Eurasian Journal of Physics and Functional Materials

2023, 7(3), 139-147

The quality assessment of the MPD new inner tracker based on thin silicon pixel sensors with large area

V.I. Zherebchevsky[*,1], V.P. Kondratiev[1], N.A. Maltsev[1], Yu.A. Murin[2], V.V. Petrov[1]

[1]Saint-Petersburg State University, St Petersburg, Russia

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

E-mail: v.zherebchevsky@spbu.ru

DOI: **10.32523/ejpfm.2023070301**
Received: 23.09.2023 - after revision

Today one of the important problems of elementary particle and high energy physics is the study of strongly interacting matter under extreme conditions. In experiments with relativistic heavy ion reactions, a new phase of matter: quark-gluon plasma is being studied. It make possible to shed the light on the first seconds of the Universe existence, as well as to quantitatively describe the processes of neutron star merger. Ultra-high density nuclear matter states could be investigated in the collisions of heavy nuclei at energy range 4 - 11 GeV by studying of the particles yields which contained charm quarks in the Multi Purpose Detector experiment at the NICA collider. In this work, the concept of tracking detector was proposed together with the corresponding modeling of such detector whose inner layers consist of new generation large area thin (40 μm) monolithic active pixel sensors, and whose outer layers are built of pixel sensors (50 μm) currently used in high-energy physics experiments. The identification capability of a vertex detector that uses 40 μm and 50 μm thick pixel sensors was obtained. These data give the possibility to reconstruct the decays of D^+ mesons produced in gold-gold collisions in the NICA complex.

Keywords: vertex detectors; charged particle tracks; short lived charmed mesons; silicon pixel detectors; modeling of silicon detector complexes

Introduction

The strongly interacting matter studies are one of the important and rapidly developing directions of modern elementary particle and high-energy physics.

Experiments with colliding relativistic heavy ions open up the possibility of exploring a new state of nuclear matter, the so-called quark-gluon plasma (QGP).

By investigating of QGP properties, one can answer fundamental questions related to the equation of nuclear matter state at high densities and temperatures. These investigations allow determining presence and position of the critical point on the nuclear matter phase diagram, being able to understand the first seconds of the Universe existence, and quantitatively describe the processes of neutron star mergers. Various astrophysical experiments attempt to investigate the nuclear matter properties at huge densities, but such high-density states can also be studied in collider and fixed target experiments with relativistic heavy nuclei.

Such studies can be realized at the NICA collider at energies 4-11 GeV which is being developed in JINR Dubna [1]. It is expected that in heavy nuclei collisions (relativistic collisions of gold nuclei) the matter with high baryonic density will produce. This matter properties can be investigated by analyzing of the yields of particles containing heavy quarks which will be registered the MPD - Multi Purpose Detector and SPD - Spin Physics Detector experiments. The important physical task of the MPD experiment is to investigate of the phase diagram of high and super-dense nuclear matter [2, 3]. In this case the real interest is to study of the yield of hadrons containing heavy quarks (charm-quarks), since they are characterized by small interaction cross sections with the nuclear medium and carry undistorted information about the states of nuclear matter arising in the relativistic nuclei collision process [4, 5]. Experimentally, such particles are identified by their decay channels into charged hadrons. Due to the short lifetime of particles containing c-quarks, track detectors with high spatial resolution are needed for precise reconstruction of their decay vertex. Such track detector systems can be constructed using monolithic active pixel sensors $-$ MAPS. Therefore in this work, the concept of the inner tracker for MPD experiment has been proposed. For this concept the corresponding simulations and the quality assessment were done for two models of such tracker. First model is a hybrid tracking system whose inner layers consist of new generation large area 40 μm silicon MAPS detectors and whose outer layers are built of 50 μm MAPS detectors currently used in high-energy physics experiments. Second model is a tracking system in which inner and outer layers have only 50 μm thick MAPS detectors. In the context of tasks of D^+ mesons decay reconstruction the identification capability of hybrid model tracking system together with a model that uses only 50 μm thick pixel sensors was obtained. These data will open up the additional opportunities for studying of the charmed particles production mechanisms in the region of the transverse momentum spectrum below 300 MeV/c.

