Joint Institute for Nuclear Research
Veksler and Baldin Laboratory of High Energy Physics

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

Realistic simulation of BM@N GEM detectors: model implementation and testing

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Abstract

The Lorentz shift of electrons in a magnetic field is taken into account with simulating the response of a GEM detector. Dependences of the determined coordinate x on the track angle, the values of the Lorentz shift of electrons and its dispersion for the gas mixtures $ArC0_2$ and ArC_4H_{10} were obtained. The momentum resolution was obtained as a function of the momentum for the deuteron-carbon (dC) process, and the invariant mass of the Λ-hyperon was determined. The obtained results are close to those obtained in the experiment.

Contents

1. Introduction

Heavy ion collision experiments at high energies provide unique possibilities for studying the properties of nuclear matter at extreme densities and temperatures. In a collision, nuclear matter heats up and contracts for a very short period of time. At moderate temperatures, nucleons are excited in baryon resonances that decay with the emission of mesons. At higher temperatures baryon-antibaryon pairs are also produced. If baryons dominate, these strong interacting particles (baryons, antibaryons and mesons) constitute hadronic or baryonic matter. If the density of nuclear matter formed as a result of the interaction is sufficiently large, quark-gluon structure of nucleons appears. At more higher temperatures or densities of nuclear matter, quarks and gluons form a new phase: a quark-gluon plasma (QGP). Under such extreme conditions the following properties of strong-interacting matter can be studied: the parameters of the equation of state (EoS) of nuclear matter at high temperatures and densities of baryons; microscopic structure of strongly-interacting matter depending on the temperature and density of baryons; modification of the properties of hadrons in nuclear medium, which may be a manifestation of restoration of chiral symmetry. Theoretical models offer different possible scenarios to describe these features of strongly interacting matter. Therefore, new experimental data with high resolution and statistics are necessary in order to test various theoretical predictions. [1]- [2]

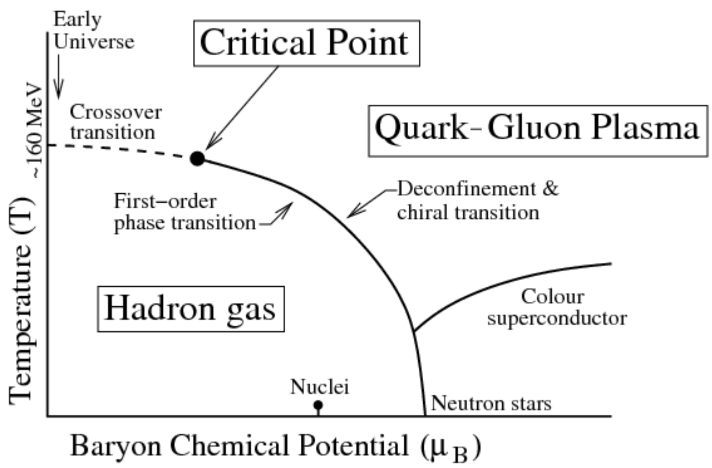


Figure 1.1: QCD phase diagramm [1]

2. BM@N project

2.1. Nica complex

BM@N experiment (Barionic Matter at Nuclotron) is located in Join Institute of Nuclear Reearch and is included in the future complex NICA (Nuclotron-based Ion Collider fAcility).

[1] https://cds.cern.ch/record/1695331/plots

The schematic view of the NICA-Nuclotron complex, as well as the location of the BM@N facility is shown in Fig. 2.2. The figure also shows sources of light and heavy ions, beam booster, Nuclotron accelerator and collider NICA. The aim of BM@N experiment is to study the interaction of relativistic heavy ion beams with fixed targets. The Nuclotron will provide the experiment by particle beams from protons to gold ions with kinetic energy in the range from 1 to 6 GeV per nucleon. For ions with a charge-to-atomic weight ratio of 1/2 the maximum kinetic energy is 6 GeV per nucleon. The maximum kinetic energy for heavy ions with the ratio $Z/A \sim 1/3$ is 4.5 GeV per nucleon. The maximum kinetic energy of protons equals to 13 GeV. The channel length for transporting the beam from the Nuclotron to the BM@N experiment is about 160 meters. It consists of 26 elements of magnetic optics: 8 dipole magnets and 18 quadrupole lenses. The planned intensity of the gold ion beam accelerated and accumulated in the Nuclotron and the booster and outputted to the BM@N facility will be up to 107 ions per second. The extracted gold ion beam is expected at the end of 2018. In the period until 2018 it is planned to accelerate and output the following bundles into the BM@N experimental zone: polarized deuteron beam in 2016 (its already done), carbon, argon and krypton beams in 2017 year. During this period the planned intensity of the beam at the BM@N facility will be 106 ions per second. Proton-proton interactions will be studied after modernization of the Nuclotron in 2018 using a proton beam and a liquid target hydrogen. [3]

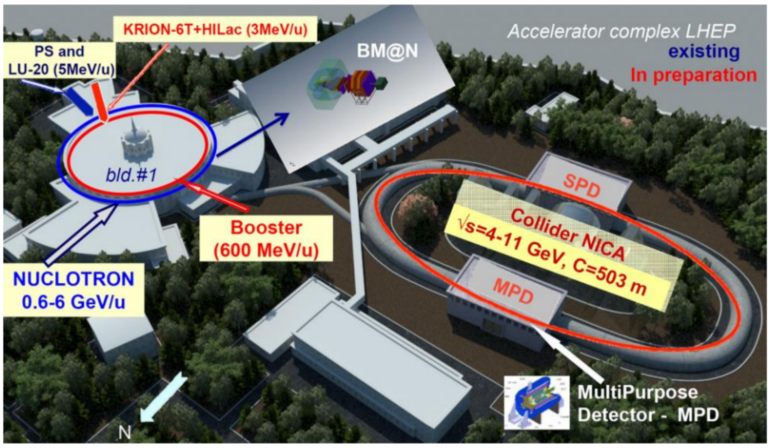


Figure 2.2: The schematic view of the NICA.

