JOINT INSTITUTE FOR NUCLEAR RESEARCH
Laboratory of Information Technologies

JINR Summer Student Programme project report

Development and testing of the alignment of GEM detectors at BM@N

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Introduction

A modern high energy detector system consists of many detector stations. A positioning of stations with respect to each other causes the additional term in the error of track reconstruction. This term can be much bigger than the inner detector resolution. This problem is solved by the mathematical procedure of finding position corrections to each detector station. The procedure is called detector alignment.

The alignment of the BM@N experiment is developed with the BmnRoot framework. Actual version of the alignment program still has some problems and further development and testing needed. One of them is a configuration of constraints for matrix equations used to obtain detector positioning corrections.

The goal of the Summer Student Programme project is to improve detector alignment algorithm at BM@N experiment selecting a proper set of constraints for the matrix equations.

To carry out the project goals it is neccessary to perform the following tasks:

1. to study alignment methods of tracking system;
2. to study the MillePede program, the BmnRoot framework and the BM@N alignment algorithm;
3. to perform actual alignment procedure for GEM tracking system;
4. to develop and test the alignment procedure with new constraints.

1. BM@N experiment

The description of the experiment

BM@N (Baryonic Matter at the Nuclotron) is a fixed target experiment located at Joint Institute of Nuclear Research [1]. The goal of the experiment is to study the nuclear matter under extreme density and temperature. These extreme conditions are well suited for the investigation of the compressibility of the nuclear matter, in particular, the stiffness of the nuclear equation-of-state (EOS). The theoretical models suggest different possible scenarios for these modifications, so that new experimental data with high resolution and statistics are needed in order to disentangle the different theoretical predictions. The research program on heavy-ion collisions at the Nuclotron of the Joint Institute for Nuclear Research includes investigation of the reaction dynamics and nuclear EOS, study of the in-medium properties of hadrons, production of (multi)-strange hyperons at the threshold and search for hyper-nuclei [2].

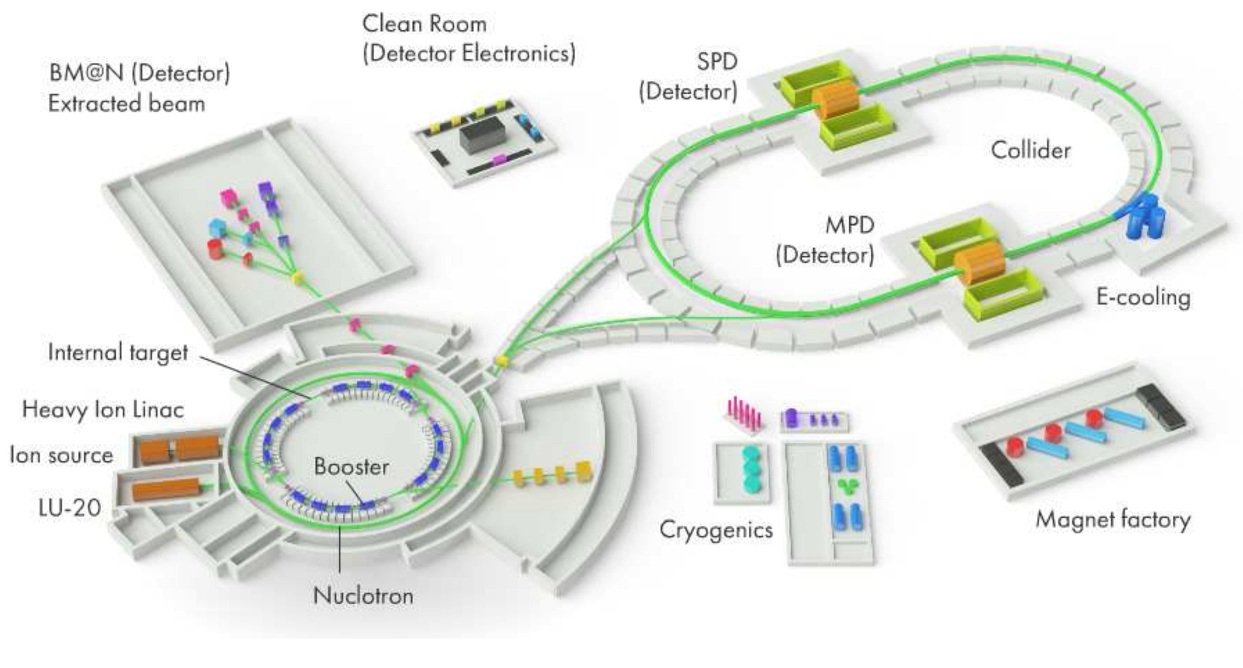

Figure 1.1 — BM@N experiment at extracted Nuclotron beam

The schematic view of the BM@N experiment and NICA collider is presented in figure 1.1. The BM@N facility is one of the main elements of the first stage of the NICA development aimed to study hot and dense matter in heavy ion collisions.

