JOINT INSTITUTE FOR NUCLEAR RESEARCH
Veksler and Baldin laboratory of High Energy Physics

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

Study of realistic response simulation for MPD TPC

Supervisor:
Oleg Vasilievich Rogachevsky

Student:
Bogdan Kutsenko, Russia
Novosibirsk State University

Participation period:
June 30–August 17

Dubna, 2019

Contents

Abstract

The Multi-Purpose Detector (MPD) is a 4π spectrometer capable of detecting of charged hadrons, electrons and photons in heavy-ion collisions at high luminosity in the energy range of the NICA collider. Precise 3-d tracking system provided by the Time Projection Chamber (TPC). Existing model of MPD TPC simulation in MpdRoot framework consist of following steps: event generation by Monte Carlo method, particle transport, TPC response simulation, pad cluster (hit) finding and track reconstruction based on Kalman Filter technique. Particle transport, TPC response simulation and pad cluster finding was thoroughly researched, description and visualization of every significant step provided.

1 Introduction

The main objective of studying heavy-ion collision in general and NICA project in particular is to explore nuclear matter under high pressure and extreme temperature condition. In these collisions, a large fraction of the beam energy is converted into newly created hadrons, and new color degrees of freedom may be excited. At very high temperature or density, this hadron mixture melts and their constituents, quarks and gluons, form a new phase of matter, the quark-gluon plasma (QGP).

One of the main physics objective of NICA project is the search for signs of the phase transition between hadronic matter and QGP in the region of the collider energy $\sqrt{s_{NN}}=4-11\,Gev$ and search for new phases of baryonic matter. Another one big physics objective is to study basic properties of the strong interaction vacuum and QCD (Quantum chromodynamics) symmetries. In order to achieve this objectives high-precision detectors should be used. Two interaction points are foreseen at NICA for two detectors. One of these detectors, the Multi-Purpose Detector (MPD) would be capable of unique measurements of heavy-ion collisions including high-precision tracking and particle identification in the full phase-space as well as very accurate event characterization (Figure 1) [1].

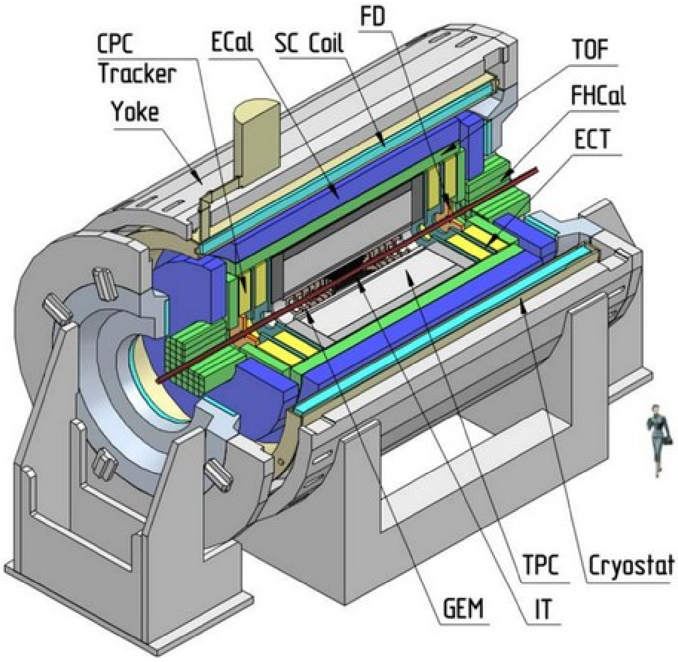

Figure 1. Schematic view of the MPD detector

The Time Projection Chamber (TPC) is the main MPD tracking detector. It covers the barrel and endcap parts of MPD. TPC divided by total of 24 sectors (12 on each side of barrel). Every sector is filled with readout rectangular pads, 3968 on each sector [2]. The TPC is the main detector for track reconstruction and particle identification via specific energy loss. Therefore TPC is responsible for particle momentum measurements, vertex determination, two track separation, dE/dx measurements and particle identification. TPC will provide the momentum resolution for charge particles under 3%

in the transverse momentum range $0.1 < pt < 1\, GeV/c$ [2]. Hadron and lepton identification by dE/dx measurements with a resolution better than 8% [2].

To achieve high-quality track reconstruction from TPC data, properly software should be developed. It should reconstruct track using the signal from readout pads from TPC. To calibrate software and review detector efficiency, signal from readout pads should be simulated. Data processing model during MPD TPC simulation consist from following steps: event generation, particle transport through TPC, response simulation, pad cluster finder, track and dE/dx reconstruction. Study of the realistic response simulation of the TPC, particle transport and pad cluster finder (hit reconstruction) was the main objectives of this work.

2 TPC for the MPD Central Tracking

2.1. Main TPC parts and working principle

The main TPC parts (Figure 2) is electric field cage containment cylinders (C1-C4) and 24 readout chambers (ROC) on end cap. Whole TPC chamber is filled with the gas mixture of 90% argon and 10% methane (90% Ar + 10% CH4) at the constant temperature and the constant over pressure. Inside the field cage perpendicular electric field generated between central high voltage electrode and voltage dividing network at readout end plates and inner cylinders. Voltage divider is important to homogeneous field creation. In order to make the drift velocity stable and low sensitive to temperature and pressure fluctuation electric field was chosen as *E=140 V/cm* [2].