2.2. BM@N experiment and GEM detectors

The schematic view of the proposed experimental setup is shown in Fig. 2.3. The experiment combines measurement of track parameters with high accuracy with time-of-flight information for the particle identification and involves measurement of the total energy for analyzing the centrality of collisions. The momentum and multiplicity of charged tracks will be measured using 2-axis GEM detectors (Gas electronic multipliers) located behind the target inside the analyzing magnet, as well as drift/straw cells (DCH, Straw) located outside the magnetic field. GEM detectors are able to function at high loads particles, as well as in a strong magnetic field. The gap for detectors between poles of the analyzing magnet is about 1 meter. The magnetic field can vary up to a maximum value of 1.2 T, which allows to optimize the geometric efficiency (acceptance) and pulse resolution for the BM@N detector in various processes and with various beam energies. Time-of-flight detectors based on mRPC technology (Multigap Resistive Plate Chambers) with strip read allows you to separate Hadrons (π, K, P), as well as light nuclei with momentum up to several GeV/c, formed in multiparticle events. The ZDC Calorimeter (Zero Degree Calorimeter) is designed for determining the impact parameter of the collision (centrality) by measuring energy of particle-fragments of the beam. The T0 detector, partially overlapping the rear hemisphere around the target, is planned to be used to measure the centrality of a heavy ion collision, the formation of a trigger, and the starting signal (T0) for mRPC-1,2 detectors. Electromagnetic calorimeter will be installed behind the drift/straw chambers and mRPC-2 detector for studying processes with formation in the final state $\gamma, e\pm$.

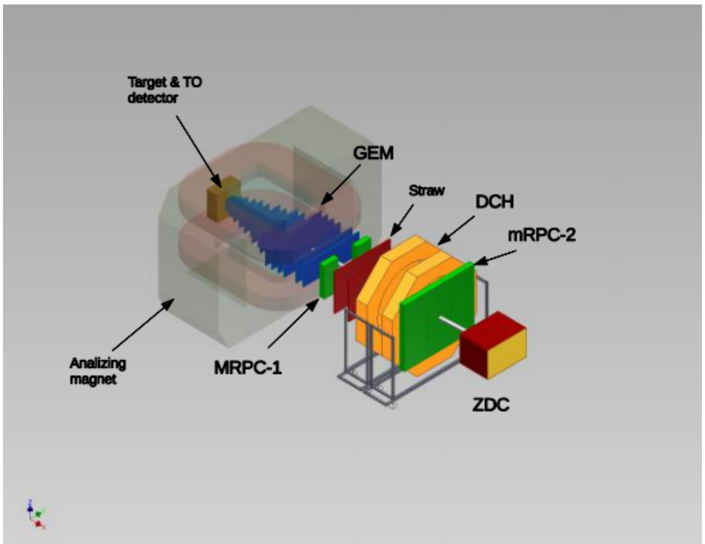


Figure 2.3: The schematic view of the BM@N experiment.

The central track system of the BM@N experiment is based on 2-coordinate Detectors GEM (Gas Electron Multiplier), each detector with 3 electrodes- multipliers of electrons. The GEM detectors are manufactured using technology, developed at CERN. They have already been used in various experiments (COMPASS, JLAB, STAR, CMS).

The Gas Electron Multiplier (GEM) consists of a thin, metal-clad polymer foil 50 μm thick, and coated on both sides with copper foil 5 μm thick,, chemically pierced by a high density of holes (typically 50 to 100 per mm^2). The holes are in the form of a double cone and are arranged in the form of a hexagonal matrix; Their pitch is 140 μm, and the diameter of 60-80 μm for metal and 40-60 microns in the center of the film. On application of a difference of potential between the two electrodes, electrons released by radiation in the gas on one side of the structure drift into the holes, multiply and transfer to a collection region. Each hole acts as an individual proportional amplifier. The multiplier can be used as detector on its own, or as a preamplifier in a multiple structure; in this case, it permits to reach large overall gains in harsh radiation environment. Simpler, sturdier and more effective are detctors using multiple cascaded GEM foils. The separation between amplification stages and read-out contribute to the safety of operation and permit freedom of design of the charge collecting electrode. [5]

3. Simulation of BM@N GEM detectors

3.1. Description of the model

At this moment active work is underway to simulate the BM@N experiment by the Monte Carlo method. Modeling for optimizing BM@N detectors is performed using the generated Au + Au events. For this purpose, a special software environment BMNRoot was developed [6]. In order to obtain a realistic response of the facility to interactions, a detailed geometric description of each of the detectors was realized.

Our task was to take into account the Lorentz shift of drifting electrons in the modeling of the response of the GEM detector. As it is known, the equation of motion of an electron in an electromagnetic field has the form

$$\frac{d\boldsymbol{p}}{dt} = e\boldsymbol{E} + \frac{e}{c}\left[\boldsymbol{v}, \boldsymbol{B}\right]. \tag{3.1}$$

Therefore, the electrons formed after the passage of the particle through the GEM detector will shift relative to their initial position along the axis perpendicular to the plane of the electric and magnetic field vectors. The software GARFIELD ++ was used to determine the mean shifts of electrons under the action of Lorentz force. The structure of the GEM detector used in the simulation is presented in Fig. 3.4. The mean electron shiftt and their diffusion depend on the distance to the readout plane. These dependences were approximated with polynomials of different degrees. In particular, for the gas mixture $ArCO_2$(70/30), the electron diffusion is piecewise continuous, and for the mixture ArC_4H_{10} (90:10), the diffusion was approximated with a polynomial of the fifth degree.

