this arrangement, the high voltage circuit is a voltage divider with 12 separate sectors for each foil. Before mounting it to the detector, the boards are tested by taking the main supply voltage up to 4.5 kV and measuring the bias current to verify that the boards have proper Ohmic behavior. The boards are cleaned, coated, and retested.

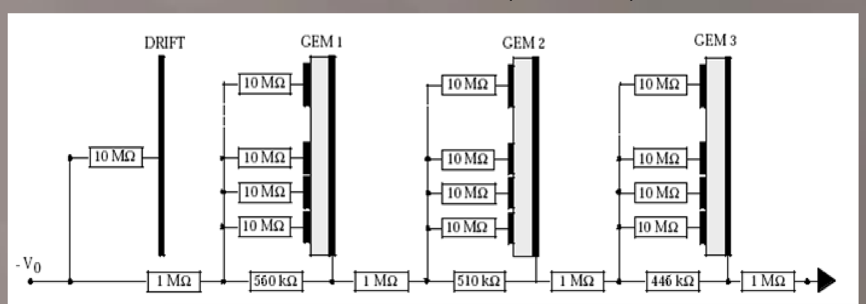

Fig. 6. High voltage circuit., the electronic diagram updated by TERA foundation group from COMPASS experiment design.

Initial Readout Electronics

The analog front-end (FE) amplifier is based on "Gassiplex" chips, each of which is connected to 96 channels (developed by CAST experiment at CERN). We have developed adapter card to handle the interface between the Gassiplex front-end and our detectors, since these chips have 96 channels and each connector on the readout of our detectors has 128 channels.

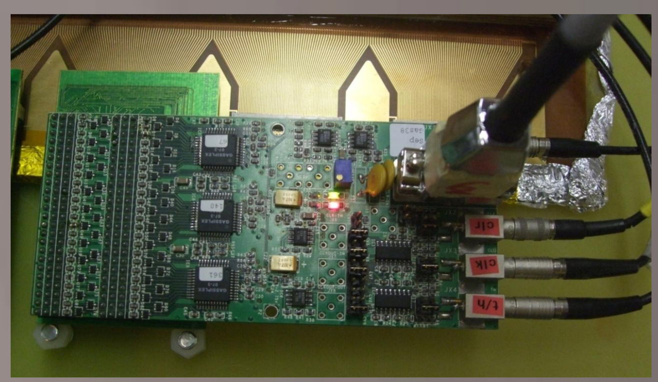

Fig.7. Gassiplex front-end fully connected and operational.

We use a NIM crate to power the system, VME based DAQ with 4 CAEN CRAMs and a data sequencer. The CRAM modules receive the data signal from the Gassiplex cards (two per CRAM). The sequencer card receives the trigger signal, produces the control signals for the Gassiplex and for the CRAMs, receives a Data Ready signal if there are data available, and clears the CRAMs modules at the end of an event readout. The sequencer card is connected to a PC and the acquired signal is read out with LabView software. To trigger our system we use scintillators panels and photomultipliers (PMT) from the Quarknet educational program of Fermi Lab. The DAQ board is controlled with a PC, the board provides discriminators and trigger logic for four channels of PMTs, but for our propose two channels.

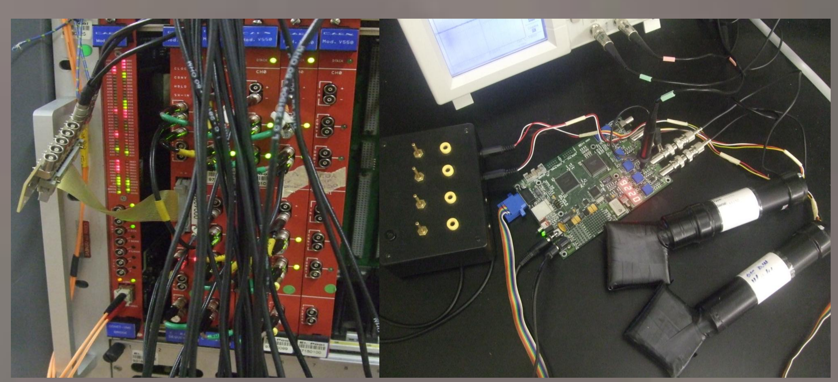

Fig. 8. VME readout crate, the sequencer card is at the left (left). Two 5cm × 5cm scintillators with the PMTs for the trigger (right).

GEM Detector Commissioning

The detectors were first tested under HV at 100% CO_2 and then operated with an $ArCO_2$ 70:30 counting gas mixture. They were placed on a Cu X-ray test bench, and at 3.8 kV signal pulses become visible. We connect all the strips of one sector of the readout together and take the counts of each sector. A total of 6 detectors were tested with this procedure and all of them show similar behavior. No sparks were observed during any of the tests and the signal was acquired with very low electric noise, for all the assembled detectors.