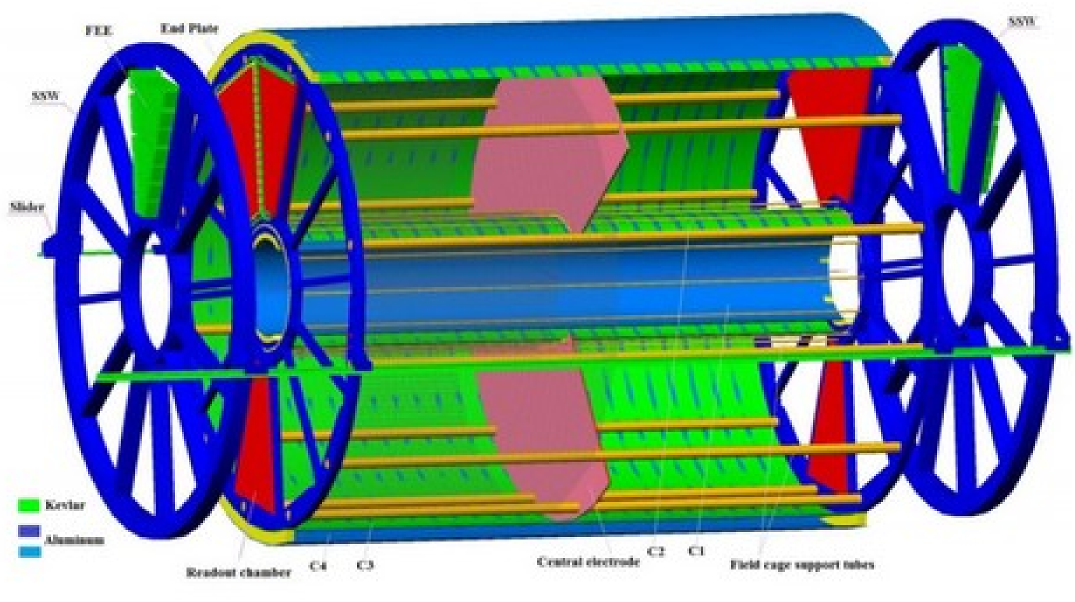

Figure 2. Schematic view of the MPD detector. Picture taken from [2].

Main TPC parts is following: readout chamber (ROC), front-end electronics, laser calibration system, gas system, field cage support tubes. On the basis of requirements of NICA project, basic TPC parameters were chosen, they summarized in Table 1.

Table 1. *The basic parameters of the TPC [2].*

Item	**Value**
Length of the TPC	340 cm
Outer radius of vessel	140 cm
Inner radius of vessel	27 cm
Length of the drift volume	163 cm (of each half)
Electric field strength	~ 140 V/cm
Magnetic field strength	0.5 Tesla
Drift gas	90% Ar+10% Methane
Gas amplification factor	~ 10^4
Drift velocity	5.45 cm/μs
Number of readout chambers	24 (12 per each end-plate)
Pad size	5x12 mm^2 (inner plane) and 5x18 mm^2 (outer plane)
Pad row numbers	53
Number of pads	95232
Maximal event rate	< 7 kHz (Luminosity 10^{27})
Two-track resolution	~ 1 cm

A physical basis of tpc working if following, if a charged particle travels through the gas volume, it excites and ionizes gas atoms along its track. As a consequence, it loses an amount of energy per unit track length *(d E/d x)* which is specific for every particle type, which allow to identification particle in detector.

Cause of energy lose could be different. The most significant is inelastic collisions with the atomic electrons of the matter, which is usually divided into soft collision and hard collision. In soft the electrons of the matter only excited and in hard collision ionization process take place. If the ionized electrons themselves cause substantial secondary ionization, they are sometimes referred to as δ-electrons.

Inelastic collisions are statistical in nature and therefore only the average energy loss per unit path length could be calculated. To identification of particle from average energy loss data from TPC, modified Bethe-Bloch formula is used [4]

$$\left(\frac{dE}{dx}\right)=\frac{4\pi Ne^4}{mc^2}\frac{z^2}{\beta^2}\left(\frac{1}{2}\ln\left(\frac{2mc^2E_{max}\beta^2\gamma^2}{I^2}\right)-\frac{\beta^2}{2}-\frac{\delta(\beta)}{2}\right), \qquad (1)$$

where mc^2 is the rest energy of the electron, z the charge of the projectile, N the number density of electrons in the matter traversed, e the elementary charge, β the velocity of the projectile, I the mean excitation energy of the atom and E_{max} is transferred energy in which δ -electron form a second track. E_{max} value is modification to Bethe-Bloch formula, which is allow to take into account δ -electrons contribution to energy loss.

Other possible cause of energy loss, such as elastic scattering from nuclei, is negligible in comparison with particle and electron collision, because the masses of the nuclei of traversed matter are larger then a mass of the incident particle. Other less significant possible reaction like Cherenkov radiation, nuclear reaction, bremsstrahlung or transition radiation is extremely rare and is not registered by TPC.

