The simulation of interactions in the straw-based SPD track detector and primary vertex reconstruction
Моделирование взаимодействий в трековом детекторе SPD на основе строу-трубок и реконструкция первичных вершин

S.D. Morozova[a,1], *A.V. Shipilova*[a,b,2]

С.Д. Морозова[a,], *А.В. Шипилова*[a,b]

[a] Samara National Research University, Samara, Russia

[b] Joint Institute for Nuclear Research, Dubna, Russia

[a] Самарский национальный исследовательский университет, Московское шоссе, 34, г. Самара, 443086, Россия

[b] Объединенный институт ядерных исследований, ул.Жолио-Кюри, д.6, г. Дубна, Московская область, 141980, Россия

In this work we simulate the SPD NICA straw tracker detector response in the trigger-less regime using GEANT4 tools. We study the temporal structure of signals and investigate the vertex reconstruction efficiency using the simulation data. We develop a part of prototype software for event reconstruction at the stage of online data filtering.

В данной работе мы моделируем отклик строу-трекера SPD детектора коллайдера NICA в бестриггерном режиме с помощью инструментов GEANT4. Исследуется временная структура сигналов и эффективность реконструкции вершин по данным моделирования. Разработана часть прототипа программного обеспечения для реконструкции событий на онлайн этапе фильтрации данных.

PACS: 44.25.+f; 44.90.+c

Introduction

The Spin Physics Detector (SPD) at JINR NICA complex is currently under construction [1]. The SPD is a universal facility for study of spin-related phenomena with deuteron and proton beams. The detector has a multi-layered structure, and one of its layers is a straw tracker, that should provide the measurement of the secondary and primary particles momenta with high precision. For the stage of the SPD active operation it is necessary to develop fast data processing algorithms for online data collection, event selection and primary vertices reconstruction.

---

[1] E-mail: svtmorozova09@gmail.com

[2] E-mail: shipilova.av@ssau.ru

Detector Model

The straw tracker is the inner part of the SPD detector. Using the GEANT4 software package [2] we model a geometry of the SPD straw tracker (ST), its sensitive volumes and their response. We adopt a number of simplifications against the real ST geometry which would be insignificant for this stage of our study. We model the ST by a system of nested cylinders each constructed by one layer of parallel cylindrical tight-fitted straw tubes, as illustrated in the Fig. 1, right. The ST tubes have the outer polyethylene shell of thickness $R = 0.036$ mm and the inner cylindrical volume of radius $R = 4.934$ mm filled by $Ar(70\%) + CO_2(30\%)$ gas mixture, which includes tungsten wire (anode) of radius $R = 0.03$ mm, see Fig. 1, left. We assign a sensitive detector object of GEANT4 to the inner volume of each tube and adopt the tube numbering scheme where the unique number corresponds to the each tube.

The length of the time slice in the experiment is 10μs, while the proton bunch crossings occur every 76 ns. The probability of proton-proton interaction in a one pp bunch crossing is simulated by Poisson distribution $f(k) = \frac{\lambda^k}{k!} e^{-\lambda}$ with expected value of $\lambda = 0.3$. The interaction point is placed into $(0, 0, z)$, where z is defined by Gaussian distribution $f(z) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{z-z_0}{\sigma}\right)^2}$ with $\sigma = 30$ cm and central value of $z_0 = 0$. The charged reaction products are modelled by muons carrying the energy of $E = 1$ GeV and the momentum p which direction is uniformly distributed in the 4π space. The number of muons produced in the pp collision is defined by a Poisson distribution with expected value of $\lambda = 7$.

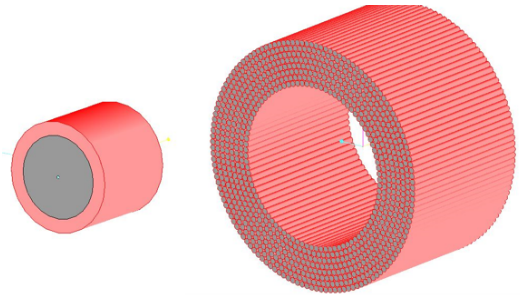

Fig. 1. Single straw (left) and 8 layers of straw detector model (right). Red layer – polyethylene, grey – gas, green – tungsten wire.

Straw tubes response time simulation

The propagation of the charged particle through the gas leads to its energy loss. We declare the hits collection object to store the characteristics of particle energy loss points. To simulate the ST response time we should define the shortest distance from the particle track to the anode (e.g. tube axis). In case there are several energy loss points in the same logical volume we adopt the approximation where the only first and last points are considered, then the shortest distance is calculated by crossing lines formula. The dependence of the electron avalanche drift time on the distance was simulated using Garfield simulation software [3], [4], see TDR [5]. We approximated this dependence by the analytic formula and used it to obtain the time distributions of ST response. The results of our simulation are presented in the fig. 2, where all the histograms were created using CERN ROOT tools [6]. We found a significant overlap of the ST response times for particles produced in different bunch crossings from the same time slice. This fact points out to the problem of signal decoding for event reconstruction when collecting data in a real experiment.