Experimental setup

A sketch of the proposed experimental setup is shown in figure 1.2. The experiment combines high precision track measurements with time-of-flight information for particle identification and uses total energy measurements for the analysis of collision centrality. The charged track momentum and multiplicity will be measured with the set of two coordinate planes of GEM (Gaseous Electron Multipliers) detectors located downstream of the target in the analyzing magnet and the drift/straw chambers (DCH, Straw) situated outside the magnetic field. The GEM detectors can resist to high rates of particles and are operational in strong magnetic field.

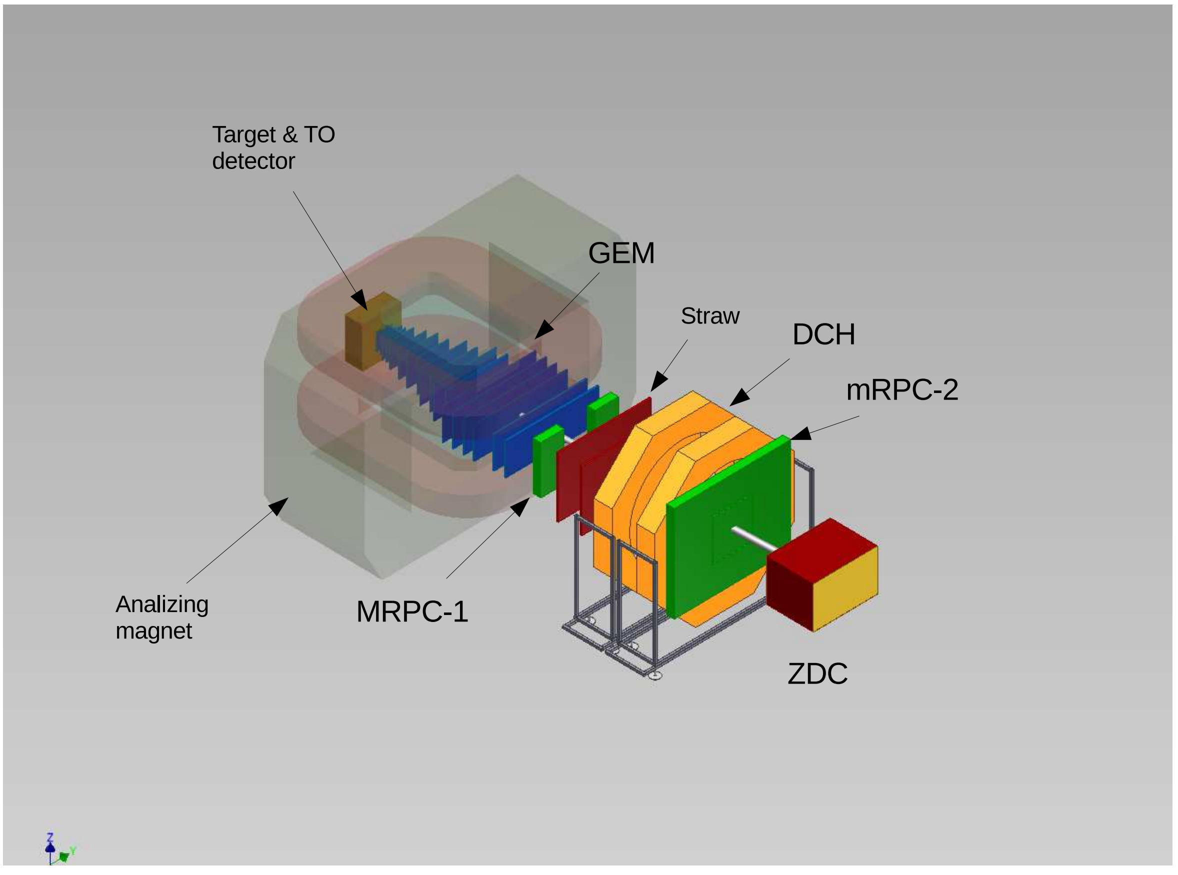

Figure 1.2 — The scheme of the full setup of BM@N experiment

The gap between the poles of the analyzing magnet is around 1 m. The magnetic field can be varied up to 1.2 T to get the optimal BM@N detector acceptance and momentum resolution for different processes and beam energies.