In the work, only the mixtures mentioned above were considered. Namely, for the gas mixture $ArCO_2$ (70/30)and the fields $E = 1000 : 2500 : 3750 : 6300$ V/cm: the mean shift is approximated by a polynomial of the third degree with the following coefficients:

$$p_0 = 0.000227984; p_1 = 0.0614758; p_2 = 0.157119; p_3 = -0.0799265.$$

[3]D.Baranov [4]

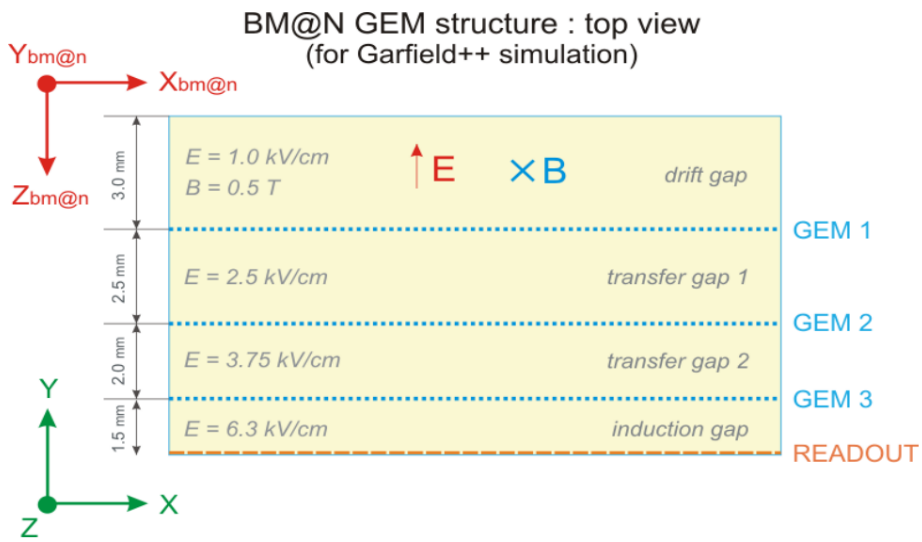


Figure 3.4: Structure and characteristics of GEM module for $ArCO_2$(70/30) and fields: E = 1000:2500:3750:6300 V/cm, B = 0.5 T.[3]

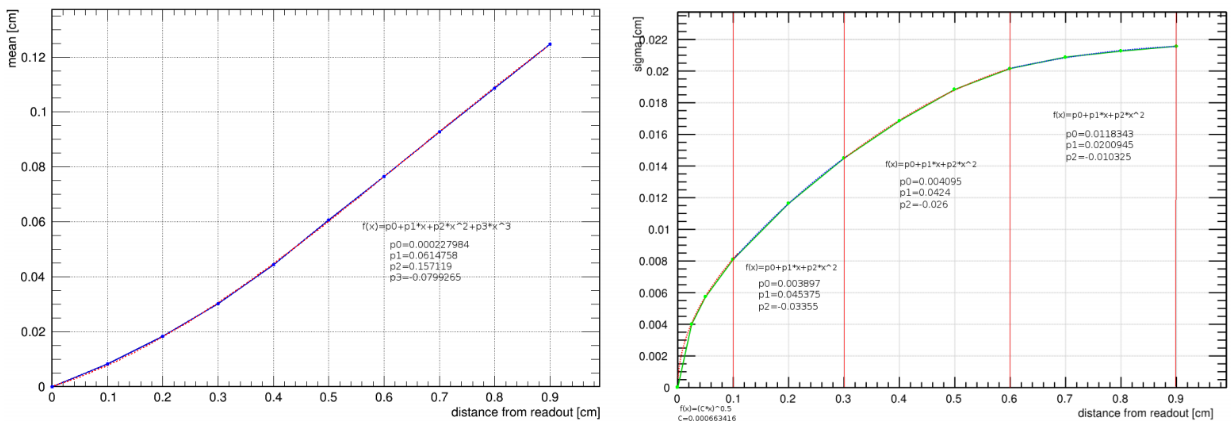


Figure 3.5: Diffusion and drift of electrons in an electromagnetic field of GEM module, obtained with the software package Garfield $ArCO_2$(70/30) and for fields: E = 1000:2500:3750:6300 V/cm, B = 0.5 T.

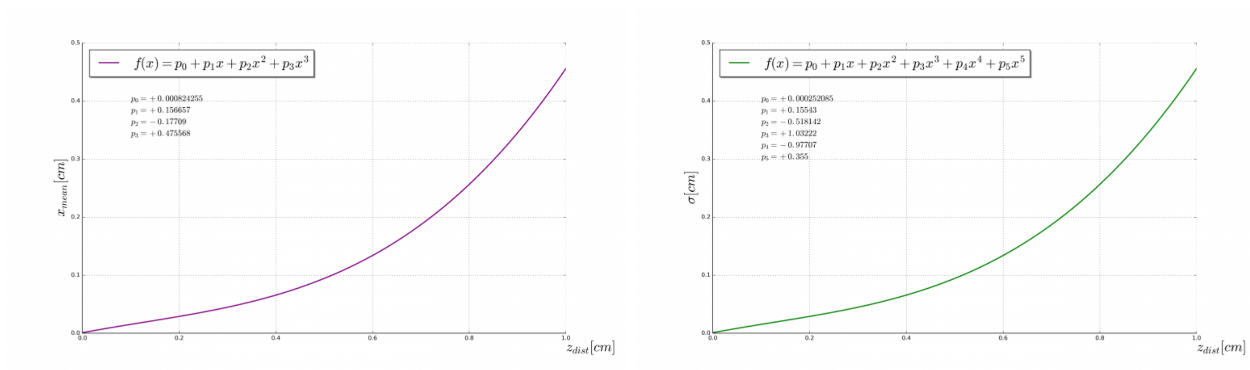


Figure 3.6: Diffusion and drift of electrons in an electromagnetic field of GEM module, obtained with the software package Garfield ArC_4H_{10} (90/10) and fields: E = 880: 1920: 2780: 3160 V/cm, B = 0.8 T