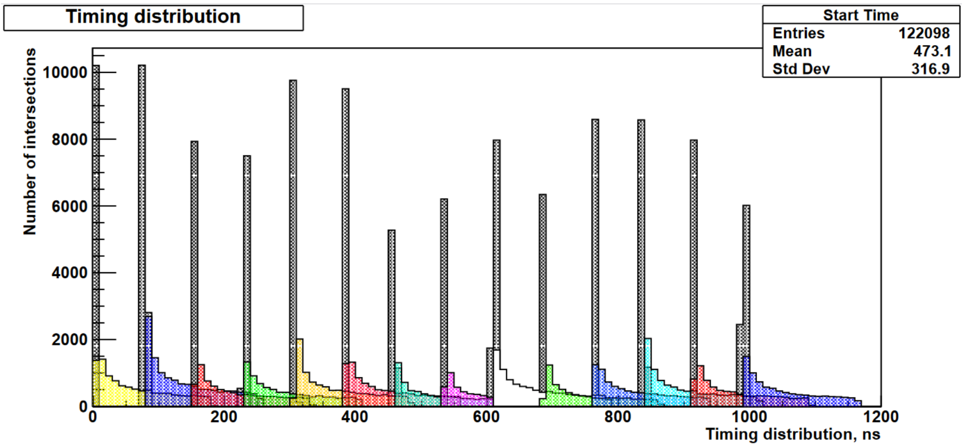

Fig. 2. Timing distribution averaged by 1000 time slices. Grey area – the sample particle intersection time of the sensitive volume. Coloured area – ST response time distribution.

Primary vertex reconstruction

Using the hits collection data one can perform a reconstruction of particle tracks. We skipped the hits recovery step assuming the coordinates of the particles energy loss points are already known. We suppose a uniform magnetic field along z axis of $B = 1$ T without endcup effects. Thus, we approximate the sample charged particle trajectories in the XOY plane transverse to the field by parabolic function $y = a_1x^2 + a_2x + a_3$, where the coefficients a_i, $i = 1, 2, 3$ are determined from the hits data using the least-squares method. The simulated tracks and hits in the XOY plane from the primary particles of one time slice are illustrated in the fig. 3, left, while the corresponding example of track-approximating curve is shown in the right. The coefficients a_i determine the $z(l)$ dependence for each primary particle, where l is the arc length of the parabolic segment. It can be calculated by the simple formula $l = \int_0^{x_0} \sqrt{1 + (2a_1x + a_2)^2} dx = \frac{1}{4a_1} \ln\left(\left|\sqrt{(2a_1x + a_2)^2 + 1} + 2a_1x + a_2\right|\right) + (2a_1x + a_2)\sqrt{(2a_1x + a_2)^2 + 1}.$

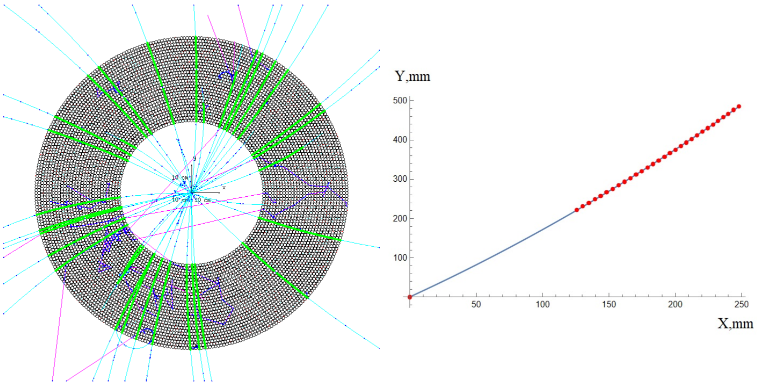

Fig. 3. The hits (green) and tracks (cyan) of one time slice simulation, XOY plane (left). Example of one track approximation in XOY plane (right).

Then, $z(l)$ can be approximated by the linear function, which should be extrapolated to the intersection with z-axis to determine the primary vertex position. The simulated tracks and hits in the ZOY plane from the primary particles of one time slice are illustrated in the fig. 4.

