Study of GEM-based detectors spatial resolution

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Abstract. Gas Electron Multiplier (GEM) based coordinate detectors are used at different high energy physics centres and at Budker Institute of Nuclear Physics particularly. These detectors possess a spatial resolution in ten micron scale together with high rate capability up to $10^7\ cm^{-2}s^{-1}$. Thus, the precise investigation of best possible spatial resolution, achieved with GEM-detectors, is the subject of interest. The experimental data, accumulated by the moment, gives the possibility to compare it with the simulation results. The simulation of applied detector configurations includes transport of electrons through the detector and tracking of avalanche evolution inside the working volume, as well as obtaining signal distribution on the readout strips. The spatial resolution, obtained in the simulation of an individual detector, is found to be essentially better (the difference is about two standard deviations) than the experimental results. Further efforts to find out the reasons of the contradiction between the simulation and measurements were made. In particular, the simulation of complete experimental set-up (including tracking detectors) was performed. The results of individual detector simulation and the simulation of complete set-up were determined to generally coincide.

1. Introduction

Tracking detectors based on Gas Electron Multipliers [1] are used in several projects [2], [3] at Budker Institute of Nuclear Physics. Firstly, they operate at the Tagging System of the KEDR experiment at the electron-positron collider VEPP-4M since 2010 [4], [5]. Secondly, GEM-based detectors are included to the Photon Tagging System of the DEUTERON facility at VEPP-3 storage ring [6], [7]. The readout in these detectors is provided by straight and inclined strips with a pitch of 500 μm. Thirdly, a new detector for Test Beam Facility (TBF) at VEPP-4M collider [8], [9], having orthogonal strips with a pitch of 250 μm, was assembled in 2018 and its characteristics were measured [10]. The present work is aimed to study the limits of spatial resolution of the triple-GEM detectors, which could be measured experimentally. For this purpose the simulation of complete experimental set-up was developed and different readout structures were considered. The results of simulation were compared with the measurements performed with the detectors.

2. General simulation description

The simulation study on spatial resolution of the triple-GEM detectors [11], [12], [13] was performed in two stages. At first, primary 1 GeV electrons with momentum perpendicular to the detector plane and randomly distributed initial transverse coordinates were transported through the complete model of the detector, described in GEANT4 [14] (Table 1). After recording of all energy depositions in the drift gap, the second stage was started that included

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Table 1. Materials of the triple-GEM detector.

Name	Material	Width
First layer	Kapton	50 μm
Cathode	Copper	5 μm
Drift gap	Ar-CO_2(25%)	3.0 mm
GEM-1	Table 2	60 μm
First transport gap	Ar-CO_2(25%)	1.5 mm
GEM-2	Table 2	60 μm
Second transport gap	Ar-CO_2(25%)	1.5 mm
GEM-3	Table 2	60 μm
Induction gap	Ar-CO_2(25%)	2.0 mm
Anode	Copper	5 μm
Last layer	Kapton	50 μm

Table 2. Materials of one GEM. The thinned out factor is 0.8.

Name	Material	Width
Up GEM Electrode	Thinned out Copper	5 μm
GEM Kapton	Thinned out Kapton	50 μm
Down GEM Electrode	Thinned out Copper	5 μm

introduction of gas gain fluctuation, electrons diffusion, distribution of signal on readout strips, accounting of electronics noise and calculation of the measured track position with Centre-Of-Gravity (COG) method. Gas gain fluctuations were accounted by multiplication of every energy deposition on random Gauss value with centre at one and standard deviation, equal to (0.3/2.35), which corresponds to the experimental results [15] on study of photon absorption in triple-GEM detector. The coefficient of transverse electron diffusion was set equal to 300 $\mu m/\sqrt{cm}$ according to previously obtained results on detailed simulation of electron diffusion process [10]. The electronics noise was accounted by adding to the signal at each strip a random Gauss distributed value with centre at zero and standard deviation, corresponding to average energy deposition in the drift gap (set to be 1 keV) and pre-defined value of Signal-to-Noise Ratio (SNR), which, in turn, was chosen according to the experimental parameters and was equal to 150. Thus, standard deviation of electronics noise was constant and equal to (1 keV/SNR). We were interested in one-coordinate resolution only.