The electrons created by ionization, drift towards ROC, acceleration of electron is interrupted by collision with gas molecules. Therefore, drift velocity is constant in the homogeneous field and equal to

$$v_D = \frac{eE}{m}\tau = \mu E, \tag{2}$$

where μ the mobility, e is the electron charge, m the electron mass, τ the average time between collisions. Important to take in account diffusion process which lead to dispersion of electron cloud. Electron distribution in the cloud shows a Gaussian distribution after time t [3]

$$\rho = \left(\frac{1}{\sqrt{4\pi D_L t}}\right)\left(\frac{1}{\sqrt{4\pi D_T t}}\right)^2 \exp\left(\frac{-(x^2+y^2)}{4 D_T t} - \frac{(z - v_D t)^2}{4 D_L t}\right), \tag{3}$$

where D_L and D_T are the longitudinal and transverse diffusion constants.

The magnetic field in the TPC is parallel to the electric field and because of that Lorentz force is not applied to drifting electrons and drift direction is parallel to the electric field. Due to diffusion (3) registered track is smeared, but this effect could be mitigated by a strong magnetic field, which is force electrons to move in a spiral around magnetic field lines. Due to this effect, the transverse diffusion coefficient is reduced by the factor

$$\frac{D_T(\omega)}{D_T(0)} = \frac{1}{1+\omega^2\tau^2}, \tag{4}$$

where $\omega = \frac{eB}{m}$ - is cyclotron frequency and τ is mean time between collisions.

The magnetic field in the TPC is provide additional curvature of charged particle track. Momentum could be calculated from curvature r as [3]

$$p_{\perp}[GeV] = 0.3 \cdot B \cdot r\,[T \cdot m]. \tag{5}$$

2.2. Readout system

Readout system of the TPC is based on multiwire proportional chamber (MWPC) with cathode pad readout. Image charges are induced on pad plane from electron avalanches, which is formed near anode wire. Image charges recorded from ROC as a function of time. Electron avalanche is produced due to amplification of drifted electrons. In the vicinity of anode wire electric field grows as $1/r$. With higher electrical field applied electron energy rises, which is lead to gas ionization. Just formed electrons could ionize gas again which is lead to further ionizations and mean, that avalanche process started.

The MWPC setup (Figure 3) provide possibility for three dimensional reconstruction of the track of the charged particle. Two dimension (x-y plane) accessible due to triggered pad coordinate, an z coordinate reconstruct due to time of primary electron drift. Time of drift is easy to calculate due to constant drift velocity (1). Another function of TPC – particle identification is achieved by independent energy loss measurement in each triggered pad. It is important to note that in this work Signal from pad is represented as avalanche charge, but MWPC work in proportional voltage region which is mean that signal collected from pad is proportional to initial electron charge. Therefore signal from pad could be used as track energy loss per unit path length dE/dx.

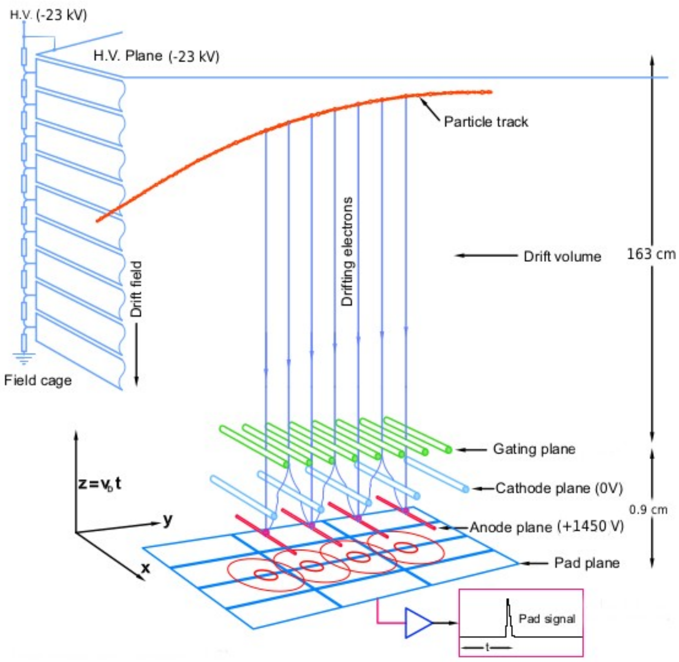

Figure 3. Schematic illustration of the working principle and the read-out chambers of the TPC. Picture taken from [4].

To satisfy the NICA project requirement, the TPC data readout system has to transfer the mean data stream of 7 GB per second with the mean multiplicity per event of about 300 tracks and maximum multiplicity up to 1000 tracks. Besides TPC data readout system should amplify low noise signal, to provide productive data processing [2]. In order to achieve this goals new 32-channel ASIC SAMPA[] was adopted to utilization in front-end card of MPD detector. Main parameters of the front-end electronics for TPC are specified in Table 2.

Table 2. Main parameters of front-end electronics for MPD TPC[2]

Parameter	**Value**
Total number of channels	95 232
Signal to noise ration	>30:1
ADC resolution	10-bit
Peaking time	160 ns
Sampling rate	10 MHz
Sampling depth	310 time buckets

Transmission function for ASIC SAMPA, which is should be implemented in code for readout system simulation analytically could be described as following [9]

$$f(x) = A\left(\frac{x-t}{\tau}\right)^{N} e^{-N\left(\frac{x-t}{\tau}\right)} + B_l \quad (5)$$

Here, the waveform amplitude is obtained from Ae^{-N} , where A is the peak and $N = 4$ is the shaping order of the amplifier. B_l is the baseline, τ is the decay time, and t is the start time of the signal. Example of waveform from ASIC SAMPA fiited by transmission function is represented in Figure 4.