MPD Inner Tracker

The tracking system of MPD experiment consists of two parts: Inner Tracker (used as a vertex detector) and Time Projection Chamber - TPC. In our early works [6, 7], the concept of MPD vertex detector based on thin MAPS (50 μm thickness) which operating today in upgraded Inner Tracker of the ALICE experiment at the LHC in CERN [8] was considered.

In the proposed Inner Tracker model (IT-1) the MAPS detectors with a sensitive area of one detector unit about 1.5 cm $\times$ 3.0 cm and a thickness of 50 μm are grouped into staves arranged along the surface of five coaxial cylindrical layers surrounding the interaction point with beam pipe diameter about 40 mm [6, 7]. The MAPS detector fabricated using CMOS technology [8,9] with substrate and high-resistivity epitaxial layer (sensitive volume of the sensor). On top of epitaxial layer by especial metallization, the charge collection diodes (formed the pixel matrix) have been produced together with front-end electronics for digitization of the pixel signals.

The cross sectional scheme of the IT-1 model in a five-layer configuration is viewed on Figure 1. with geometric parameters - layer radius and layer length, which adapted to 40 mm beam pipe. The length of the staves with MAPS detectors (layers: L_1, L_2, L_3, which are the nearest to the beam pipe) is 750 mm. The outer detector layers (L_4, L_5) of the Inner Tracker have the length about 1526 mm.

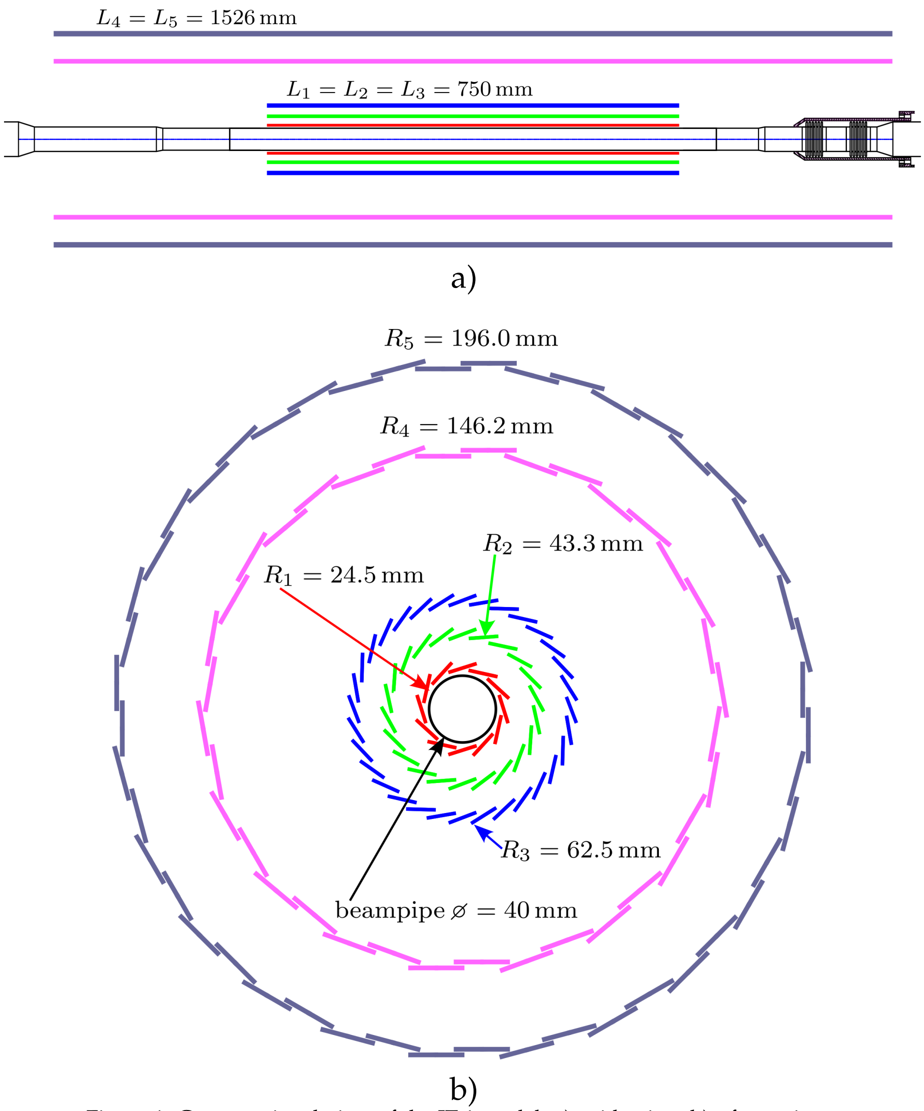


Figure 1. Cross sectional view of the IT-1 model: a) - side view, b) - front view.