The design parameters of the time-of-flight detectors based on multi-gap resistive plate chambers (mRPC-1,2) with a strip read-out allow one to discriminate between hadrons (π, K, p) as well as light nuclei with the momentum up to a few GeV/c produced in multi-particle events. The zero degree calorimeter (ZDC) is designed for the analysis of the collision centrality by measuring the energy of forward going particles. The T0 detector, partially covering the backward hemisphere around the target, is planned to trigger central heavy ion collisions and provides a start time (T0) signal for the mRPC-1,2 detectors. An electromagnetic calorimeter will be installed behind the outer drift/straw chambers and mRPC-2 wall to study processes with electromagnetic probes ($\gamma, e^{\pm}$) in the final state.

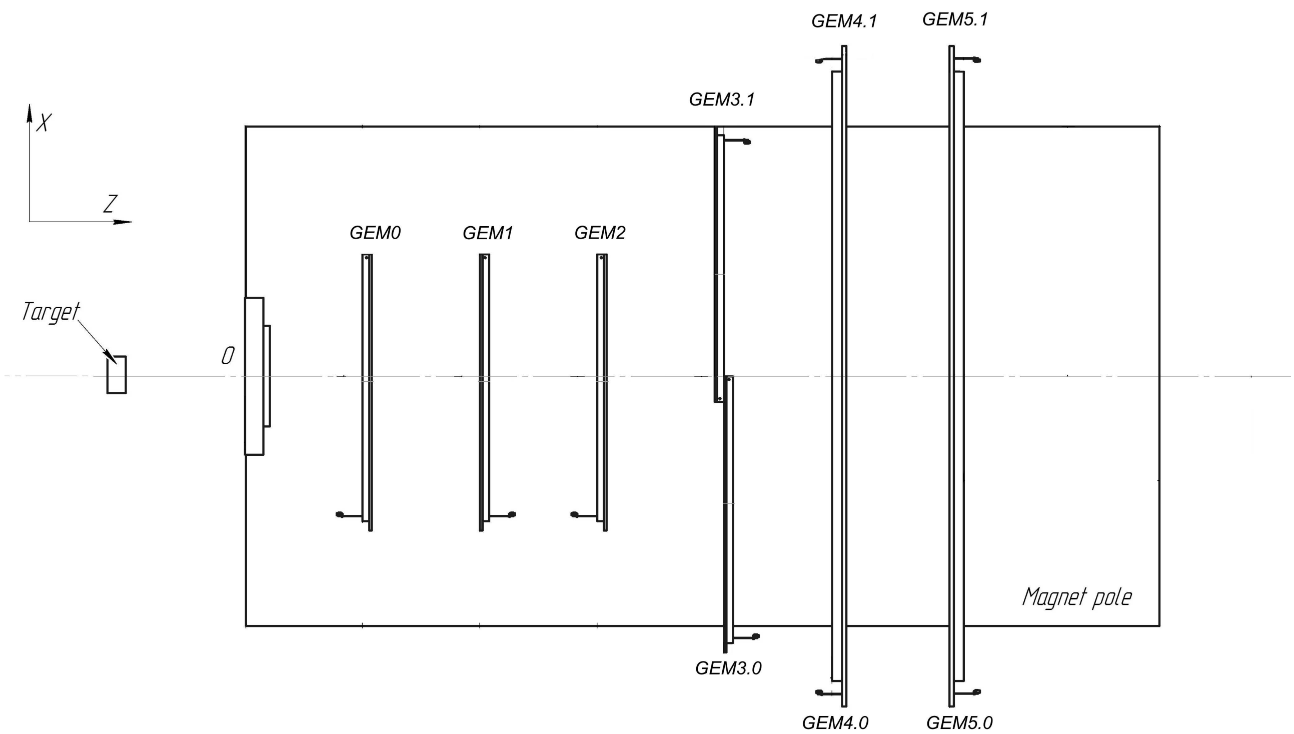

Figure 1.3 — The scheme of the GEM stations setup of BM@N experiment at 2017

The first technical run of the BM@N detectors was performed with the deuteron and carbon beams in March 2015. For the August 2017 the CPC detector and Straw Tubes are not installed yet. There are 6 GEM stations of 12 as well.

The scheme of GEM station setup for run of 2017 is presented on the figure 1.3.

The following reference frame is used at the experiment. Z axis is directed along the beam. Y axis is vertical down up. X axis is built in horisontal plane for right-hand system.

BmnRoot software package

The software and computing parts of the BM@N project are responsible for such activities as evaluation and calibration of the detector; storing, access, reconstruction and analysis of data; development and maintenance of the distributed computing infrastructure for physics analysis. The software framework BmnRoot is developed to support these tasks. It provides a powerful tool for detector performance studies, event simulation, and development of algorithms for reconstruction and physics analysis of data recorded by the BM@N facility. The BmnRoot is implemented in C++ programming language and based on the ROOT [4] environment and the object-oriented framework FairRoot [5] (which is developed for the FAIR experiment at GSI Institute).