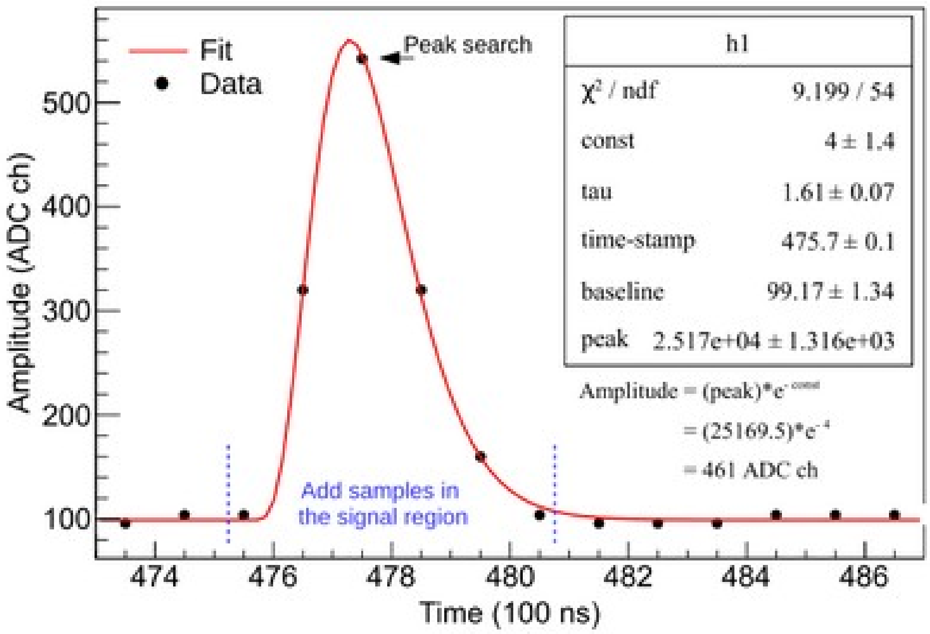

Figure 4. Transmission function of SAMPA electronic in TPC. Waveform fitting shown in solid line (red curve), actual signal is represented by black dots. Picture taken from [9].

3 Realistic simulation of MPD TPC

3.1. MPD simulation software

The software MpdRoot are developed for the MPD event simulation, reconstruction of experimental or simulated data and following analysis of heavy ion collision. MpdRoot is based on Fair Soft framework which provide complex algorithms for data analysis and detector performance studies[5]. FairRoot contains different tools for simulation data analysis such as GEANT3, Virtual Monte-Carlo, GEANT4, UrQMD and other.

