Spatial resolution of the detectors based on Gas Electron Multipliers

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INSTR-2020 – Instrumentation for Colliding Beam Physics
Novosibirsk, Russia, 24 – 28 February 2020

Abstract

Coordinate detectors based on Gas Electron Multipliers (GEM) are used in experiments at many high energy physics centers and at Budker Institute of Nuclear Physics particularly. Spatial resolution of these detectors is known to be in tens microns scale. Also the detectors possess a rate capability up to 10^7 cm^{-2} s^{-1}. Consequently, the precise study of best possible coordinate resolution, achieved with GEM-detectors, is a significant task. The experimental data, collected by the moment, provides the possibility to compare it with the results of the simulation. The simulation of the detector performance includes transport of electrons through the detector medium, tracking of an avalanche evolution inside the working volume, as well as registering of the signal distribution on the readout strips. The simulation of individual detector shows that its spatial resolution is considerably better than the experimental results with the difference about two standard deviations. In order to find out possible reasons of the contradiction between measurements and the simulation of the individual detector, the simulation of complete experimental set-up (including tracking detectors) is performed. The results of complete set-up and individual detector simulations are determined to coincide in general.

Introduction

Tracking detectors based on Gas Electron Multipliers [1] are used in several projects [2] at the 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 [3]. Secondly, GEM-based detectors are included to the Photon Tagging System of the DEUTERON facility at VEPP-3 storage ring [4]. 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 [5], having orthogonal strips with a pitch of 250 µm, was assembled in 2018 and its characteristics were measured.

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 whole experimental set-up was developed and different readout structures were considered. The results of simulation were compared with the measurements performed with the detectors.

General simulation description

The simulation study on spatial resolution of the triple-GEM detectors 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 (Table 1). After recording of all energy depositions in the drift gap, the second stage was started that included 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 Center-Of-Gravity (COG) method.

Gas gain fluctuations were accounted by multiplication of every energy deposition on random Gauss value with center at one and standard deviation, equal to (0.3/2.35), which corresponds to the experimental results [6] 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 [7] on detailed simulation of electron diffusion process with HEED, ANSYS and Garfield++ programs. The electronics noise was accounted by adding to the signal at each strip a random Gauss distributed value with center 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.

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

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. 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 Fig. 1. The results of individual detector simulation are shown in Fig. 2 and in Table 3.