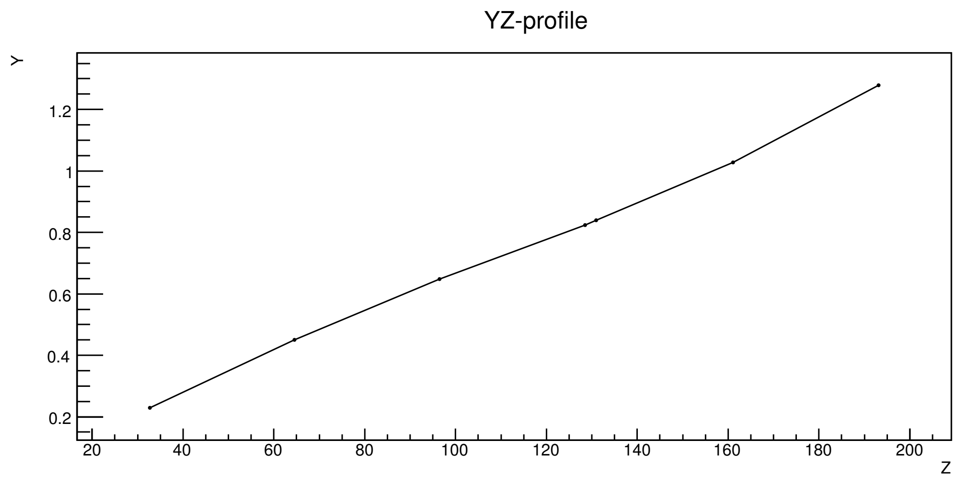

Figure 1.5 — The YZ projection of the beam track for simulated data with real magnetic field map and kinetic energy 4GeV/nucl.

The flexibility of the BmnRoot framework is gained through its modularity. The physics and detector parts could be written by different groups. The detector

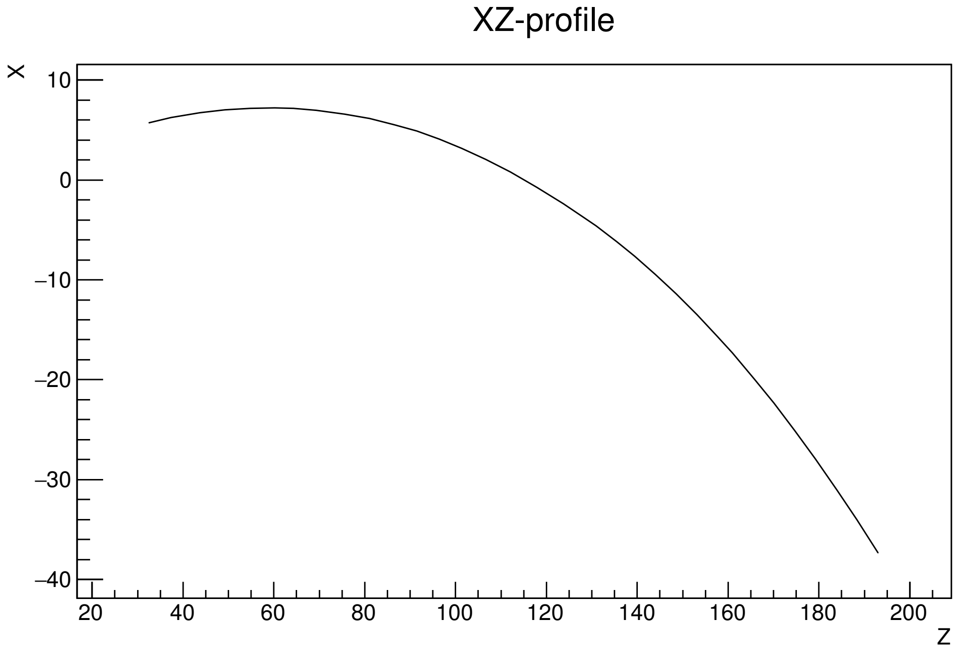

Figure 1.4 — The XZ projection of the beam track for simulated data with real magnetic field map and kinetic energy 4GeV/nucl.

response simulated by a package which is based on the Virtual Monte Carlo concept allows one to switch between Geant3, Geant4 transport packages without changing the user code. For a realistic simulation of various physics processes, an interface to the event generators for nuclear collisions (UrQMD, LAQGSM e.t.c.) is provided. One can easily choose between different modules, e.g. event generators. The same framework is used to define the experimental setup, provides simulation, reconstruction, and physics analysis of simulated and experimental data. Using the same internal structure user can easily compare the real data with the simulation results.

The BmnRoot environment also includes the tool for event navigation, inspection and visualization. The BM@N event display for Monte Carlo and experimental data is based on the EVE (Event Visualization Environment) package of the ROOT. The event display macro can be used to display both Monte Carlo points and tracks, and reconstructed hits and tracks, as well as a BM@N detector geometry. The Event Manager implemented in the framework delivers an easy way to navigate through the event tree and to make cuts on energy, particle PDG codes, etc. in selected events.

