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Measurements on triple-GEM detectors with highly segmented readout board in test beam

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Summary. — A Low EMittance Muon Accelerator scheme (LEMMA) has been proposed for the future Muon Collider. This solution provides muon beams through the reaction $e^+e^- \to \mu^+\mu^-$. In this context, a test beam campaign was planned to detect the two narrow collimated muon beams and measure their intensity and emittance. Such a measurement requires detectors with high spatial resolution ($O(100\ \mu\text{m})$) to track the produced muon beams. In the setup, we propose to include triple-GEM detectors with digital readout capable of reaching spatial resolution below 100 μm. This article shows the performance studies, in terms of efficiency and spatial resolution, held on small size prototypes of triple-GEM detector with a special read out board during the RD51 Test Beam held in October 2021.

1. – Introduction

The Muon Collider project [1] represents one interesting option to explore the Standard Model and to probe Beyond Standard Model theories after a full exploitation of the High-Luminosity LHC. One of the major challenges in the project of a Muon Collider apparatus on a technological level consists in the production of a muon beam having low emittance and high luminosity. One possibility is the LEMMA scheme, that works as a positron driver scheme [2]: a positron beam hits a target and annihilates with the electrons of the material, at a centre of mass energy just above the threshold for the $\mu^+\mu^-$ production. The resulting muons are highly collimated and have low emittance:

they do not require any additional cooling, they can reach 500 μs lifetime in the laboratory frame and can undergo the subsequent acceleration stages. In order to measure the intensity and the emittance of the muon beams, a dedicated test beam campaign is being prepared. The experimental setup was designed to provide a precise measurement of the trajectories and momentum of the two final state muons. For this purpose, a spatial resolution of the order of $O(100\,\mu\mathrm{m})$ is needed in the x and y directions. The tracking system of this experiment envisages CMS pixel/strip Phase-2 detectors and $10 \times 10\,\mathrm{cm}^2$ triple-GEM detectors with improved spatial resolution with respect to the standard 400 μm pitch, to be positioned before and after the magnet. These devices have been built at the CERN EP-DT Micro Pattern Technology (MPT) Workshop in 2020. In this paper, we discuss the results of a preliminary test on the detector prototypes aimed at assessing their detection efficiency and spatial resolution as well as smooth integration with LEMMA DAQ.

2. – Prototypes under test

The four chambers under test are triple GEM detectors with an active area of $100\,\mathrm{cm}^2$. The amplification foils are the standard GEM foils [3]; the gap dimensions between the foils follow the standard LHCb and CMS configuration (3/1/2/1 mm), that are intended to maximize the transparency and the time response of the detector. The readout anode consists of two planes of strips arranged perpendicularly to each other and mounted on a PCB. The top plane of strips is insulated from the bottom through 50 μm of kapton. The strip width is 50 μm for the top, 220 μm for the bottom. The strip pitch is 250 μm for both layers and thus the estimated spatial resolution is 75 μm: for odd cluster size, the central strip is taken as the centre of the charge, and the uncertainty on its position is $250\,\mu\mathrm{m}/\sqrt{12}$; for even cluster size, the centre of charge is taken in the middle of two strips and, again, the uncertainty is given by $250\,\mu\mathrm{m}/\sqrt{12}$. All the chambers have been subjected to a series of quality controls in the laboratories at INFN and University of Bari to ensure good operations [4]: first, the foils are cleaned applying high voltage; the gas tightness is verified; the stability under HV of the GEM stack is then checked; finally, the effective gas gain and the efficiency to cosmic muons are measured to establish the detector working point. From these measurements, the muon detection efficiency has been found to be $\sim 90\%$ for a stable working point at a gain of $\sim 2 \times 10^4$ using $\mathrm{Ar/CO_2}$ 70/30 gas mixture.

3. – The test beam setup and data taking

The performance of the telescope built with these four chambers has been measured in test beam in October 2021, on the H4 line of the CERN North Area, with 150 GeV muons. The setup includes two CMS GEM detector [5], which are not discussed here, one pair of 10×10 triple-GEM detectors on the front and the back of those prototypes with respect to the beam direction, positioned at 70 cm from each other and perpendicularly to the beam direction. Additionally, three scintillators, two on the front and one on the back, are used for the trigger signal. The tracking detectors have been powered on through one HV channel of the power supply delivering high voltage among the GEM foils through a resistor divider. The detector working point is then expressed in terms of current drawn by the powering circuit. All detectors are read out by the VFAT3 front-end ASIC [6]. The trigger signal from the scintillators is sent to the front-end after being synchronized to the 40 MHz clock. The raw DAQ data are sent via optical links to a