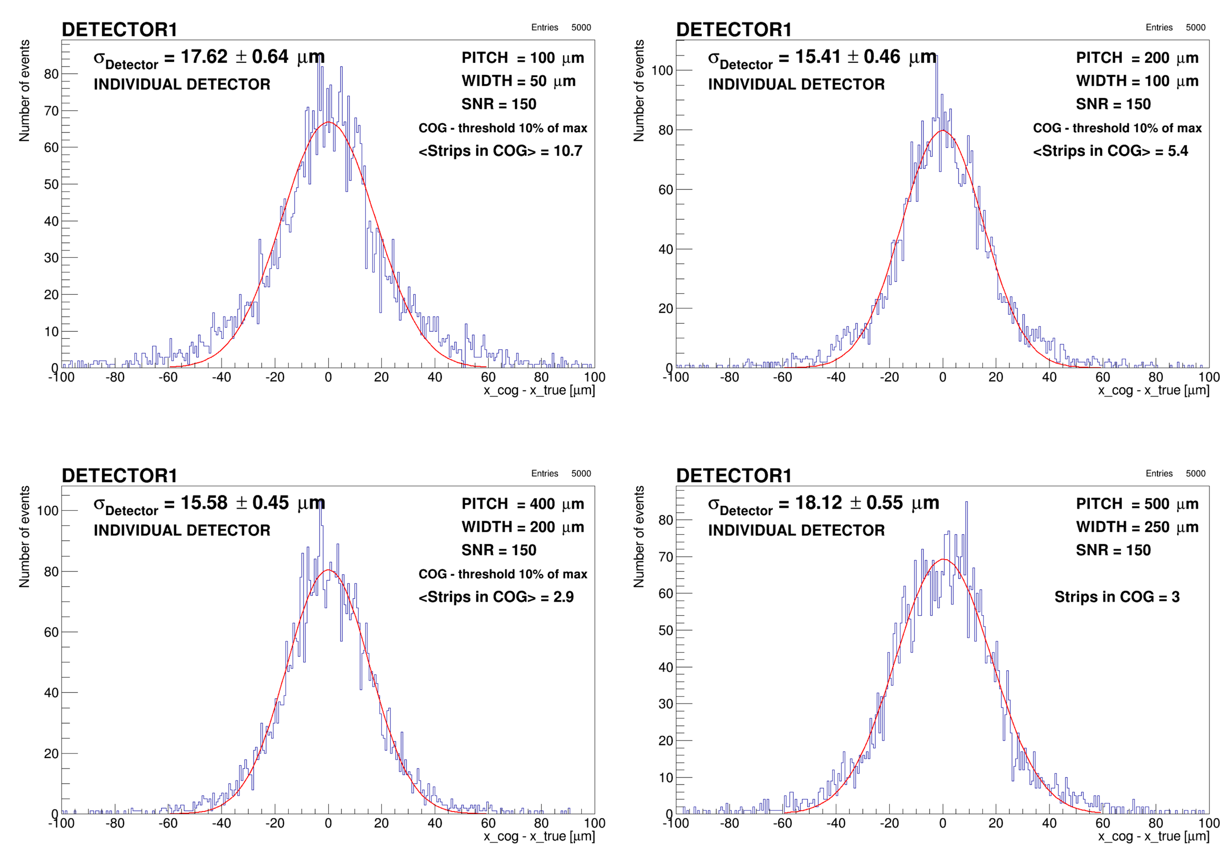

Fig. 1. Residuals distributions, obtained in the individual detector simulation.

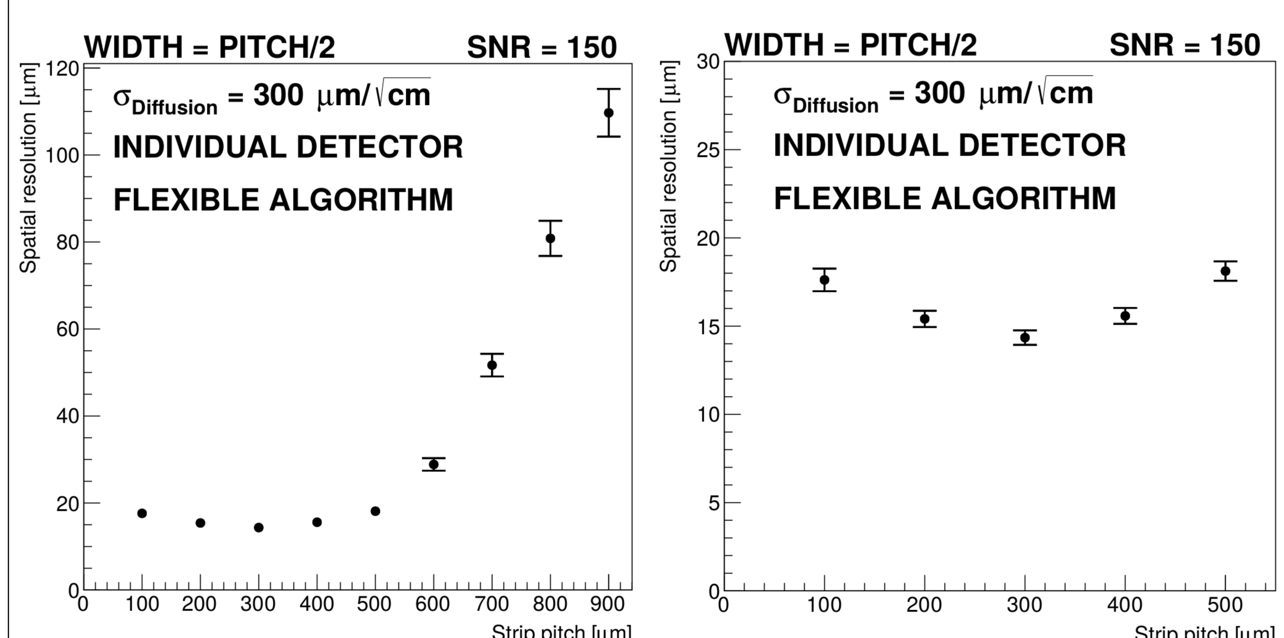

Fig. 2. Spatial resolution of individual triple-GEM detector in the simulation.

Table 3. Spatial resolution parameters in the individual detector simulation.

Strip pitch, µm	$\sigma_{Detector}$, µm	Algorithm	$<N_{strips}>$	Approximation
100	17.62 ± 0.64	10% threshold	10.7	Gauss
200	15.41 ± 0.46	10% threshold	5.4	Gauss
300	14.35 ± 0.41	10% threshold	3.7	Gauss
400	15.58 ± 0.45	10% threshold	2.9	Gauss
500	18.12 ± 0.55	3 strips	3.0	Gauss
600	28.87 ± 1.44	3 strips	3.0	Uniform, Δl = 100 µm
700	51.96 ± 2.60	3 strips	3.0	Uniform, Δl = 180 µm
800	80.83 ± 4.04	3 strips	3.0	Uniform, Δl = 280 µm
900	109.70 ± 5.48	3 strips	3.0	Uniform, Δl = 380 µm
1000	144.34 ± 7.22	3 strips	3.0	Uniform, Δl = 500 µm

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 counted 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 and spatial resolution of central detector was determined.