3. Individual detector simulation

Firstly the simulation of individual detector was performed. The coordinate of the track, passing through the simulated detector, was known exactly in this case. Standard deviation of the difference between true and measured (calculated with COG algorithm) coordinates (residuals) was the spatial resolution of individual detector. The simulation was provided for the readout structure, where each second strip could accept signal. Hence, strip pitch was two times larger than strip width. Such structure corresponded to one, implemented at DEUTERON and TBF types of the detector. Strip pitch for DEUTERON readout structure was equal to 500 μm, and for TBF type – equal to 250 μm. The simulation was carried out for different values of strip pitch. Number of strips, involved in the coordinate calculation with COG method, should be varied in order to account the signal distribution shape correctly. Therefore for strip pitch 100 – 400 μm a strip was involved in COG calculation (triggered) if signal on it exceeded 10% of maximum signal, corresponding to the considered distribution. The study showed that average number of triggered strips for 400 μm pitch was equal to 2.9. Consequently, 400 μm pitch is a critical value, which defines the border between algorithms, because minimum number of strips in COG calculation is 3 for providing correct results with this method. Besides number of strips, involved in the calculation, the procedure of residuals approximation, providing the final value of spatial resolution, is of significant interest. For strip pitch 100 – 500 μm Gauss distribution was applied in order to find out the coordinate resolution. For a pitch 600 – 1000 μm the distribution of residuals was similar to uniform with enhancement (~ 2 times) of events number at sidebands. The change of distribution shape for 600 – 1000 μm pitch is the consequence of COG with three strips algorithm application for the case when only one or two strips are triggered. So resolution in the case of 600 – 1000 μm was determined as standard deviation of uniform distribution with Δl width, i.e. $\Delta l/\sqrt{12}$ with 5% error of Δl estimation. The residuals distributions for individual detector simulation are shown in Figure 1. The results of individual detector simulation are shown in Figure 2 and in Table 3.

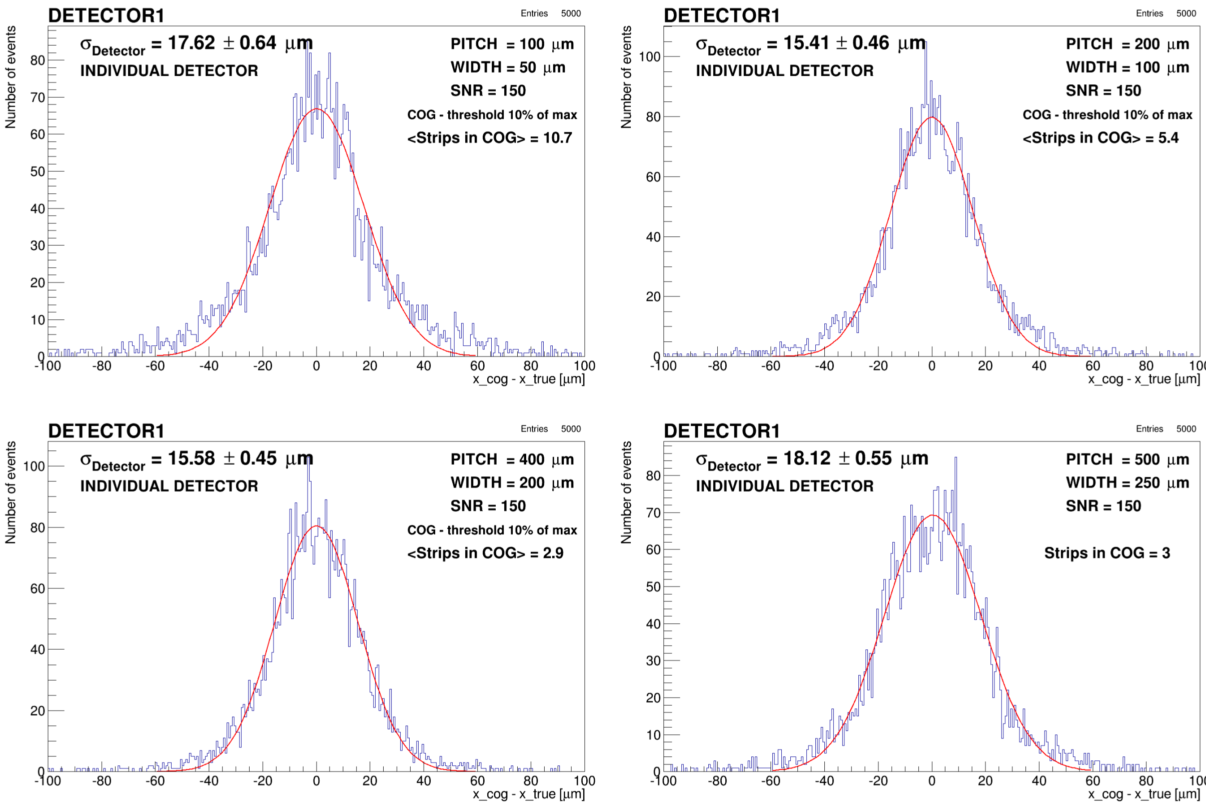
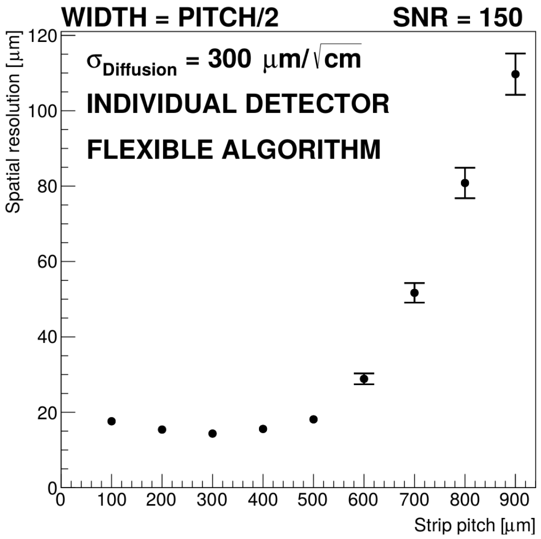