Examples of beam track projections obtained by applying BmnRoot simulation are presented in figures 1.4 and 1.5. The real magnetic field map was used. The kinetic energy of simulated collisions is 4 GeV.

2. Detector alignment

Introduction to detector alignment

The error of hit reconstruction is defined by two main factors. First is an inner resolution of detector and second is a measurement of detector position in global reference frame. The second term is preliminary defined by survey measurements but such approach affects a big impact to error with respect to the inner resolution.

The aim of alignment procedure is to reduce the second term in order to be closer to the inner resolution. It is reached by calculation of position corrections for each detector in the system.

The idea of the procedure is to minimize the χ^2-criteria which is a function of track-to-hit residuals:

$$\chi^2 = \sum_{i=1}^{n_{track}} \sum_{j=1}^{n_{det}} \frac{[S_{ij}(u_{ij}, \alpha_i^t, \alpha_j^a)]^2}{\sigma_j^2}, \tag{2.1}$$

where S_{ij} is a track-to-hit distance, u_{ij} is coordinate of the hit, i is index of a given track, j is index of a given detector station, n_{track} is number of the considered tracks, n_{det} is number of detectors in the system, α_i^t are local parameters of track, α_j^a are global parameters of alignment, σ_j is the detector resolution [6].

The residual S_{ij} can be extended into series up to first order:

$$S_{ij} = S_{ij}^0 + \sum_k \frac{\partial S_{ij}}{\partial \alpha_k} \alpha_k, \tag{2.2}$$

where α is a vector of all local and global parameters.

Expression 2.2 allows one to formulate an optimization problem. The derivative of χ^2 should be equal to 0:

$$\frac{1}{2} \frac{\partial \chi^2}{\partial \alpha_m} = \sum_i \sum_j \frac{1}{\sigma_j^2} \frac{\partial S_{ij}}{\partial \alpha_m} (S_{ij}^0 + \sum_k \frac{\partial S_{ij}}{\partial \alpha_k} \alpha_k) = 0. \tag{2.3}$$

This equation system gives global alignment parameters as a solution. Implementation of these corrections to positions of detectors gives a new description of detector geometry. This procedure can be used iteratively until the detector positions become known precisely.

Alignment of GEM detectors at BM@N

The alignment procedure is implemented within the BmnRoot framework. The first step of each iteration is a track reconstruction. One can use zero values as well as calculations from previous runs to be used for first approximation of position corrections in the reconstruction procedure.

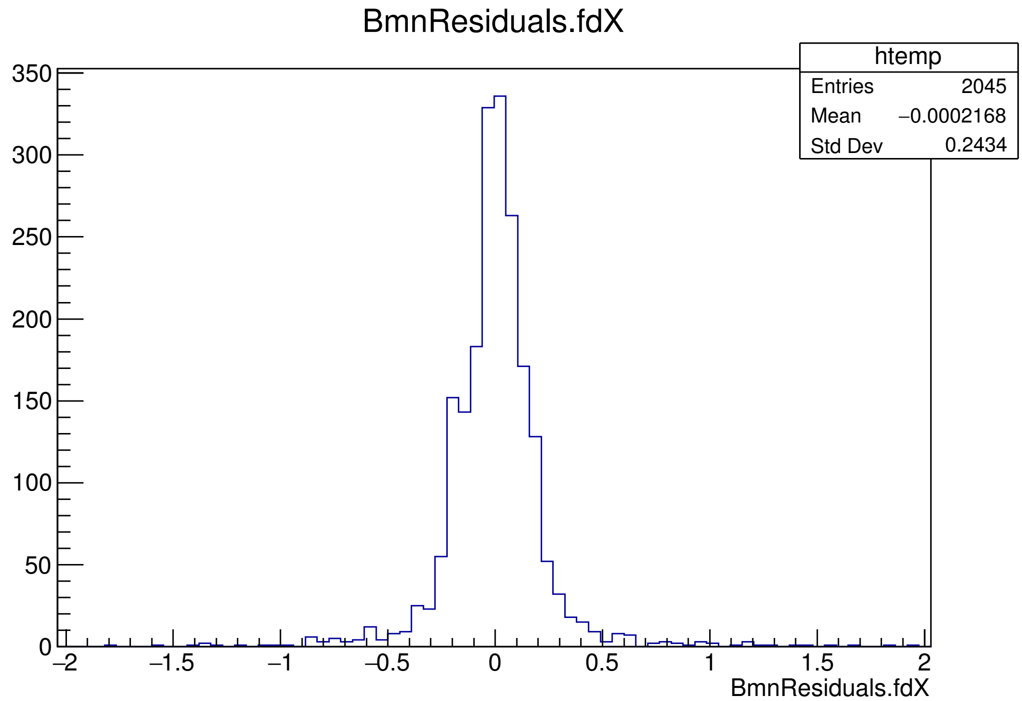

Figure 2.1 — Track-to-hit X-residuals (along Y-direction) for all detector stations (no alignment procedure performed)