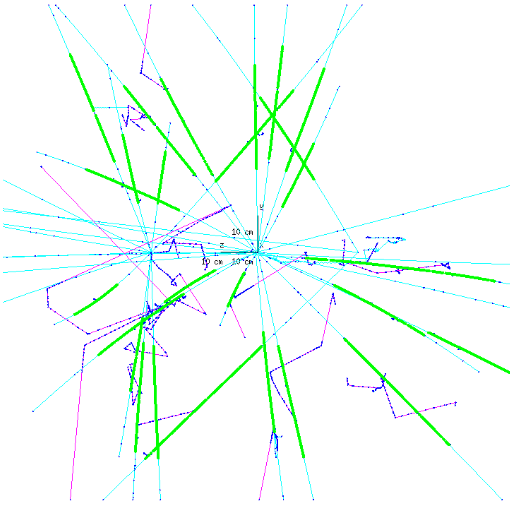

Fig. 4. The hits (green) and tracks (cyan) of one time slice simulation, ZOY plane.

After recovering the starting z-position of each track, name z_0, it is necessary to separate the tracks into clusters with common vertices and evaluate the vertex recovery efficiency. The set of initial z_0 values was sorted in ascending order, then divided into the groups starting from some boundary z_0 with step H. In the beginning, the boundary z_0 was the smallest z_0 in the whole set, and then the smallest one from the remaining set. Within a track group we determine the mean value of z_0, name z_c, this will be the expected vertex of the group of tracks which z_0 lie close enough to the mean value. Within a step we can distinguish only one vertex. Then we calculated the distance from the z_c to the true vertices z_T of the tracks belonging to this group. The efficiency was calculated as the ratio of the number of correctly recovered true vertices to the total number of true vertices. A correctly reconstructed vertex is considered to be the vertex that can be distinguished on the interval H, and all the assigned tracks actually belong to this vertex. The distribution of the distance between the reconstructed vertex and the true vertex is presented in fig. 5. We analysed a set of step values H to achieve the maximum efficiency. At the current moment the achieved recovery efficiency value is 61%. However, we imposed the most strong conditions on the track recovery purity.

In practice, the requirements on the purity of vertex recovery can be reduced if we impose restrictions on the energies of the particles which trajectories to be fitted, that will improve the efficiency. Thus, we can separate the tracks by their z_0 and then combine them into the clusters with common vertices, which will correspond to the separate bunch crossings points.

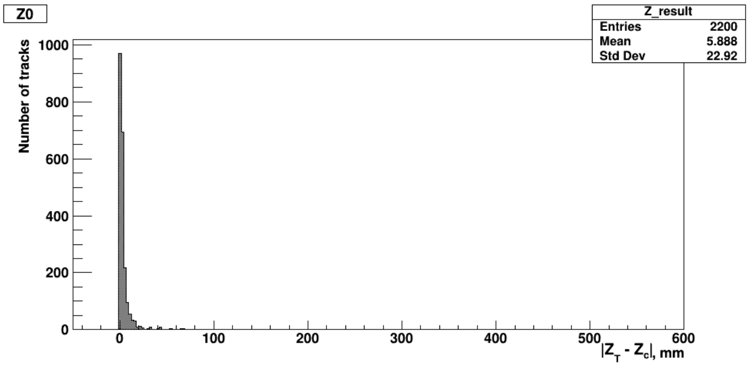

Fig. 5. The distribution of the distance between the reconstructed vertex (z_c) and the true vertex (z_T), the step $H = 6$ cm.

Conclusions

In this study we created a simplified model of the straw tracker of SPD NICA detector using GEANT4 software tools. Introducing the hit collections, we studied the temporal structure of the events, and found a significant overlap of straw tubes response times from different bunch crossings. Using the hits collection data we developed an algorithm for primary vertex recovery with current efficiency of 61%, obtained with the most strict conditions on the purity of reconstruction. These results are to be a part of prototype for the online data processing software.

Acknowledgements

The authors are grateful to I.I. Denisenko, A. S. Zhemchugov and other participants of SPD NICA Collaboration for the useful comments and fruitful discussions.

This work is carried out by the support of the Program for targeted research work financing for scientific groups collaborating within the megaproject "NICA Complex", contract no. 100-01515.

REFERENCES

1. NICA Complex // nica.jinr.ru — 2020. — URL: http://nica.jinr.ru/ru/complex.php/
2. Software package GEANT4 // geant.web.cern.ch — 2020. — URL: https://geant4.web.cern.ch/download/11.1.1.html
3. Software package GEANT4 // garfieldpp.web.cern.ch — 2023. — URL: https://garfieldpp.web.cern.ch/garfieldpp/ https://garfieldpp.web.cern.ch/garfieldpp/
4. *R. Veenhof* Garfield, a drift chamber simulation program // — 1993. — Conf.Proc.C 9306149 P. 66–71.
5. The SPD collaboration, Technical Design Report of the Spin Physics Detector // — 2023. P. 133–177. — URL: http://spd.jinr.ru/wp-content/uploads/2023/03/TechnicalDesignReport_SPD2023.pdf
6. Software package CERN ROOT // https://root.cern/ — 2023. — URL: https://https://root.cern/install/