Diffusion is given by a piecewise-continuous function in the form

$$\sigma = \begin{cases} \sqrt{0.00063461 z_{dist}}, & \text{if } z_{dist} < 0.1\,[cm] \\ 0.003897 + 0.045375 z_{dist} - 0.03355 z_{dist}^2, & \text{if } 0.1 \leq z_{dist} < 0.3\,[cm] \\ 0.004095 + 0.0424 z_{dist} - 0.025 z_{dist}^2, & \text{if } 0.3 \leq z_{dist} < 0.6\,[cm] \\ 0.0118343 + 0.0200945 z_{dist} - 0.010325 z_{dist}^2, & \text{if } z_{dist} \geq 0.6\,[cm]. \end{cases}$$

For the gas mixture ArC_4H_{10} (90/10) and the fields $E = 880 : 1920 : 2780 : 3160$ V/cm : the mean shift is approximated by a polynomial of the third degree with the following coefficients:

$$p_0 = 0.000824255; p_1 = 0.156657; p_2 = -0.17709; p_3 = 0.475568.$$

Diffusion is given by a polynomial of the fifth degree with the following coefficients:

$$p_0 = 0.000252085; p_1 = 0.15543; p_2 = -0.518142; p_3 = 1.03222; p_4 = -0.97707; p_5 = 0.355.$$

Also it is proposed that the electron drift has opposite directions for even and odd GEM stations.

3.2. Results

To test the model described above, various histograms were obtained. For the gas mixture $ArCO_2$ 70/30 and fields $B = 0.5$ T, $E = 1000 : 2500 : 3750 : 6300$ V/cm the dependences of the charge distribution on the reading strips were constructed (Fig. 3.7), the dependence of determined mean coordinate x on the track angle (Fig. 3.8) for the first and second stations.

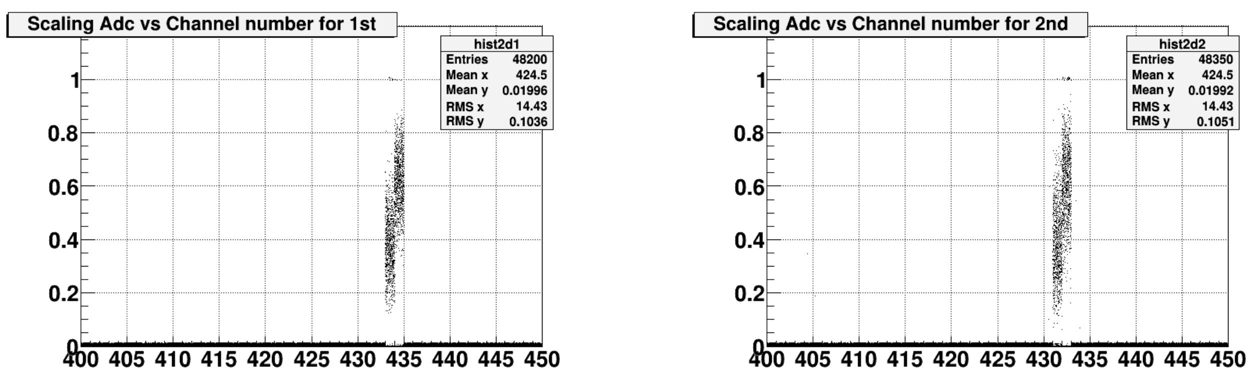


Figure 3.7: The normalized charge distribution on the strips for the first and second stations, respectively. Fields $B = 0.5$ T, $E = 1000 : 2500 : 3750 : 6300$ V/cm, gas mixture $ArCO_2$ 70/30.

It can be seen from the histogram that, because of the assumption that the electron drift for stations of different parity has different directions, the reading strips are different. The histogram was built for thousands of events, zero-angle track and momentum of π^--particles equals to 6 GeV.

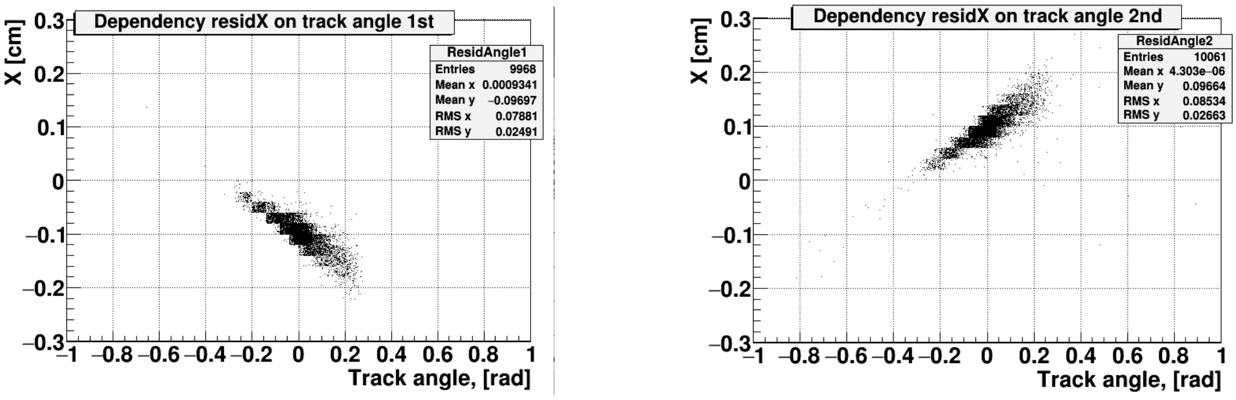


Figure 3.8: The dependence of determined mean coordinate x on the track angle in xOz-plane for the first and second stations, respectively. Fields $B = 0.5\,\mathrm{T}$, $E = 1000 : 2500 : 3750 : 6300$ V/cm, gas mixture $\mathrm{ArCO_2}$ 70/30, $2.0 < \eta < 5.0$.