The second step is a construction and evaluation of system 2.3. The problem of this step is related to a huge matrix of coefficients appeared when trying to solve above 1000 equations. The vector of variables consists of several thousands of local track parameters and dozens of global parameters. Usually methods of evaluations depend on number of equations like n^3 at least [7]. The Millepede-II algorithm used

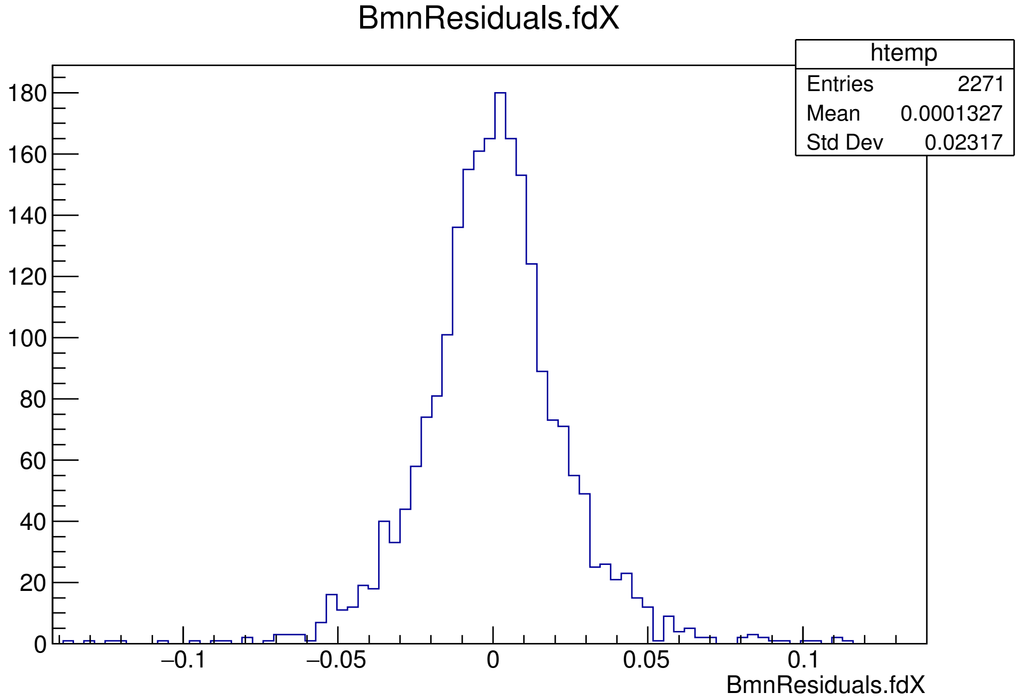

Figure 2.2 — Track-to-hit X-residuals (along Y-direction) for all detector stations (50 alignment iterations performed)

for solution of this matrix equation allows one to reduce time of evaluation significantly [8]. It appears due to the fact that some of the coefficients in the equations are equal to zero. The idea of that algorithm is to consider smaller blocks instead of inversion of the whole matrix.

The third step is a summation of corrections obtained before (at previous iterations) with the new ones.

Each step is implemented as a ROOT macro which is executed by the ROOT interpreter. The iterations are repeated until final condition of precision is satisfied. The condition could be expressed as an equality of RMS of residuals to inner resolution of the detector.

The most evident way to compare reconstruction efficiency is to build track-to-hit residuals histogram for many events. The histogram of precisely aligned detector should have the shape of gaussian and be centered at zero value. Assymetries, shifts and wrong shape if observed are evidences of detector misalignment.

The results of the applied alignment procedure to the run of the BM@N experiment are presented in figure 2.2. The used run contains straigt beam of carbon nuclei without target and magnetic field. These results were obtained after 50 alignment iterations performed. The rest misalignment after procedure performed has been reduced from 2.2 μm to 1.3 μm. Standard deviation of residuals has been reduced from 2.434 mm (figure 2.1) to 0.232 mm (figure 2.2) which is more than 10 times. Misalignment term of reconstruction error has been reduced down to the inner resolution of GEM detector which is equal to 230 μm.

Constraints of the matrix equation

Generally, the formulated optimization problem

$$\chi^2 = \sum_{i=1}^{n_{track}} \sum_{j=1}^{n_{det}} \frac{[S_{ij}(u_{ij}, \alpha_i^t, \alpha_j^a)]^2}{\sigma_j^2}, \chi^2 \to 0 \tag{2.4}$$

has more than one solution.