The high integration density of silicon-based MAPS detectors and readout electronics in a single device makes it possible to construct thin detectors with less material budget. These thin MAPS can be integrated into large area detectors by a process called stitching, which allows them to be cylindrically shaped [10, 11]. Therefore, sufficiently large and homogeneous modules, covering radius-defined Inner Tracker cylindrical layers can be built. It allows us to move first detector layers closer to interaction point of the colliding beams by shrinking the beam pipe size. In present work, a hybrid model IT-2 has been proposed for the Inner Tracker with the beam pipe diameter of 35 mm. In this model 3 inner layers consist of bent large area silicon sensors thinned to 40 μm. The design of the other two outer detector layers will be based on 50 μm thick MAPS, which are currently used in ALICE experiment [8,9]. The cross sectional view of the IT-2 hybrid model with corresponding geometric parameters (the layer radius and the layer length) adapted to 35 mm beam pipe is shown in Figure 2. For this hybrid Inner Tracker model the length of the staves with MAPS detectors (layers: L_1, L_2, L_3 , which are the nearest to the beam pipe) is 560 mm. The outer detector layers (L_4, L_5) of the Inner Tracker have the length about 1526 mm.

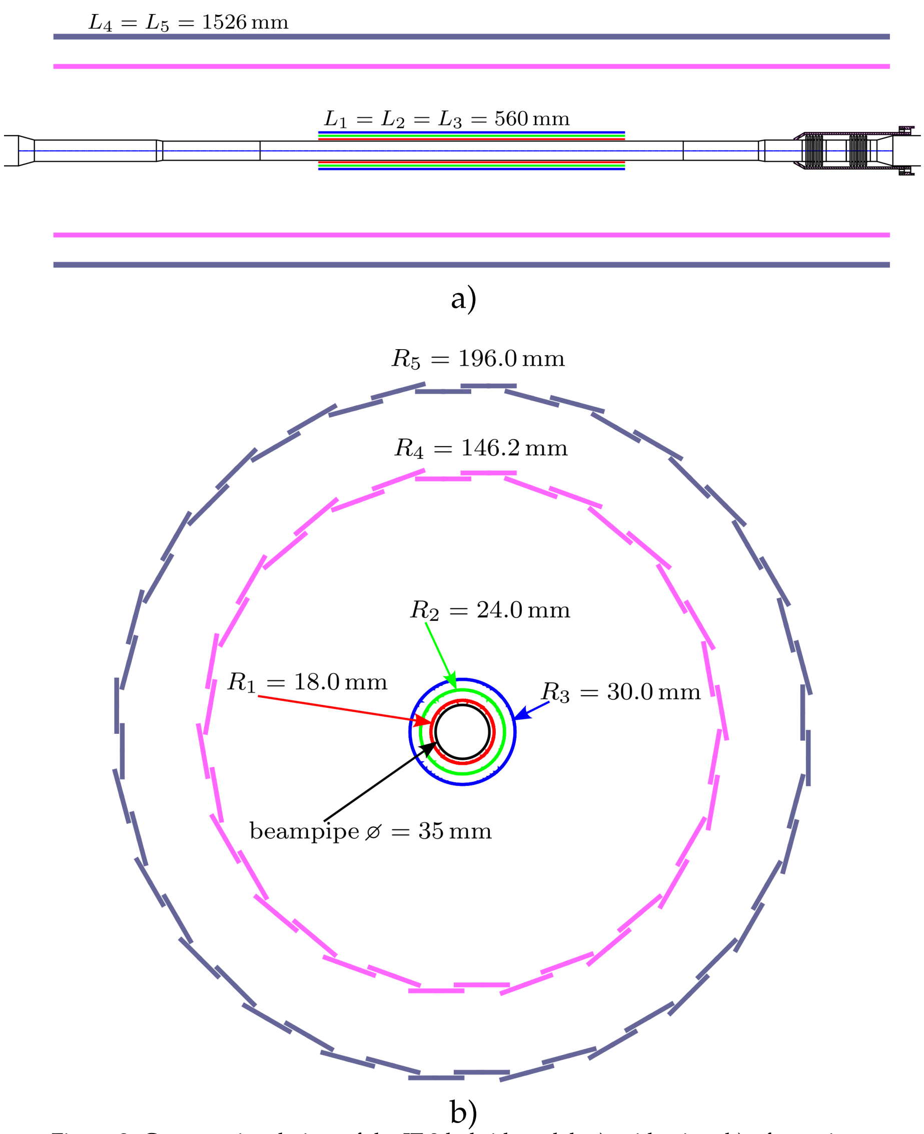


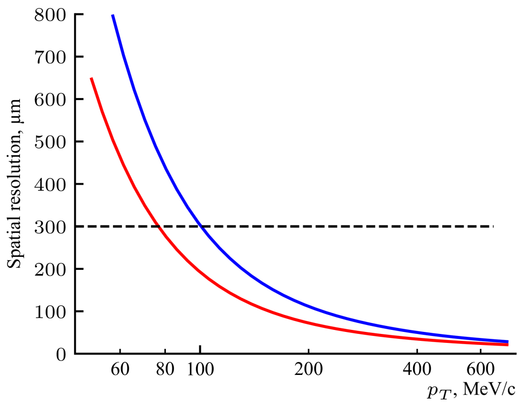
Figure 2. Cross sectional view of the IT-2 hybrid model: a) - side view, b) - front view.

The size of MAPS in the first inner layer of IT-2 is 280×56.5 mm^2, in the second layer - 280×75.5 mm^2 and in the third layer - 280×94.0 mm^2. Therefore, each of three inner detector layers consists of sensors curved at certain distances - 18, 24, 32 mm, respectively, and forming a cylinder 560 mm long.

MPD Inner Tracking System spatial resolution