From Fig.3.8 it can be seen, that there exist the dependence of determined mean coordinate from the track angle. Moreover, the shift is greater for the larger projection of the momentum on the x axis. This histogram was built for 10,000 events and for the mean z. Also, as we will see later, the coordinate z, for which there is no dependence on the track angle, exists.

Finally, for the gas mixture $ArCO_2$ 70/30 and the fields $B = 0.5\,\mathrm{T}$, $E = 1000 : 2500 : 3750 : 6300$ V/cm the mean shift of the center of the electron cluster was determined due to the Lorentz shift in a magnetic field $x_{mean} = 0.095257\,\mathrm{cm}$ and its dispersion $\sigma = 0.01\,\mathrm{cm}$.

Also, in experiment the gas mixture ArC_4H_{10} (90/10) and fields $E = 880 : 1920 : 2780 : 3160$ V/cm was used and below all results are given for this gas mixture. The dependences of the residual x on the track angle for the first and second station was obtained (Fig. 3.9-3.10), the mean shift of the center of electron cluster and its dispersion were determined (Fig. 3.11), the residual x reconstructed from the tracks and from the hits were obtained for four stations (see Appendix), a comparison of the residual x obtained from the model and from the experiment for the fourth station is shown(Fig. 3.12), an impulse resolution for the dC process was constructed (Fig.3.13) and also invariant mass of Λ-hyperon obtained with this model was obtained (Fig. 3.14).

The dependence of the x coordinate on the track angle in xOz - plane is shown in Fig. 3.9 - 3.10. This histogramms was obtained for different z-coordinate (mean and out). Note that we also observe a dependence on the value of z for which we define x. So, from the form of this dependence, we propose that for some value of z the coordinate x will not depend on the angle.

The mean shift of an electron clusteris shown in Fig. 3.11. From histogramm we can determine that Lorentz shift equals to 0.21 cm, and its dispersion - 0.06 cm. When this shift

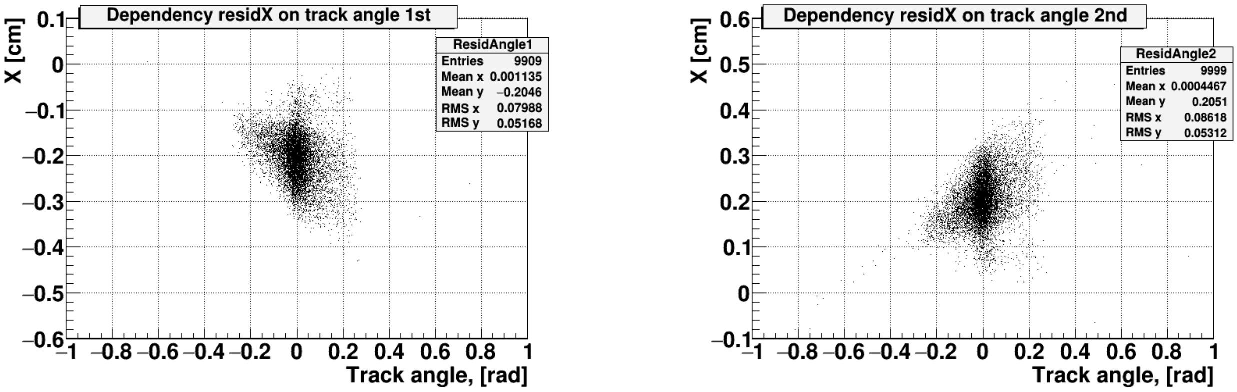


Figure 3.9: Dependences of the coordinate x (mean) on the track angle in the xOz plane for the 1st and 2nd station. Number of events = 10000.

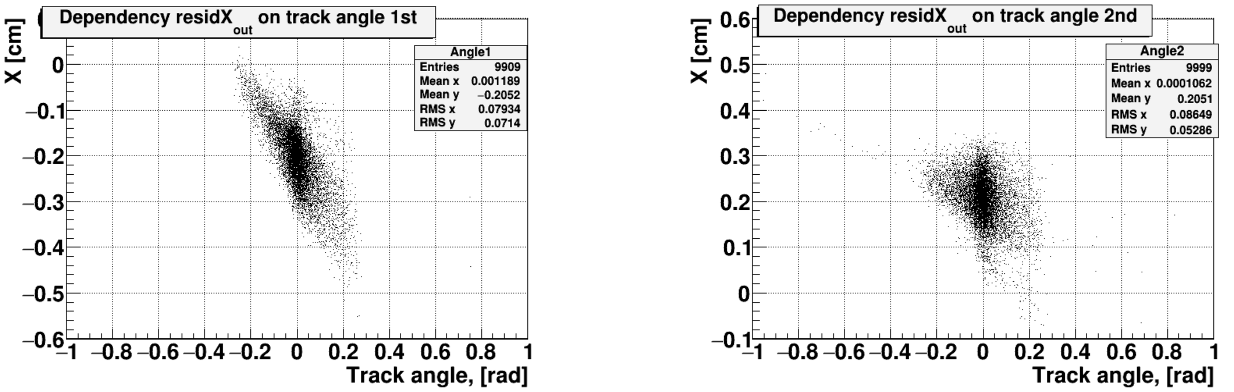


Figure 3.10: Dependences of the coordinate x (out) on the track angle in the xOz plane for the 1st and 2nd station. Number of events = 10000.