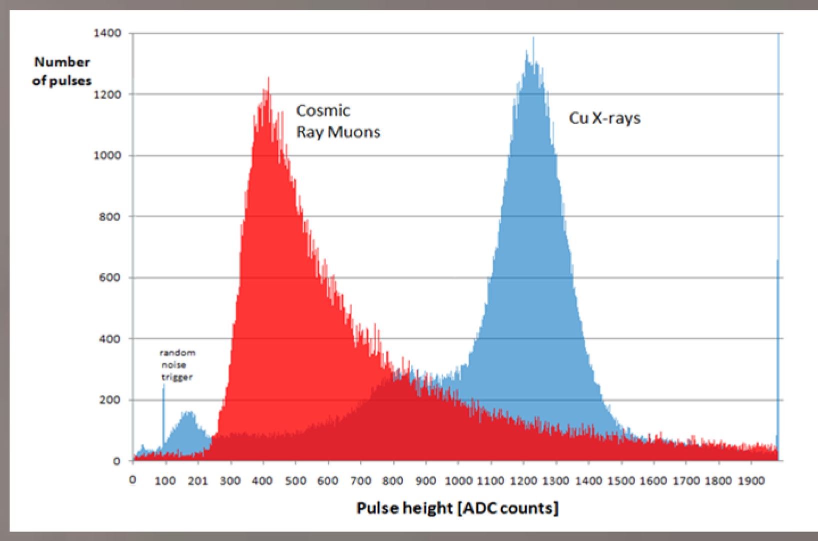

Fig. 9. Energy spectrum obtained with Cu X-rays, showing a ~ 20% energy resolution (FWHM) for 8 keV X-ray (blue). Cosmics ray muon pulse height distribution (red).

Cosmic ray muon data was collected with two of the detectors. 100,000 events were recorded using 1/6 of the total active area (with only strips from one connector in the readout) for 5 hours. We expect 45,000 counts at sea level, but since Geneva is at 373 m above the sea level, more cosmic ray particles are detected.

GEM Detectors Performance

The gain of the detectors is defined as ratio of collected charges with the readout to primary charge, this is done measuring the collected current at a known radiation flux. We used a 8.04 keV collimated X-ray generator and GDD-CERN's lab electronic to calculate the gain of one of the six detectors made. A logarithmic behavior with a gas gain up to 2 × 10^4 was obtained as expected and gain non-uniformity a few percent along x-strips

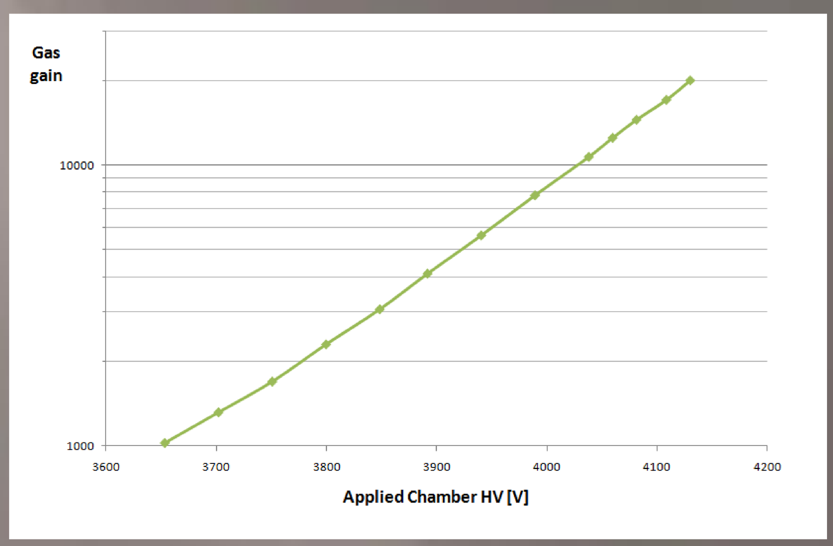

Fig.10. Gas gain of one of the triple GEM detectors in ArCO2 70:30, obtained with GDD-CERN's electronics.

The gain in GEM detectors depends on geometry of the holes, external fields and gas mixture,.These issues were studied for COMPASS experiment to obtain the maximum efficiency. The rate of counted X-rays shows a plateau at 3.9 kV.