The inner tracker spatial resolution was estimated within the framework of a semi-analytical model, to allow the charged particle tracks to be reconstructed through cylindrical layers of MAPS detectors with given radiation length. At each simulation step the multiple Coulomb scattering of a particle is taken into account for the layer with a certain radius. It determines the angle of particle emission from a certain layer.

The spatial resolution depending on charged pions and kaons (typical decay products of charmed mesons) transverse momentum was compared for two models: IT-1 and IT-2. The results are shown in Figure 3. It is clearly seen that for the central Au-Au collisions at $\sqrt{s_{NN}}$ = 9 GeV the spatial resolution at the level of 300 μm makes it possible to reconstruct the D^+ mesons ($c\tau$ = 312 μm) decay vertex in channel $D^+ \rightarrow K^- + \pi^+ + \pi^+$ with transverse momentum $p_T > 400$ MeV$/c$ for IT-1 model and with transverse momentum $p_T > 300$ MeV$/c$ for IT-2 model.



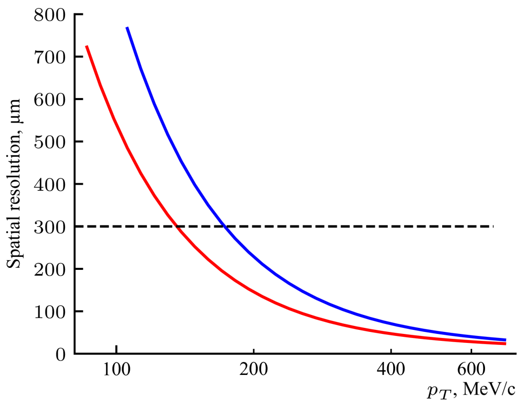


Figure 3. Spatial resolution of IT-1 model (blue line) and IT-2 model (red line) as a function of the transverse momentum of pions (a)) and kaons (b)) in the transverse plane.

Reconstruction of D^+ mesons decay

One way to reliably identify short-lived particles such as charmed mesons is to determine the invariant mass of their charged decay products. For high-efficient reconstruction of the decay vertices, detectors with high pointing resolution are needed. Another important task is to suppress the large background of all charged particles arising in heavy ion collisions by applying the strict signal selection criteria.

To compare the identification power of two developed models, the reconstruction quality of D^+ meson decays originated in relativistic collisions of gold nuclei was evaluated. The gold-gold collisions at $\sqrt{S_{NN}} = 9$ GeV with an impact parameter from 0 to 4 fm, simulated within the QGSM event generator [12], were taken as background events. Signal events (D^+ decays along the channel $D^+ \to K^- + \pi^+ + \pi^+$) were simulated using a thermal generator [13] tuned to the same energy.