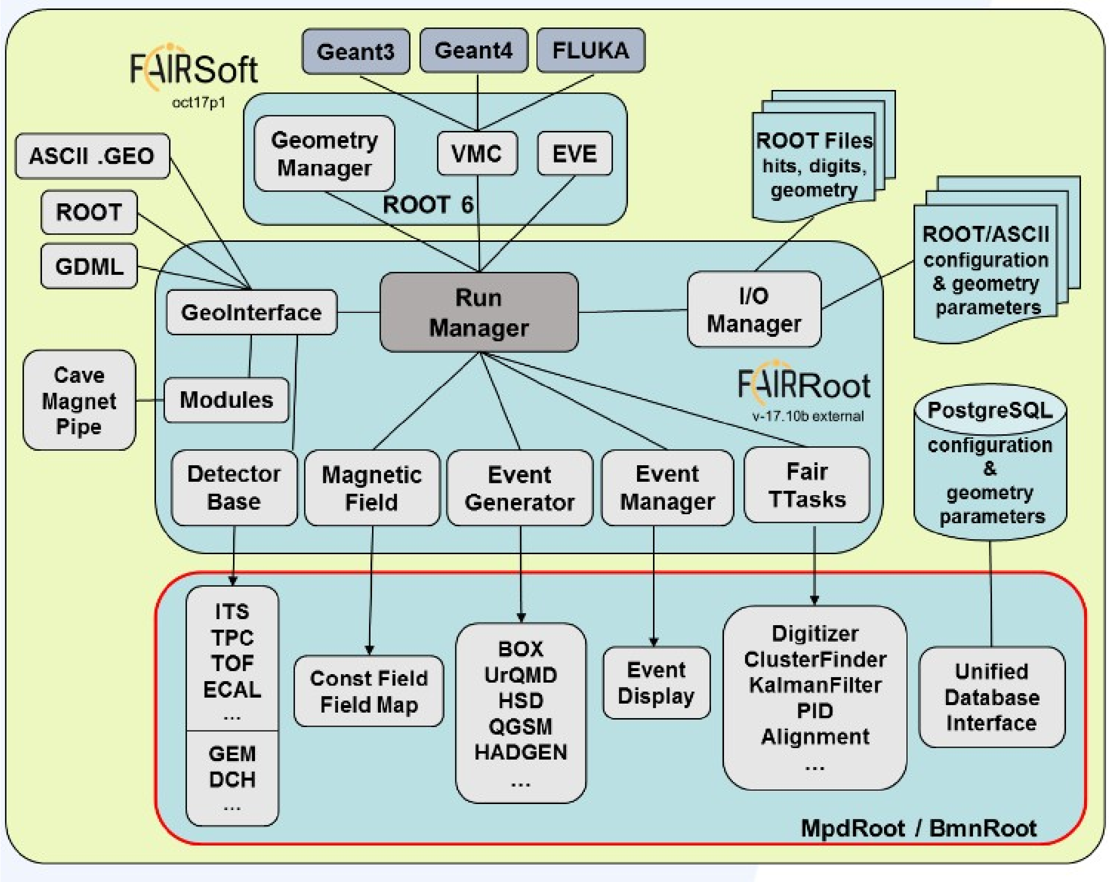

Figure 5. MpdRoot design. Picture taken from [6]

3.2 TPC response simulation overview

Main goal of readout system simulation is to use tracks, generated due to Geant3 Monte Carlo generation method (Figure 4), in order to create output signal from readout pad. Every generated track in the TPC area consist from consecutive points, each of them contains coordinate in global detector system, current vector of momentum, energy loss on distance between two consecutive points, current time of flight and track ID. This points represented as MpdTpcPoint object in MpdRoot framework. A generalized method of output signal generation is represented in figure 5.

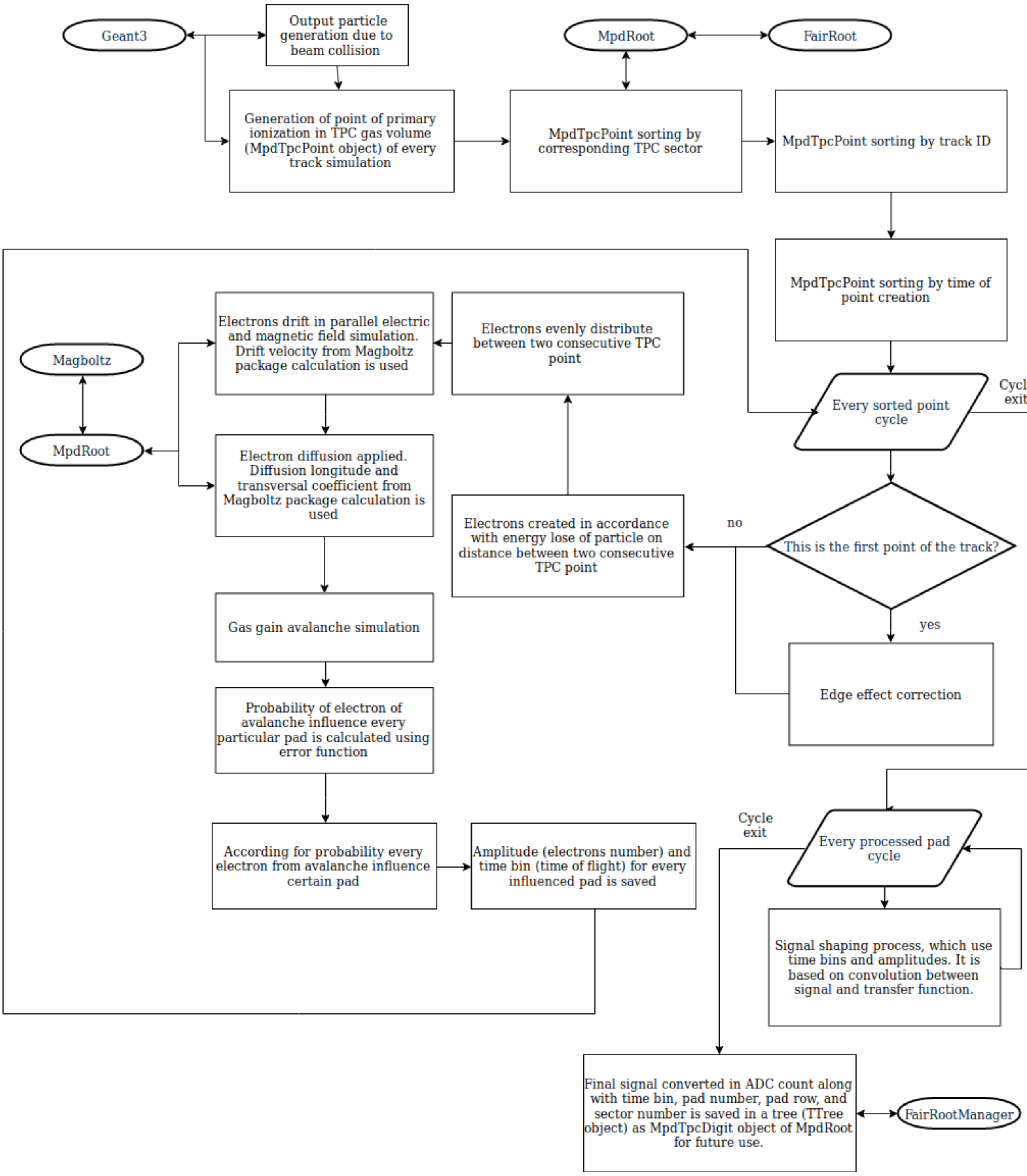

Figure 6. Flowchart of readout system signal simulation

Example of work presented at figure 6. In figure 6 one multiple events was simulated by HADGEN generator [5]. Electron diffusion was applied and spatial distribution of electrons in x-y plane represented in this figure. The following process considered in process of TPC response simulation : primary ionization, drift and diffusion of ionization electrons, gas gain fluctuations, pad response, electronics shaping and signal digitization.