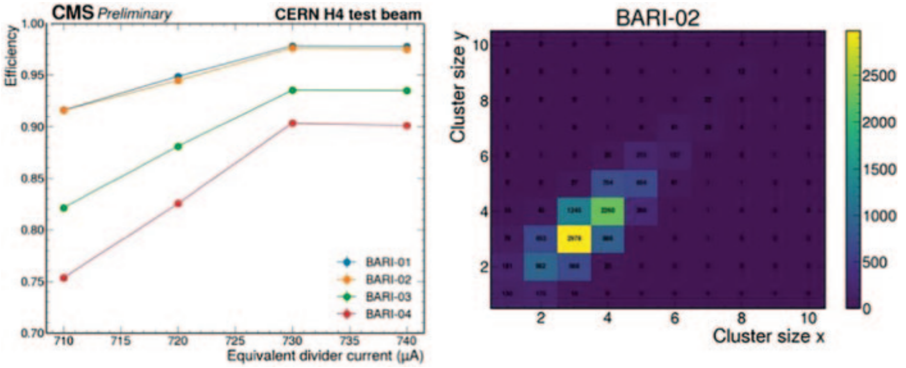

Fig. 1. – Left: efficiency curves for each of the four tracking chambers as a function of the detector working point, expressed in terms of divider current. Right: cluster size distribution for the x and y strips for tracking chamber BARI-02.

network interface card on the DAQ machine and are stored locally for the reconstruction. The test beam campaign lasted around three weeks, the first days being dedicated to commissioning of the detectors and debugging of the setup. Before data taking, the level of noise has been measured for all the detectors in order to set proper values for the threshold of the VFAT channels. For the tracking chambers, a high level of noise was observed (on average between 0.5 and 1 fC for all VFATs) and the VFAT thresholds have been set accordingly.

4. – Analysis and results

In the local reconstruction, clusters of neighbouring strips are grouped together to form reconstructed hits (rechits). The coordinate of the rechit is obtained from the center of the associated cluster of strips, with uncertainty given by pitch × cluster size/$\sqrt{12}$. A track trajectory is found from a fit to the tracker rechits and the fit is used to interpolate the track positions to the CMS Phase-II detector positions. At offline analysis level, the position of the hits is corrected for misalignment effects in the x and y directions and in the angle with respect to the beam direction using an iterative algorithm. The spatial resolution and efficiency of each tracking detector have been measured. Figure 1 (left) shows the efficiencies for the four detectors, there indicated as BARI-01, BARI-02, BARI-03 and BARI-04, as a function of the divider current corresponding to the applied voltage to the divider. The efficiency is obtained requiring that the extrapolated hit of the track on the test chamber falls in the active area of the chamber itself and that it matches a two-dimensional reconstructed hit. The efficiency of two of the tracking chambers is likely limited by the high front-end thresholds set.

The spatial resolution is extracted from the width of the gaussian fit of the residuals distribution, where the residual distribution is computed as the differences between the position of rechits on the detector and the position of the hit obtained from the extrapolated track. Figure 2 (right) shows an example of the residual distribution with no selection on the cluster size for BARI-02. The distribution is fitted with a gaussian function. We assumed that the width of the residual distribution coincides with the spatial resolution of the detector, neglecting the contribution of the extrapolation error. The quoted spatial resolution is 81.3(3) μm, which is close to the estimated value of 75 μm.

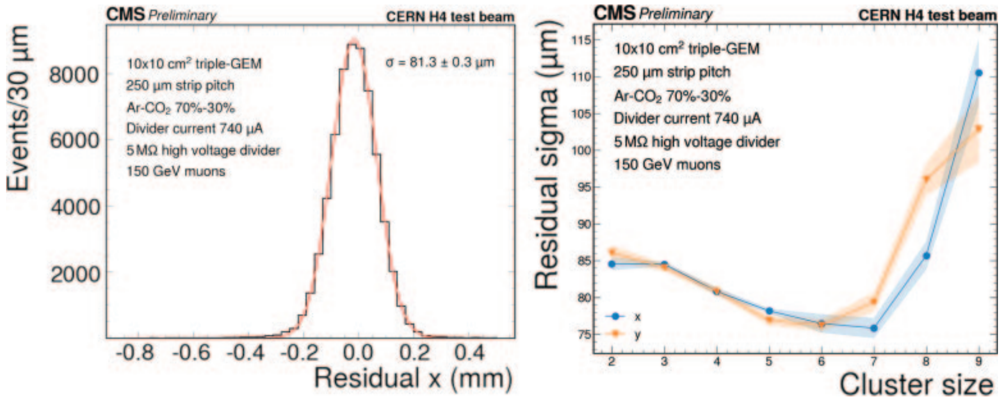

Fig. 2. – Left: residuals of BARI-02 for all cluster sizes. Right: dependence of spatial resolution on the cluster size for the same detector.

As shown in fig. 2 (right), the spatial resolution is strongly dependent on the event cluster size. The best resolution is between 4 and 7 strips. High cluster size events can be attributed to the production of delta rays, which spread the avalanche among a higher number of strips and the center of cluster is not a good estimate for the hit position. For low cluster size events, on the other hand, one possible explanation can be related to the low signal to noise ratio of the tracking chambers: strips of the real cluster fall below the VFAT threshold, thus biasing the cluster center position. Furthermore, as it can be seen from fig. 1 (right), the cluster spreads on average among 3-4 strips. Therefore, the resolution on the position of the center of the cluster improves when increasing the cluster size.

5. – Conclusions

The RD51 test beam showed good performances of the high spatial resolution triple-GEM prototypes, measuring for the spatial resolution a value of 81.3(3) μm, close to the estimated value of 75 μm. In particular, we demonstrated the capability of the chambers of performing tracking complying with the requirements of the LEMMA program. Efficiency at the working point (730 μA) lays between 85% and 100% for all the tracking chambers; the DAQ integration has been proved successfully.

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