To select D^+ signal the method of mixed events was used. In this method the resulting invariant mass spectrum is obtained by summing the signal and background spectra that are processed separately and normalized to the same statistics taking into account the multiplicity of D^+ and the branching ratio of their decay channel.

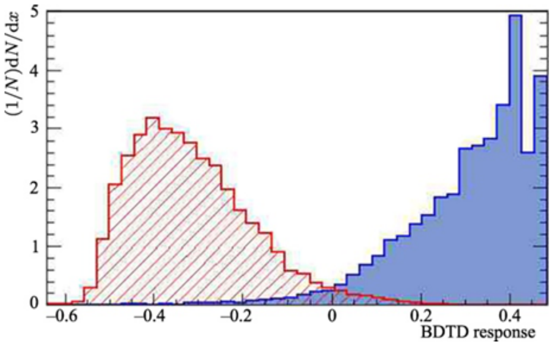
The simulation for Inner Tracker models was performed on the base of the object-oriented MpdRoot software [14]. The main simulation tasks include generation of the detector responses (hits), the reconstruction of particle tracks using generated hits and the reconstruction of the primary and secondary interaction vertices using reconstructed tracks.

The GEANT4 framework which is a part of MpdRoot software provides Monte Carlo (MC) transport of all charged particles through the Inner Tracker + TPC. In this stage the hit maps of MAPS detectors are accumulated, containing the information of the column and row numbers for the fired pixels.

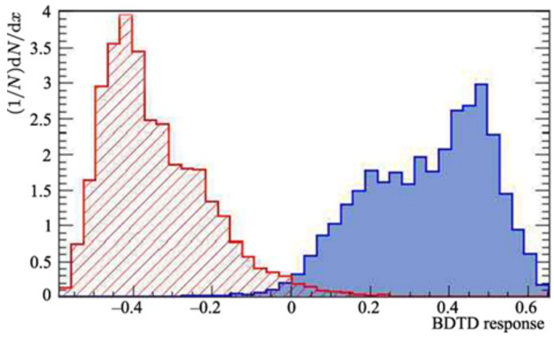
The charged particle tracks were reconstructed using the Kalman filter (KF) method [15]. The essence of this method is to calculate the state vector r of the track at the current step based on information about current measurement information of the state vector at the previous step. The state vector $r(x, y, sin(\varphi), tg(\lambda), q/p)$ of the charged particle track, which is given by the two local coordinates x and y in the transverse plane, the azimuthal angle φ of momentum in the (xy) plane and the inclination angle λ of momentum to the transverse plane, as well as the magnitude of momentum p and charge q, varies from one measurement to another. The uncertainty of the state vector setting is determined by the covariance matrix. The evolution of the track parameters between the state of the current measurement and the next one is given by a linear equation relating the two measurements by means of a process evolution matrix. The arbitrary noise caused by multiple scattering of the particle in the detector material is taken into account by adding a noise covariance matrix. The reliability of the KF is evaluated by the Pearson criterion (χ^2).

The selection of D^+ signals on the combinatorial background was carried out by using the Toolkit for Multivariate Data Analysis (TMVA) [16] which uses the machine learning methods. The main goal of TMVA is to reduce N selection variables V to the one-dimensional variable R (response): $V^N \to R$, the cut of which is applied to signal and background data sets.

The BDTD (Boosted Decision Trees Decorrelation) classifier was used in this work to test and evaluate the input data sets. The following selection parameters were chosen dictated by the topology of three particle decay: a) two-track separation for each pair of decay products, b) decay path of mother particle, c) pointing angle between the vector connecting the primary and secondary vertices and the vector of the reconstructed momentum of the mother particle. The response of the classifier to signal and background events in the tracking system including the TPC and the considered inner tracker models is shown in Figure 4. To separate signal and background, the optimal value of the resulting classifier response parameter (for IT-1 the BDTD_response > 0.25, for IT-2 the BDTD_response > 0.20) was applied to the signal and background events. After that, the resulting invariant mass spectrum $M(K^{-}\pi^{+}\pi^{+})$ was reduced to the statistics of 100 M events of gold-gold collisions.



a)



b)

Figure 4. Distribution of classifier responses to signal $D^{+} \to \pi^{+} + \pi^{+} + K^{-}$ and background events in a tracking system including the TPC and TPC + IT-1 model (a)) and TPC + IT-2 model (b)).