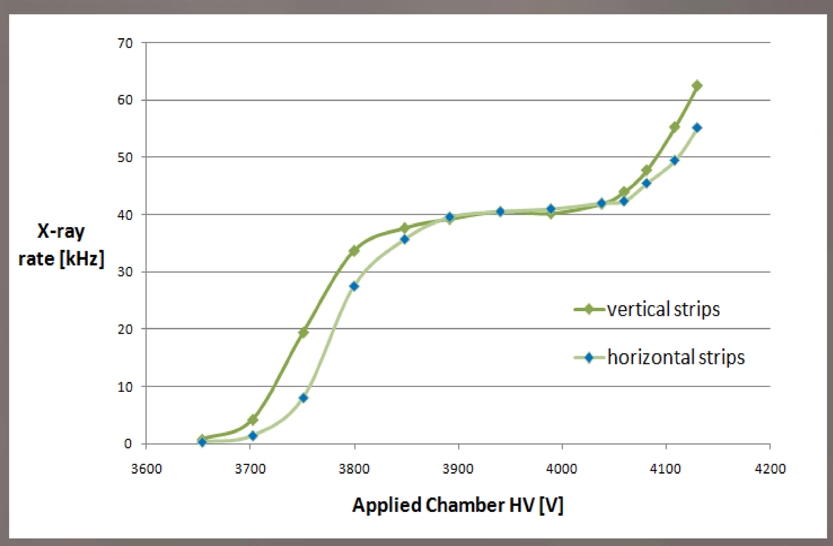

Fig.11. X-rays count rate plateau (vertical strips were measured with lower discriminator threshold than horizontal strips).

Notice that figure 11 is not the typical efficiency plateau curve since we are only counting the recorded X-rays events, this does not directly measure the efficiency. However, this curve indicates that the 3-GEM chamber becomes efficient for X-rays around 3.9kV. The actual efficiency must be measured with an independent trigger either from scintillators or with other GEM. After 4.2kV, the curve started increasing again because this is the point where the first transfer gap starts becoming efficient for X-rays, so that you get some pulses from a "double GEM" detecting X-rays on top of the "triple GEM" pulses. The charge sharing between x- and y-strips accounts for about a factor of two, since the detectors show a very close to equal charge sharing. However almost all the events are recorded on several strips, this allow an accurate estimate of the coordinate by charge interpolation.

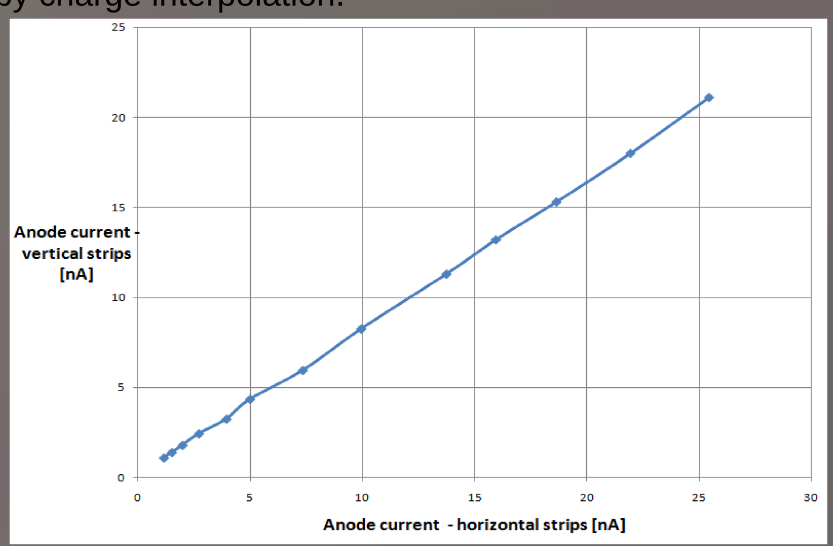

Fig.12. Charge sharing x - y strips for increasing HV with 40 kHz Cu X-rays.

First MT Prototype Station

A simple design was chosen for a mechanical stand for our first prototype station that accommodates multiple top and bottom GEM detectors with 30 cm × 30 cm active areas. The stand can be adjusted to study the effect that various detector gaps have on the tomographic imaging. The data from measurements will be compared against predictions made by simulations and used to optimize our tomography images. Future studies will focus on designing an imaging station that can accommodate GEM detectors on two vertical sides as well, defining an imaging volume with detectors on a total of four sides.