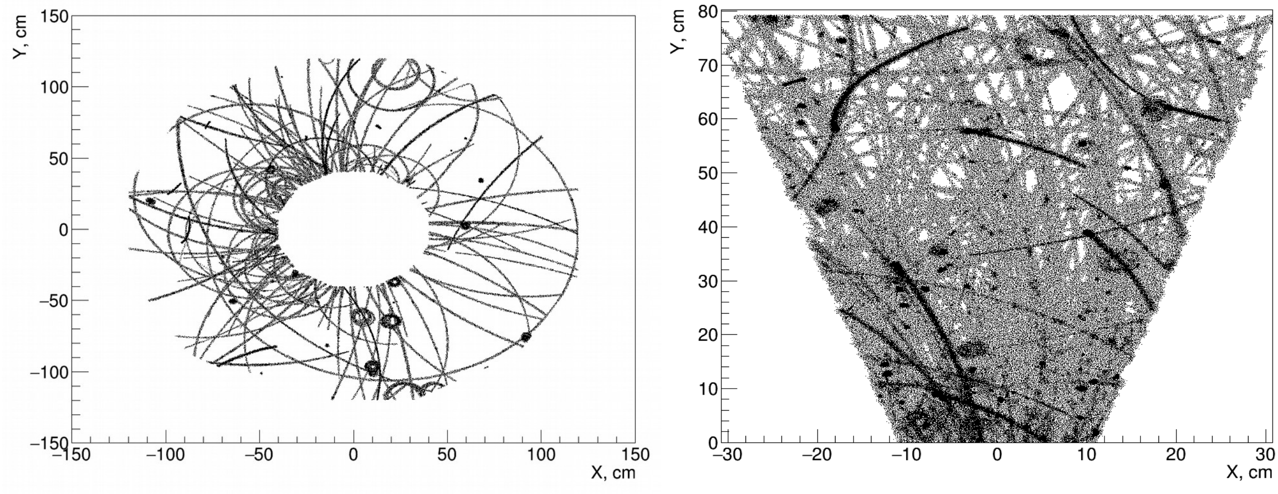

Figure 7. Simulated track projection on x-y plane in global detector coordinate system (left) and local sector coordinate system (right)

Particularly should me mentioned how electron from avalanche probability to influence particular pad was calculated. Electron in avalanche assumed to have Gauss spatial distribution with a standard deviation equal to experimental data results. Probability of electron to comply with particular pad is could be calculated as following for x coordinate

$$P(x_l < X < x_r) = F_{a,\sigma^2}(x_r) - F_{a,\sigma^2}(x_l) = \Phi_{0,1}\left(\frac{x_r - a}{\sigma}\right) - \Phi_{0,1}\left(\frac{x_l - a}{\sigma}\right) = \int_{-\infty}^{\frac{x_r - a}{\sigma}} \varphi(u)\,du - \int_{-\infty}^{\frac{x_l - a}{\sigma}} \varphi(u)\,du, \quad (4)$$

where x_l and x_r is left and right border on one particular pad respectively, a is pad center x coordinate, σ is standard deviation from normal distribution, *F* – distribution function and *φ(u)* is probability density function for normal distribution. In code error function is used due to more simple access. Integrals from (4) could be easily transformed to error function difference.

3.3 Pad cluster search overview

The pad cluster or hit in this work means a grouping of nearby trigger pads for continuous-time bin intervals. Example of hit is represented in figure 8, edge effect correction was applied to this hit due to row edge proximity.

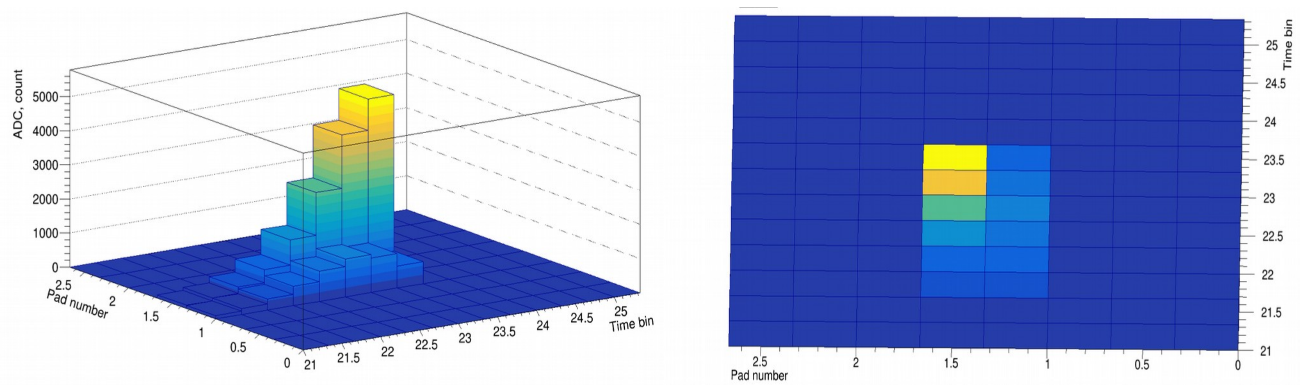

Figure 8. 3d and 2d Visualization of hit example created in cluster finder process