Indeed, there is an infinite number of detector positions which lead to zero residuals for a given track. For instance, common shift of all detectors for some vector does not change the χ^2 value. Other examples are shown in figure 2.3.

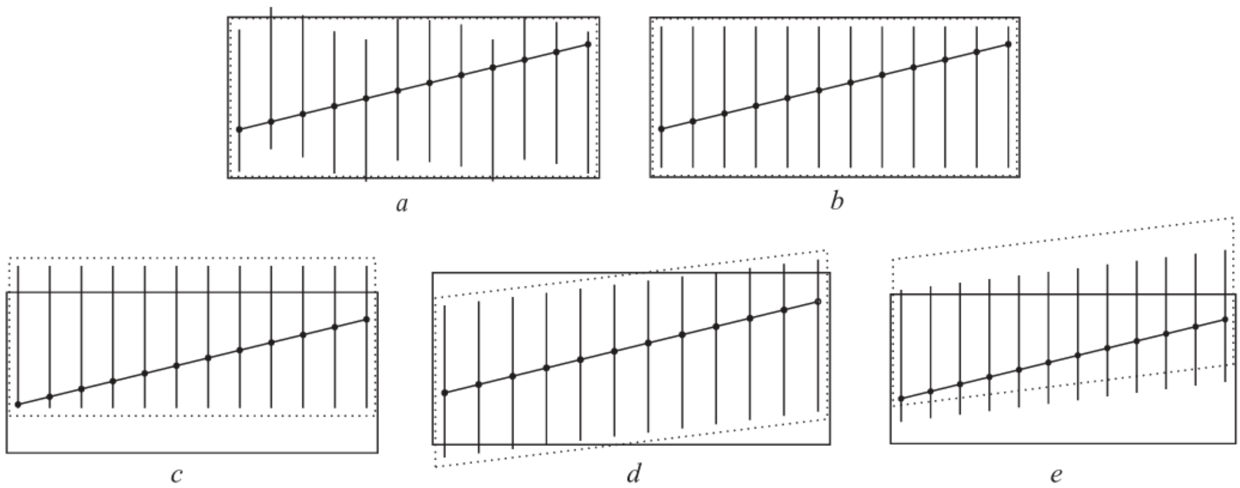

Figure 2.3 — Examples of misalignment with track-to-hit residuals zero [9]

Figure 2.3 a shows initial state of misaligned detector; figure 2.3 b is one of possible solutions of internal alignment. However the situation represented in figures 2.3 c–e also corresponds to the minimum of alignment functional (2.4). In the most common case there can be 12 external degrees of freedom:

1. 3 axis scalings;

2. 3 translations;
3. 3 rotations;
4. 3 shearings.

Thereby we have an infinite number of possible solutions and we need to be able to choose the desired one. It could be done in several ways [10]. These external degrees of freedom can be fixed by addition of constraint equations to the system (2.3).

Constraints can be linear combinations of alignment parameters

$$\sum_{i=1}^{n_{det}} w_i \cdot \alpha_i^a = C_i \tag{2.5}$$

or even just fixing a given parameter in particular

$$\alpha_i^a = 0. \tag{2.6}$$

Alignment of 3 parameters for each detector module is implemented in Bmn-Root. There are 3 detector translations. It means that there are 6 external degrees of freedom for all detector system as whole and we need 6 constraint equations respectively.

Following sets of detector constraints were used for detector alignment of GEM tracker.

Set 1. Fixation of two detector stations by addition of 6 equations of the form (2.6). Such constraints are used [11] for alignment at COMPASS experiment [12] at CERN.

Set 2. Fixation of one detector station and the center of the detector system by equations

$$\sum_{i=1}^{n_{det}} \alpha_{i,j}^a = 0, \quad j = x, y, z. \tag{2.7}$$

Set 3. Fixation of center of the system and definition of scaling of the GEM tracking system by equations

$$\sum_{i=1}^{n_{det}} \Delta z_i \cdot \alpha_{i,j}^a = 0, \quad j = x, y; \tag{2.8}$$

$$\sum_{i=1}^{n_{det}} z_i \cdot \alpha_{i,z}^{a} = 0; \tag{2.9}$$

where Δz_i is z projection of the distance between the detector i and the center of the detectors system. This approach was taken from [7].

Set 4. Fixation of one detector station and definition of scaling of the GEM tracking system.

The alignment procedure was performed for run with carbon beam with kinetic energy of 4.5 GeV/nucl. and carbon target without magnetic field. The histograms of track residuals were obtained for each set of constraints and each detector modules. The RMS and mean values of residuals were compared. The results are presented in at the tables 2.1 and 2.2 for projections of residuals on X and Y axis.