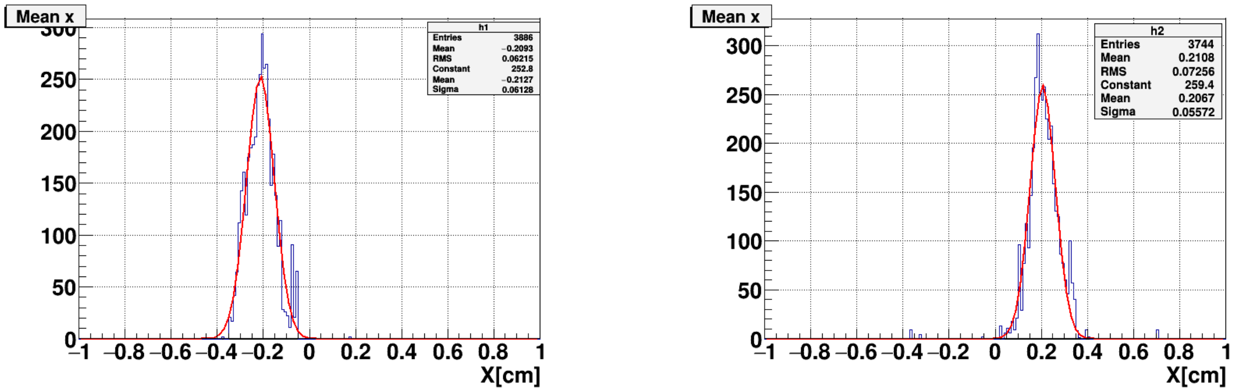


Figure 3.11: Histograms for determining the average center-shift of the cluster of electrons for the first and second stations, respectively. Number of events = 3000. $x_{mean} = 0.212826, \sigma = 0.0615281$.

value was taken into account, residual x reconstructed by tracks and hits were obtained for four stations (see Appendix). For the first station, reconstruction by tracks occurs with a large blur, since the space is limited only on one side, and this worsens the resolution for reconstructing.

For the fourth station the comparison of data obtained by the experiment and by model track reconstruction was produced. We obtain that the diffusion in both cases equals to 670 μm and 650 μm, respectively. Those, it rather well agrees with the experimental data.

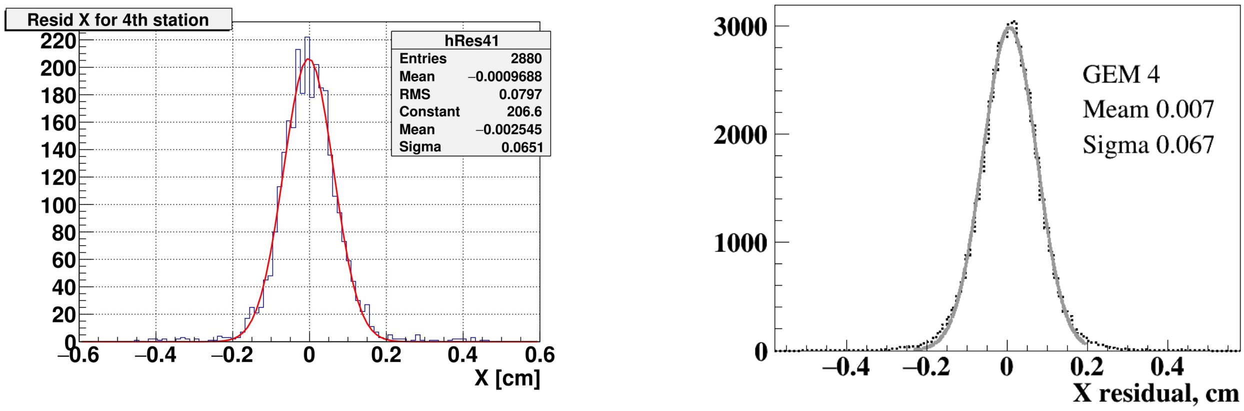


Figure 3.12: Comparison a residual x for the 4th station from the model (left) (tracks) and from the experiment (right).