The cluster (hit) finding procedure includes the following steps: finding preclusters, finding separated local maxima using the "peak-and-valley" approach [7], reconstruction of the coordinates of the found local maxima via center-of-gravities and edge effects corrections. The “peak-and-valley” procedure consist in finding local maximum (“peaks”) and check if sufficient enough “valley” separate two local maximum in one cluster. If valley is deep enough then cluster separated in two, if its not, then clusters merge in one. Resulted hit for one muon track event created by BOX generator (Figure 4) is demonstrated on figure 9. Realistic event was created by HADGEN generator and shown on figure 10. Important to note, that next step after cluster finder and hit creation is Kalman filtering technique for track reconstruction. Kalman filter allows recovering original track based on limited data (hits).

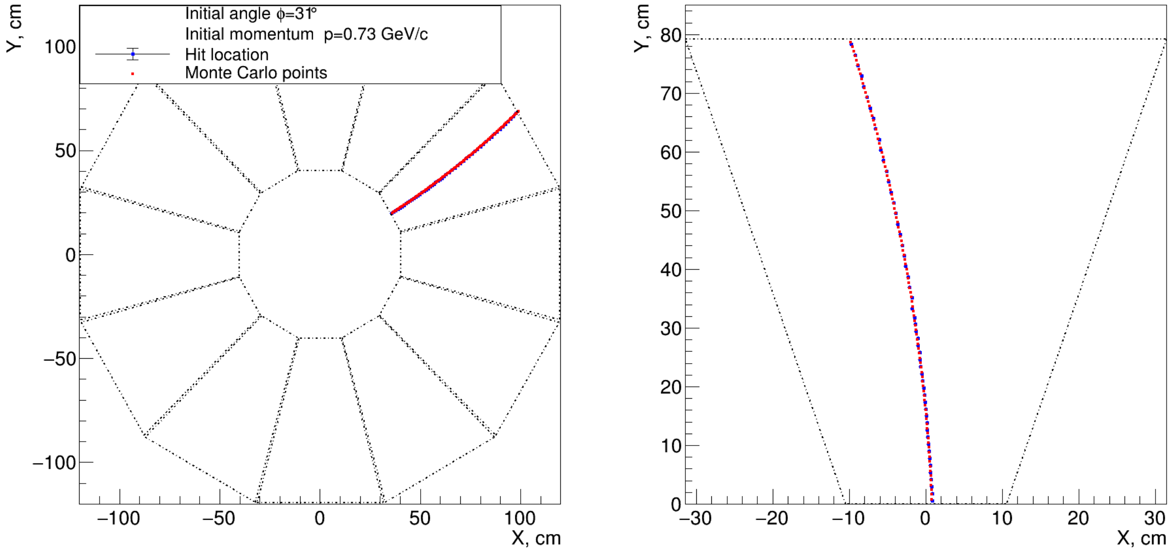

Figure 9. All hit created by cluster finder in global detector coordinate system (left) and local sector coordinate system (right)

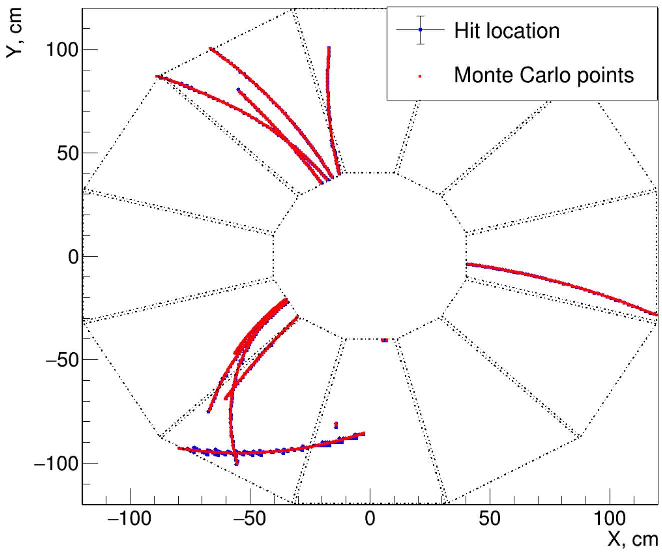

Figure 10. Event generated by HADGEN. All hit created by cluster finder in global detector coordinate system