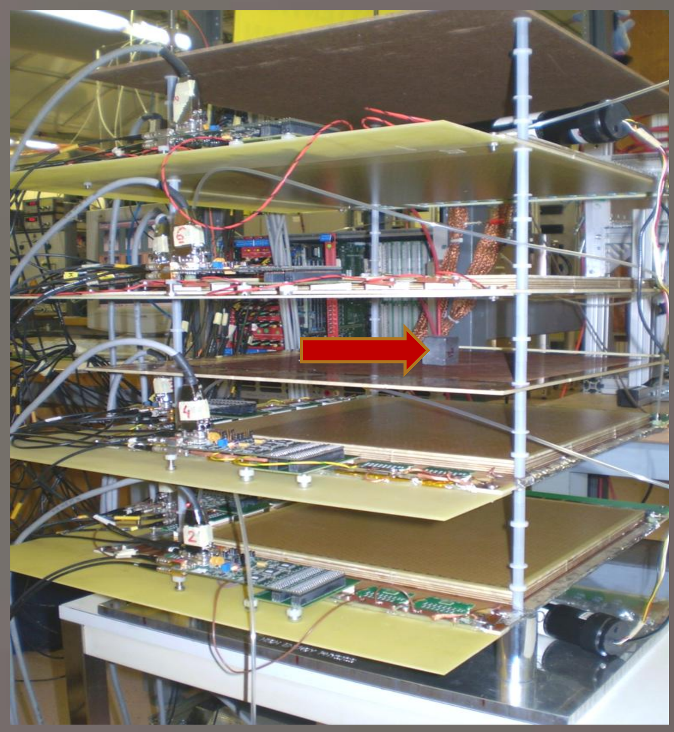

Fig. 13. First MT prototype station with 4 GEM detectors and a 3cm × 3cm × 3cm SIZE lead target in the center.

First Muon Events

We used 8 Gassiplex front-end electronics cards to read out an active area of 5 cm × 5 cm of 4 detectors in both x- and y-direction. Figure 14 shows pulses from a cosmic ray muon traversing the station and recorded simultaneously by all four detectors on x- and y-strips. The observed muon rate for this small area and solid angle is ~40 events per hour. We took two runs with different targets (iron and lead) inside the MT volume. Analysis of the data from these target runs is in progress.

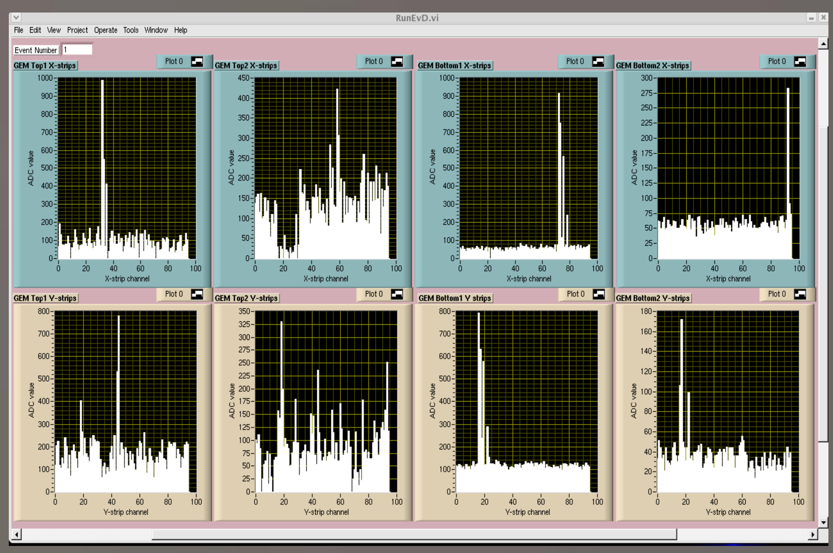

Fig. 14. Cosmic ray muon raw event recorded on x-strips (top) and y-strips (bottom). Note that pedestals are not subtracted.

Large Area GEM Detector

The next step is to build a large-area GEM-based MT station prototype to be tested under realistic conditions for vehicle or container scanning. To do so we need larger GEM detectors (~ 100 cm × 100 cm) as the base unit for our tracking station. Efforts are being made by the RD51 collaboration for various HEP applications to build GEM detectors of this large area. We plan to fully participate in different aspects of the R&D for such large-area GEM ranging from the framing and testing of the large GEM foils to the challenges associated with the electronic readout system needed for this detectors.

Summary & Conclusions

Muon tomography based on Multiple Coulomb Scattering of cosmic ray muons appears as a promising way to distinguish high-Z threat materials such as U or Pu from low-Z and medium-Z background with high statistical significance. We have constructed a first MT station prototype with 30 cm × 30 cm large GEMs to demonstrate the validity of using MPGDs as the muon tracking stations for muon tomography. A total of 8 detectors were assembled, 6 of them were tested successfully so far. Preliminary tests on the detector performances show expected and similar behavior for gains, rate plateaus, and charge-sharing among readout strips when tested with X-rays. Initial tests of the MT station showed that the communication between the VME DAQ hardware and the software is working properly. We are studying the data collected with an empty MT station and with the iron and lead targets. We are planning to use the APV-25 chip for the front-end electronics of the full prototype.

Acknowledgment & Disclaimer

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