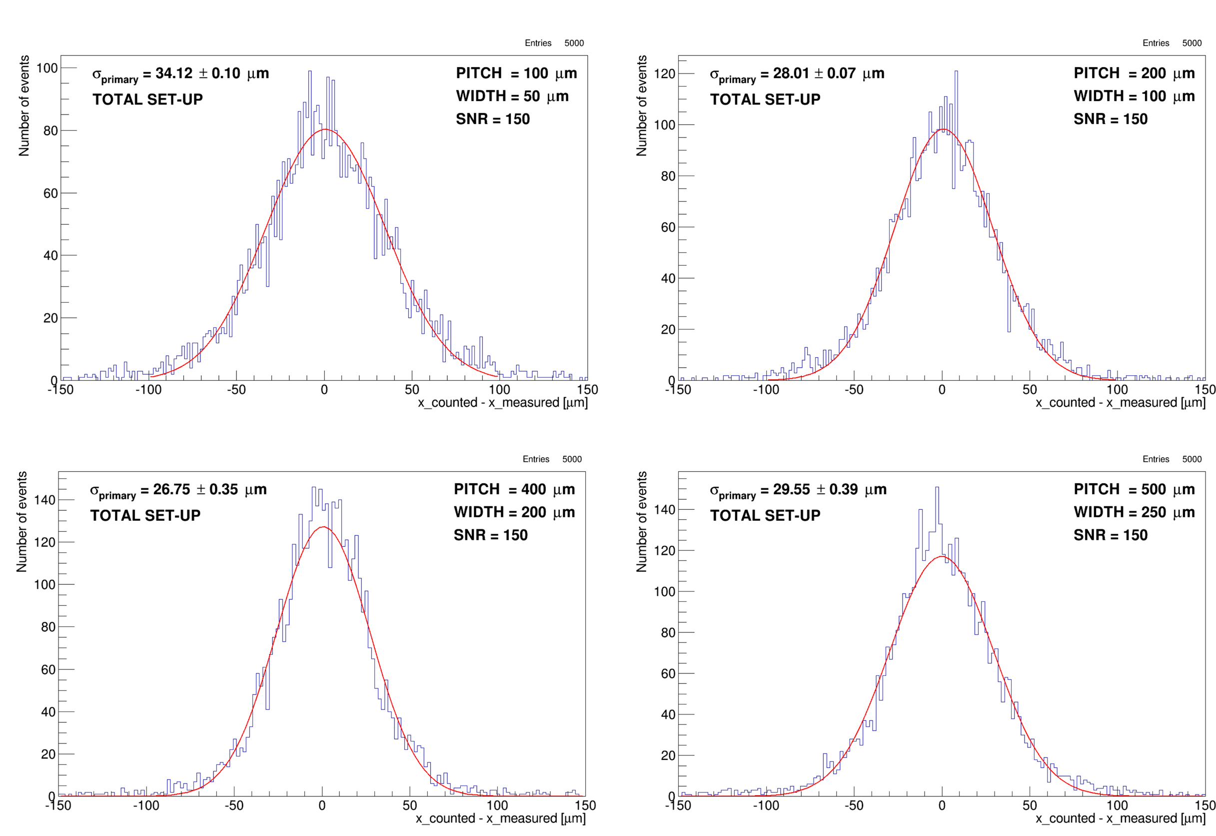

Fig. 3. Residuals distributions, obtained in the complete set-up simulation.

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 was

$$\sigma_{final} = \sqrt{\sigma_{primary}^2 - \frac{1}{2}\sigma_{Detector}^2 - \sigma_{MS}^2},$$

where $\sigma_{Detector}$ is the spatial resolution of individual detector for corresponding strip pitch, $\sigma_{MS} = \frac{\sigma_\theta L}{2}$, where, in turn, σ_θ is the standard deviation of track angle distribution due to multiple scattering in the studied detector:

$$\sigma_\theta = \frac{13{,}6}{\beta cp\ [\mathrm{MeV}]}\, z\sqrt{\frac{X}{X_0}}\left[1 + 0{,}038\ \ln\left(\frac{X}{X_0}\right)\right].$$

The amount of material (X/X_0) for the applied GEANT4 model was calculated as 0.31%. Hence, σ_θ = 0.596 mrad and σ_{MS} = 17.37 µm.

The results of complete set-up simulation for strip pitches, giving Gauss distribution of residuals, and the comparison with experimental results [7] are presented in Fig. 4 and Tables 4, 5.