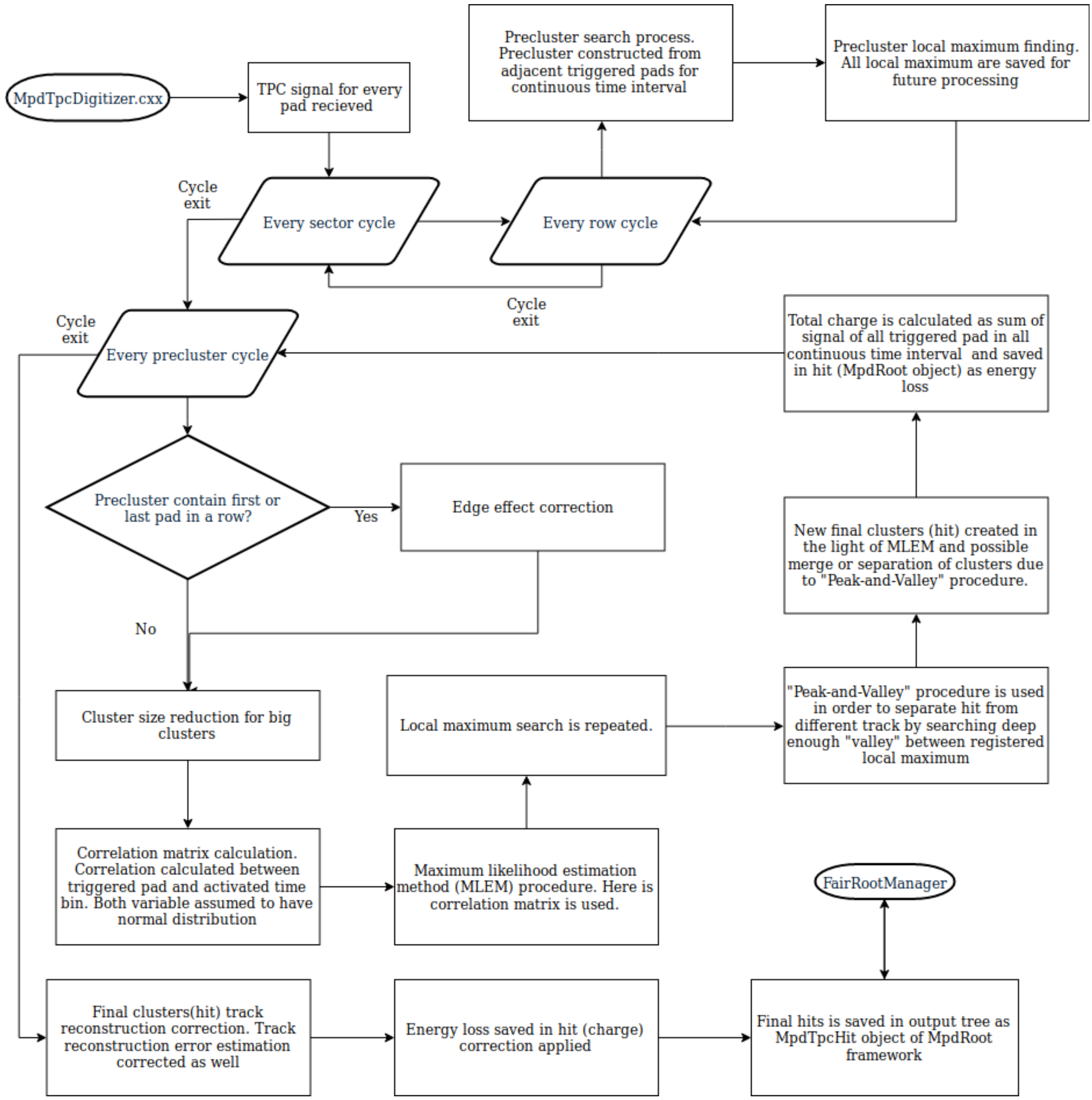

Figure 11. Flowchart of the cluster finder process

4 Conclusion

The MPD TPC response simulation and cluster finder technique was thoroughly researched. BOX and HADGEN generator from MpdRoot software [8] was used in order to generate data for track reconstruction in TPC. All significant step on track data was described, flowchart was made for more clear code description. Visualization for every important reconstruction step provided – event generation by Monte Carlo method, TPC response signal distribution, hit example created due to cluster finder process and hits comparison with the initial track. Actual and possible current code problems are identified and bug report was written.

5 Acknowledgments

I would like to thank Alexander Bychkov for his help with computer programming, including guide into MPD software. I want to thank my supervisor and scientific advisor Oleg Rogachevskiy, without whom this summer program would not take place. I want to express my gratitude to the University Center of JINR for giving me the opportunity to participate in the Summer Student Program and the management of Veksler and Baldin Laboratory of High Energy Physics for providing a financial support.

References

[1] Golovatyuk, V., et al. "The Multi-Purpose Detector (MPD) of the collider experiment." *The European Physical Journal A* 52.8 (2016): 212.

[2] Technical Design Report number 7. http://mpd.jinr.ru/doc/mpd-tdr/

[3] Kleinknecht, Konrad. *Detectors for particle radiation*. Cambridge University Press, 1998.

[4] Kalweit, Alexander. *Energy Loss Calibration of the ALICE Time Projection Chamber*. Diss. Master's thesis, Darmstadt University, 2008.

[5] FairRoot. *https://fairroot.gsi.de/*

[6] K. Gertsenberger, O. Rogachevsky. *Software development for the NICA experiments:MpdRoot & BmnRoot*. Presentation on CHEP, 2018

[7] Mudrokh, A., and A. Zinchenko. "Recent developments in track reconstruction and hadron identification at MPD." *EPJ Web of Conferences*. Vol. 138. EDP Sciences, 2017.

[8] MpdRoot.*https://git.jinr.ru/nica/mpdroot/*

[9] Tambave G. J. ALICE SAMPA-ASIC second-prototype qualification studies for LHC Run 3 and beyond //PoS. – 2017. – C. 010.