Figure 1. Residuals distributions, obtained in the individual detector simulation.

Table 3. Spatial resolution parameters in the individual detector simulation

Strip pitch, μm	$\sigma_{Detector}$, μm	Algorithm	$< N_{strips} >$	Approximation
100	17.6 ± 0.6	10% threshold	10.7	Gauss
200	15.4 ± 0.5	10% threshold	5.4	Gauss
300	14.4 ± 0.4	10% threshold	3.7	Gauss
400	15.6 ± 0.5	10% threhold	2.9	Gauss
500	18.1 ± 0.6	3 strips	3.0	Gauss
600	28.9 ± 1.4	3 strips	3.0	Uniform, $\Delta l = 100\ \mu m$
700	52.0 ± 2.6	3 strips	3.0	Uniform, $\Delta l = 180\ \mu m$
800	80.8 ± 4.0	3 strips	3.0	Uniform, $\Delta l = 280\ \mu m$
900	109.7 ± 5.5	3 strips	3.0	Uniform, $\Delta l = 380\ \mu m$
1000	144.3 ± 7.2	3 strips	3.0	Uniform, $\Delta l = 500\ \mu m$



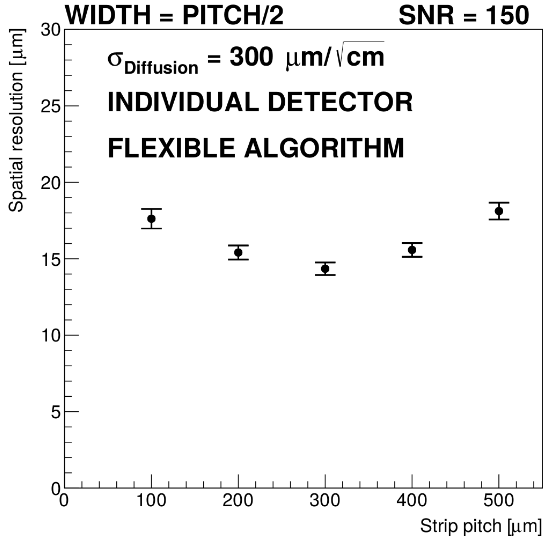


Figure 2. Spatial resolution of individual triple-GEM detector in the simulation.

4. Simulation of complete set-up

Complete (total) set-up for measuring the detector spatial resolution was simulated. Complete set-up included three equal detectors, situated at the equal distance between each other. The materials of one detector are listed in Table 1. The distance between anodes of neighboring detectors was $L = 5.829\ cm$. Central detector was under study and the others were tracking ones. Electrons with 1 GeV energy and randomly distributed x-coordinate were gun through the set-up. The distribution of the difference between calculated coordinate in the central detector (based on the measurements of the tracking detectors) and measured coordinate in the central detector (distribution of residuals) was analyzed (Figure 3) and spatial resolution of central detector was determined.