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	17.62 ± 0.64	17.37	34.12 ± 0.10	23.49 ± 0.65
200	15.41 ± 0.46	17.37	28.01 ± 0.07	15.66 ± 0.47
300	14.35 ± 0.41	17.37	26.03 ± 0.07	13.04 ± 0.42
400	15.58 ± 0.45	17.37	26.75 ± 0.35	13.08 ± 0.57
500	18.12 ± 0.55	17.37	29.55 ± 0.39	15.59 ± 0.67

Table 5. Experimental results on detectors spatial resolution.

Detector	Strip pitch, µm	Spatial resolution, µm
TBF	250	$31.63 \pm^{6.98}_{7.51}$
DEUTERON Detector #3	500	$46.57 \pm^{10.20}_{11.00}$
DEUTERON Detector #4	500	$38.52 \pm^{8.44}_{9.09}$

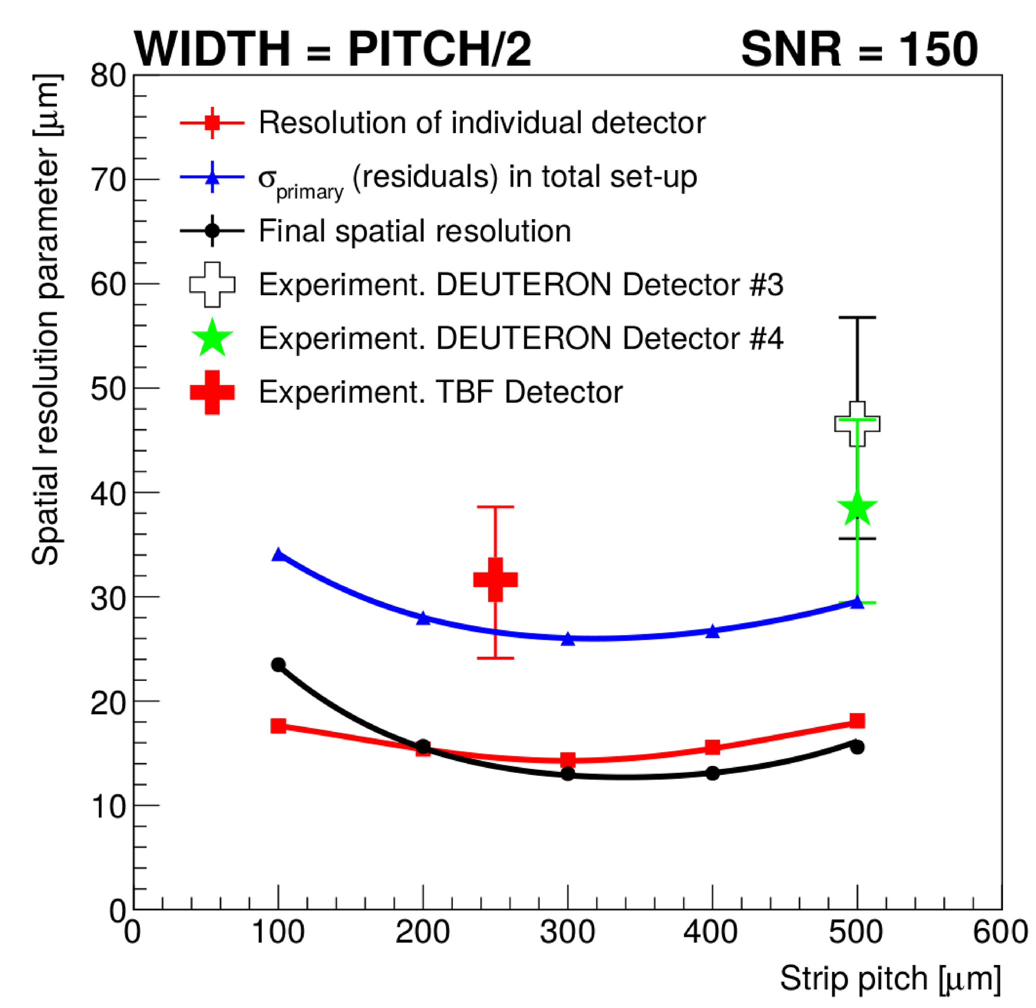

Fig. 4. Spatial resolution of triple-GEM detector within the complete set-up simulation in comparison with the experimental results.

Conclusions

Experimentally measured spatial resolution of the investigated triple-GEM detectors was found to be worse than one, obtained in the simulation of complete set-up. Particularly, experimental values are in range 30 – 50 µm, and spatial resolution in the simulation is about 15 – 20 µm. The difference between experiment and simulation is within 2 standard deviations of experimental results errors with leading systematical contribution.

References

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