The alignment procedure was performed with fixation of different detectors for constraint sets 2 and 4. The lowest residuals were obtained with fixation of GEM2 station in the both cases. The procedure was performed with fixation of different pairs of detectors for constraint set 1 also. The best result was obtained with fixed stations GEM1 and GEM4. These best results placed into the tables exactly.

It is seen from the results that track reconstruction has a big error at the Y component. The reason is the approach of hit reconstruction. Detectors have individual plane measured X coordinate of particle while Y coordinate can be obtained only by indirect calculations. So primary characteristics to compare are X residuals.

One more nuisance is values corresponding to station 5. Residuals of the station GEM5 are much worse because of, probably, some technical problems of detector.

The results show that no one of the chosen constraint sets does not lead to distinctly best resolutions with respect to another sets. Sets 2 and 4 give good results for small stations consisting of just 1 module (GEM1, GEM2, GEM3). Track reconstruction with constraint set 1 has relatively less rest misalignment, which defined by mean value of residuals. Constraint set 3 was effective for alignment of stations 3–5. Relatively small RMS and rest misalignment were obtained for these stations.

Table 2.1 — The mean value and RMS of X projecion of residuals for different sets of constraint equations; set 1 – fixation of station 1 and 4; set 2 – fixation of station 2 and the center of the system; 3 – fixation of the center of the system and the definition of scaling ; 4 – fixation of station 2 and the definition of scaling; the unit for all values is μm; the better result for each module is highlited by bold font

	station 0		station 1		station 2		station 3				station 4				station 5			
							module 0		module 1		module 0		module 1		module 0		module 1	
	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean
set 1	898.8	**–56.2**	790.1	**–22.7**	987.2	38.4	904.2	**2.8**	926.9	84.7	810.7	−187.7	**815.3**	**–2.1**	1578	812.8	1550	530.5
set 2	881.3	131.5	764.3	−18.1	930.4	−28.1	895.2	24.8	**866.3**	**13.1**	695.9	22.0	856.5	146.1	**1509**	576.1	1606.0	428.7
set 3	889.8	124.9	**752.5**	−107.3	936.7	100.6	**869.9**	94.7	882.8	32.0	699.2	42.2	833.4	64.4	1547	**393.6**	**1549**	**393.9**
set 4	**871.1**	114.9	773.6	−25.9	**920.0**	**–21.6**	914.2	32.7	869.8	−26.6	**687.9**	**3.0**	875.2	165.3	1535	565.5	1623	425.6

Table 2.2 — The mean value and RMS of Y projecion of residuals for different sets of constraint equations; set 1 – fixation of station 1 and 4; set 2 – fixation of station 2 and the center of the system; 3 – fixation of the center of the system and the definition of scaling ; 4 – fixation of station 2 and the definition of scaling; the unit for all values is μm; the better result for each module is highlited by bold font

	station 0		station 1		station 2		station 3				station 4				station 5			
							module 0		module 1		module 0		module 1		module 0		module 1	
	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean	σ	mean
set 1	2610	437.8	2381	−638.9	2570	151.0	2365	270.4	2349	473.0	2154	−45.9	2085	**–38.1**	3798	220.3	3727	**–1032**
set 2	2250	**176.4**	**2091**	−212.6	**2341**	157.6	2390	**79.6**	2228	427.1	1843	−59.6	2058	−243.7	**3209**	**102.3**	3564	−1210
set 3	**2214**	216.1	2106	**–130.1**	2427	**–30.6**	**2274**	83.0	2223	485.9	1849	**–10.9**	**1993**	−130.1	3321	241.1	3500	−1345
set 4	**2214**	191.3	2100	−190.4	2383	99.1	2353	92.6	**2184**	**426.6**	**1836**	−48.9	2067	−189.1	3277	203.2	**3464**	−1169

Conclusion

Alignment of GEM tracking system at the BM@N experiment was performed with different sets of constraint equations. The quality of alignment was verified by RMS and mean value of track-to-hit residuals.

Obtained results do not allow one to choose distinctly the best set of constraint equations. Different sets are more suitable to different detector stations.

Sets 2 and 4 give good results for small stations consisting of just 1 module (GEM1, GEM2, GEM3). Track reconstruction with constraint set 1 has relatively less rest misalignment, which defined by mean value of residuals. Constraint set 3 was effective for alignment of stations 3–5. Relatively small RMS and rest misalignment were obtained for these stations.

It is possible to study alignment with combinations of approaches, applying different constraints one after another in course of the procedure.

Also, implementation of alignment for runs with magnetic field and extension of the procedure to other tracking detectors (drift chambers, silicon strip detector) can be a big step towards further improvement aimed at obtaining more precise results.

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