The difference between individual detector simulation and the complete set-up simulation is that the contribution of tracking detectors resolution and the contribution of multiple scattering effect into extracted standard deviation of residuals distribution ($\sigma_{primary}$) should be subtracted in the last case. The formula for final spatial resolution determination is

$$\sigma_{final} = \sqrt{\sigma^2_{primary} - \frac{1}{2}\sigma^2_{Detector} - \sigma^2_{MS}}, \quad (1)$$

where $\sigma_{Detector}$ is the spatial resolution of individual detector for corresponding strip pitch, σ_{MS} is the standard deviation of track coordinate distribution due to multiple scattering in the central detector:

$$\sigma_{MS} = \frac{\sigma_\theta \cdot L}{2}, \quad (2)$$

where, in turn, σ_θ is the standard deviation of track angle distribution due to multiple scattering in the studied detector [16]:

$$\sigma_\theta = \frac{13.6}{\beta cp[MeV]}\sqrt{\frac{X}{X_0}}(1 + 0.038\log(\frac{X}{X_0})). \quad (3)$$

The amount of material (X/X_0) for the applied GEANT4 model was calculated as 0.31%. Hence, $\sigma_\theta = 0.596\ mrad$ and $\sigma_{MS} = 17.4\ \mu m$. The results of complete set-up simulation for strip pitches, giving Gauss distribution of residuals, and the comparison with experimental results [10] are presented in Figure 4 and Tables 4, 5.

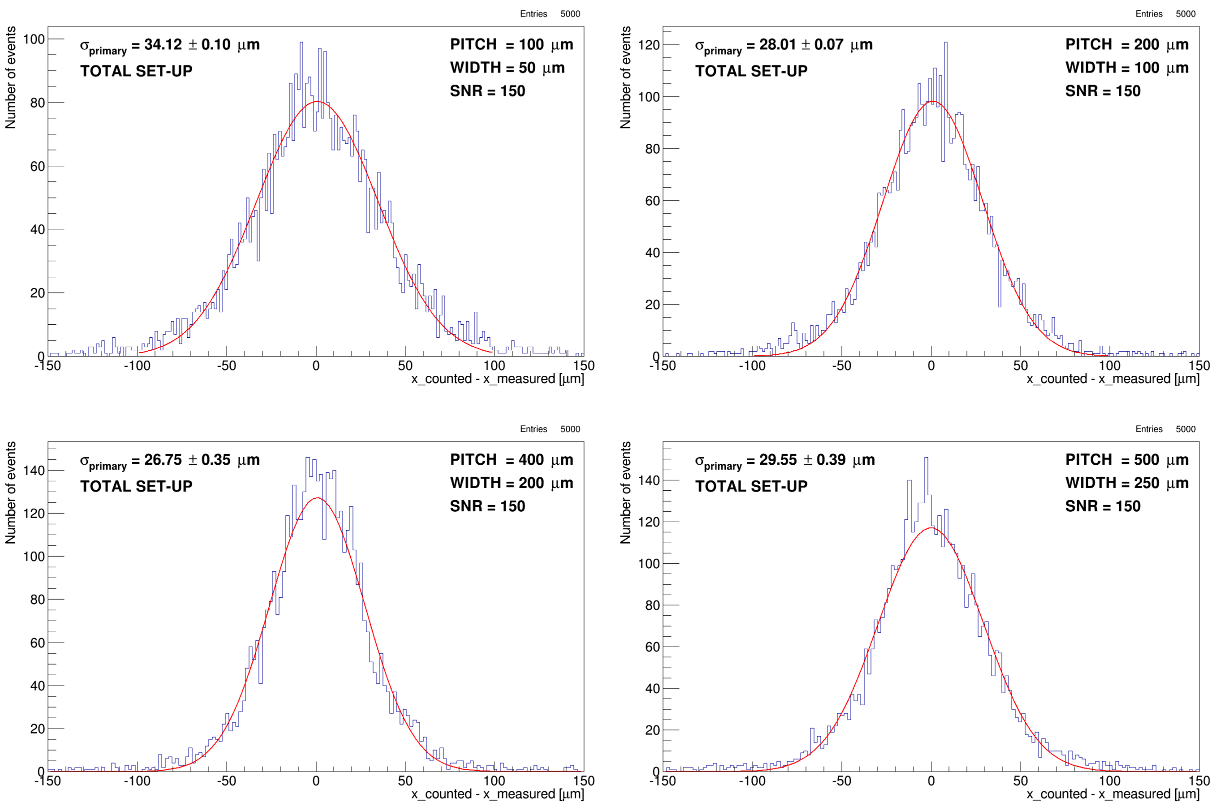


Figure 3. Residuals distributions, obtained in the complete set-up simulation.