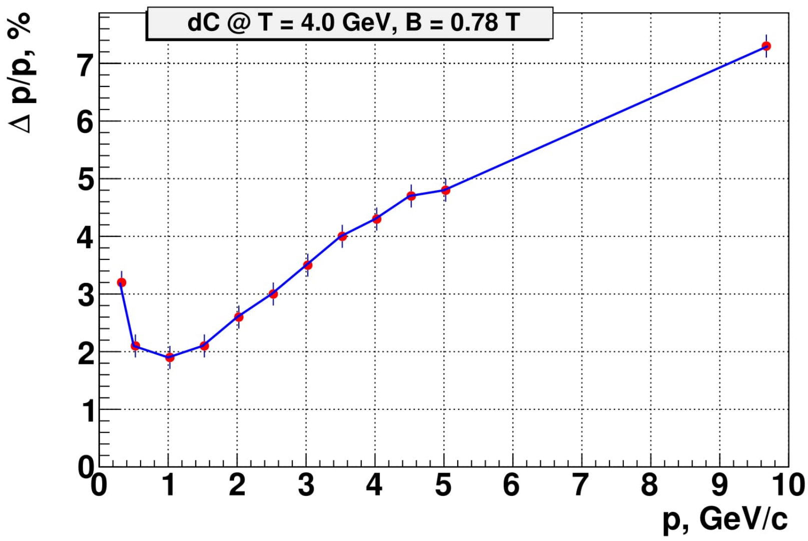


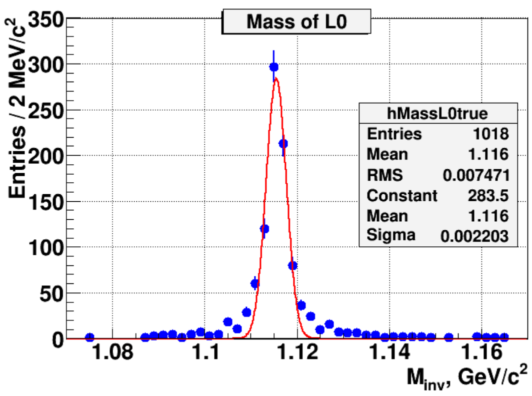
Figure 3.13: Momentum resolution dependence on the momentum. Number of events = 500000.

Also, a momentum resolution was constructed depending on the momentum. A point 9.8 GeV was added to it from the deuteron-deuteron process. The dependence for large momentum is assumed to be linear, which, taking into account the errors, is observed on the graph.

Finelly, we obtain the invariant mass of Λ-hyperon without the combinatorial background. Its value from the model equals to 1.116 GeV/c^2 and σ = 0.0022 GeV/c^2. These values are close to the experimental (Fig. 3.14 (right)).

4. Conclusion

In this paper, we took into account the Lorentz shift of electrons in a magnetic field for a realistic simulation of the response of the GEM detector. To do this, we used the data on the average shifts and diffusion from the Garfield++ software, the resulting dependencies were added to the code that implements the response.



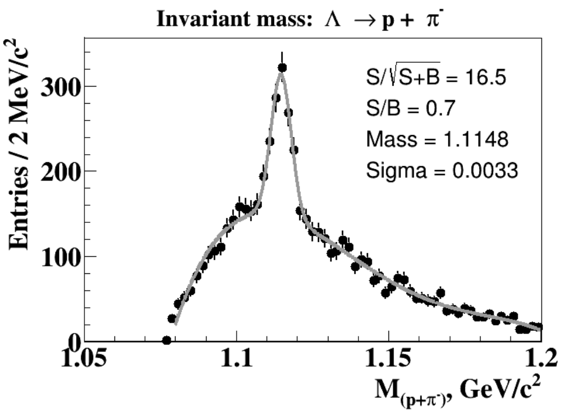


Figure 3.14: Invariant mass of Λ from the model (left) and from the experiment (right).

Simulations and reconstructions were carried out for various types of mixtures, namely for $ArCO_2$(70/30) and for ArC_4H_{10} (90/10) and for a different number of events. To check the obtained results, the residual x dependencies on the track angle in the xOz plane were constructed, the shifts and their dispersion for the track zero angle were determined, residual x dependencies were constructed taking into account the obtained mean shifts for reconstructions by tracks and hits. A comparison with experiment was made for the fourth station and it was found that the blurring was of the same order 650 and 670 μm. Also, the dependence of the momentum resolution on the momentum for the dC process was obtained and the point from the dd process was added. Finally, the invariant mass of the Λ -hyperon was determined without taking into account the combinatorial background and its resolution was 2.2 MeV, which is less than in the experiment 3.3 MeV.

To improve the results, it is necessary to take into account that in the experiment the drift region of the first two GEM chambers has a thickness of 5 mm, and consequently, the first two stations have a greater shifts and smearing.

Acknowledgements

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I want to express my gratitude to the University Center of JINR for giving me the opportunity to participate in the Summer Student Programme and the management of Veksler and Baldin Laboratory of High Energy Physics for providing a financial support.

References

[1] J. Adams et al, Nucl. Phys. A 757, 102-183 (2005)

[2] K. Adcox et al, Nucl. Phys. A 757, 184-283 (2005)

[3] Studies of baryonic matter at the Nuclotron (BM@N) http://bmnshift.jinr.ru/wiki/lib/exe/fetch.php?media=bmnproject2016_rus_short.pdf

[4] Analysis meeting http://bmnshift.jinr.ru/wiki/doku.php?id=analysis_meetings

[5] A.F. Buzulutckov "Physical basis of operation of cascade gas electronic multipliers", Bulletin of NSU, 2008 year, v. 3, r. 3.

[6] Simulation and Analysis Frameworks for MPD and BM@N at NICA http://mpd.jinr.ru