Table 4. Spatial resolution parameters in the complete set-up simulation.

Strip pitch, μm	$\sigma_{Detector}$, μm	σ_{MS}, μm	$\sigma_{primary}$, μm	Spatial resolution, μm
100	17.6 ± 0.6	17.4	34.1 ± 0.1	23.5 ± 0.7
200	15.4 ± 0.5	17.4	28.0 ± 0.1	15.7 ± 0.5
300	14.4 ± 0.4	17.4	26.0 ± 0.1	13.0 ± 0.4
400	15.6 ± 0.5	17.4	26.8 ± 0.4	13.1 ± 0.6
500	18.1 ± 0.6	17.4	29.6 ± 0.4	15.6 ± 0.7

Table 5. Experimental results on detectors spatial resolution.

Detector	Strip pitch, μm	Spatial resolution, μm
TBF	250	$31.5 \pm 0.9(stat.)^{+6.9}_{-7.5}(syst.)$
DEUTERON-3	500	$46.6 \pm 0.1(stat.)^{+10.2}_{-11.0}(syst.)$
DEUTERON-4	500	$38.5 \pm 0.2(stat.)^{+8.4}_{-9.1}(syst.)$

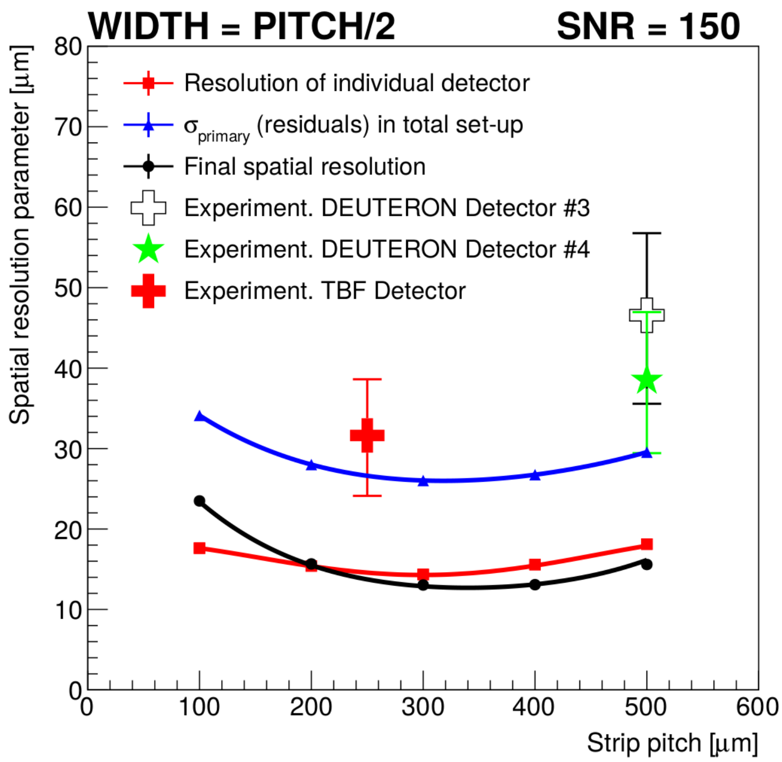


Figure 4. Spatial resolution of triple-GEM detector within the complete set-up simulation in comparison with individual detector simulation and the experimental results.

5. Conclusions

Experimentally measured spatial resolution of the investigated triple-GEM detectors is found to be worse than one, obtained in the simulation of complete set-up. Particularly, experimental values are in range $30 - 50\ \mu m$, and spatial resolution in the simulation is about $10 - 20\ \mu m$. The difference between experiment and simulation is within 2 standard deviations of experimental results errors with leading systematical contribution. We think that the reason of such difference is connected with not precise simulation of soft δ-electrons ranges in the drift volume of the detector. Characteristic values of such ranges obtained with GEANT4 simulation seems to be understated. Therefore study on this problem is to be continued.

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