Appendix

<table>
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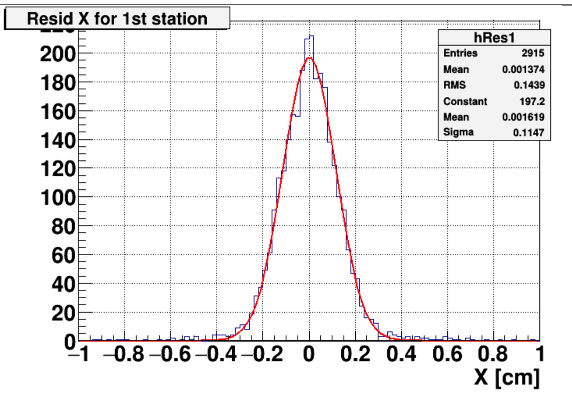
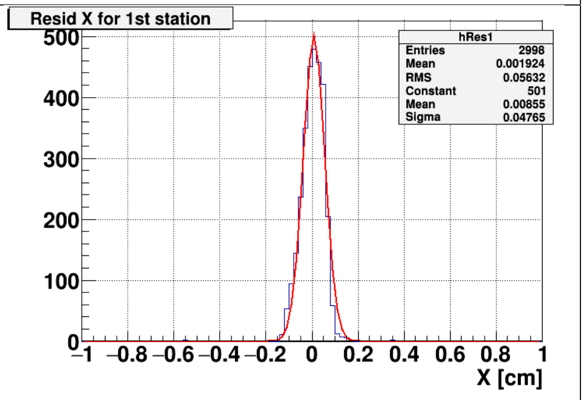
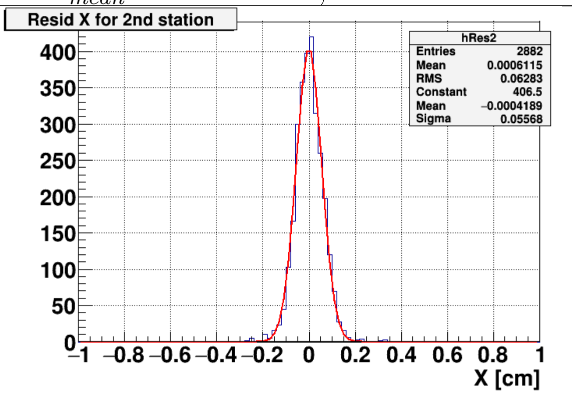
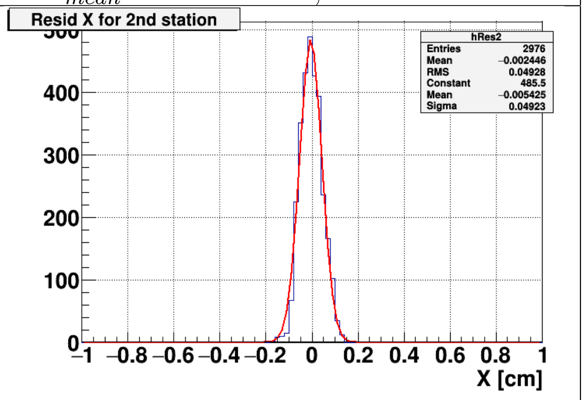
<tr><td>

$x_{mean} = 0.00161938, \sigma = 0.114708$</td><td>

$x_{mean} = 0.00855012, \sigma = 0.0476545$</td></tr>
<tr><td>

$x_{mean} = -0.000418937, \sigma = 0.055682$</td><td>

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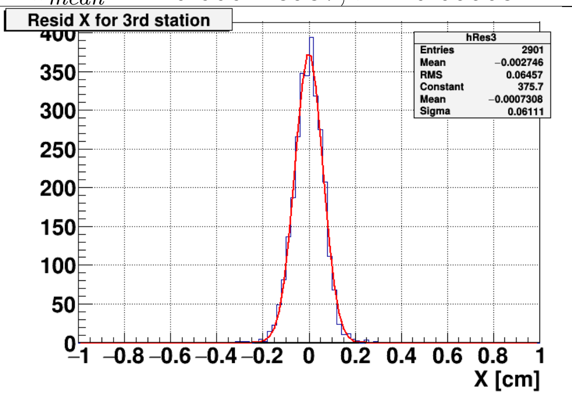
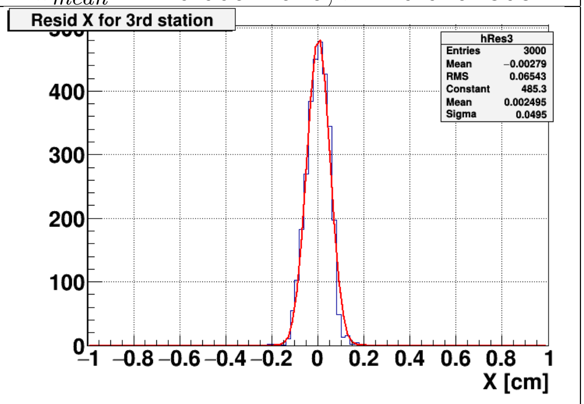
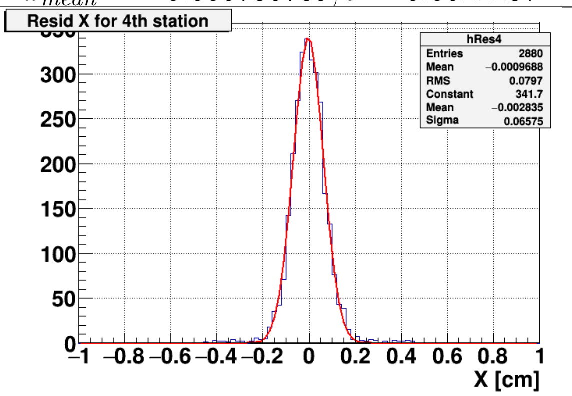
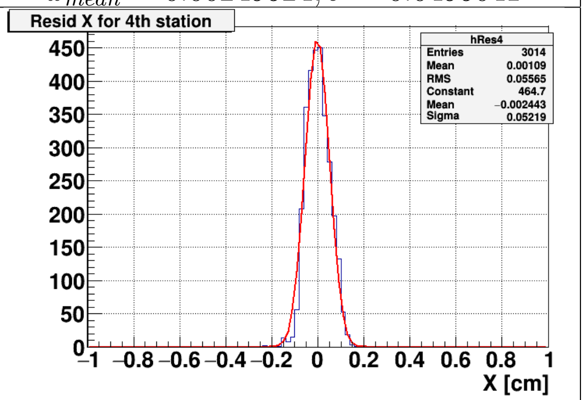
<tr><td>

$x_{mean} = -0.000730789, \sigma = 0.0611137$</td><td>

$x_{mean} = 0.00249524, \sigma = 0.0495041$</td></tr>
<tr><td>

$x_{mean} = -0.00283471, \sigma = 0.0946611$</td><td>

$x_{mean} = -0.00244324, \sigma = 0.0521881$</td></tr>
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