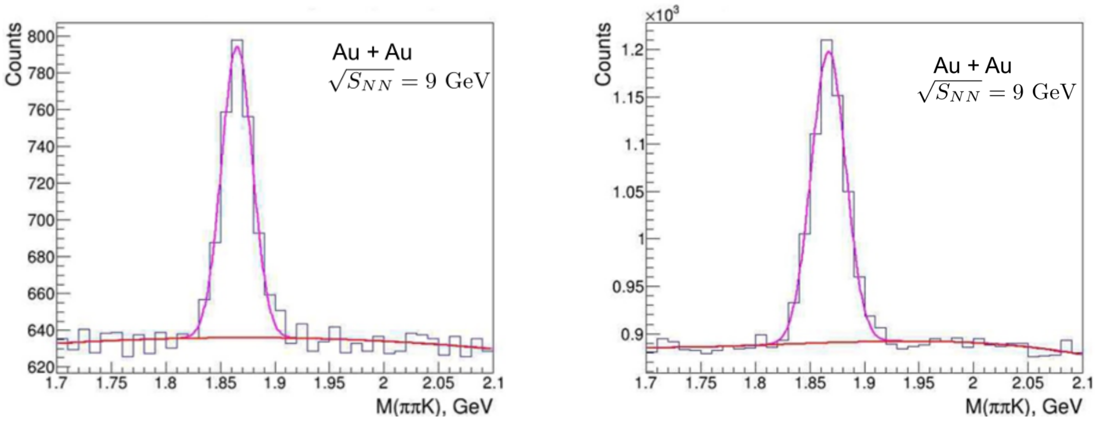
The invariant mass $M(K^{-}2\pi^{+})$ spectra of D^{+} decay products extracted in 100 M central gold-gold collisions in the tracking system including different inner tracker models (IT-1 model and IT-2 model) are shown in Figure 5.

To extract the signal in the invariant mass spectrum, the peak and the background were fitted by Gaussian with the width σ and a polynomial function respectively. The background level (B) is determined as the area under the polynomial function in the $\pm 2\sigma$ interval around the peak, and the signal level (S) is determined by the area under the Gaussian function. A comparison of the D^{+} mesons decay reconstruction parameters (signal level S, signal-to-noise ratio S/B, significance $\frac{S}{\sqrt{S+B}}$, efficiency ϵ) in the tracking system TPC + IT-1 and TPC + IT-2 is given in Table 1. One can see, the reconstruction efficiency doubles when switching to tracker with inner layers built from a new type bent large area MAPS detectors thinned to 40 μm.

Table 1.
Parameters of D^{+} meson decay reconstruction used in models in models of inner tracker IT-1 and IT-1 (S and B - number of signal and background events.

Inner tracker	S	S/B	$\frac{S}{\sqrt{S+B}}$	ϵ, %
IT-1	550	0.15	8.4	0.60
IT-2	1150	0.21	14.0	1.25

The obtained result can be improved by using an additional detector layer in the gap between the three inner and two outer layers. These simulations will be done in the next stages of work taking into account additional information about microcables, ultralight-weight carbon composite detector module support structures and detector cooling system.



a) b)

Figure 5. The D^+ mesons peak in the invariant mass $M(2\pi^+K^-)$ spectrum extracted in 10^8 central Au+Au collisions in case of event registration by a tracking system including IT-1 model (a)) and IT-2 model (b)).

Results and conclusion

The MPD Inner Tracker simulations have shown that the use of thin large-area MAPS detectors in the inner layers of the tracking system, as close as possible to the collider beams collision point, allows us to obtain a twofold gain in the reconstruction efficiency of charmed mesons. The proposed version of the vertex detector also makes it possible to lower the threshold for identifying such particles by their transverse momentum to 300 MeV/c, which opens up an additional possibility for studying the processes of charmed particle production in the softer region of the spectrum. However, it should be noted that the geometry of the considered hybrid Inner Tracker model is not optimal due to the large gap between two layers - inner and outer, which can affect to identification capability of the tracking system. Nevertheless, the hybrid model can be considered as an asymptotic limit of a more realistic 6-layer Inner Tracker design adapted to the beam pipe with the smallest achievable diameter, in which the distance between the inner and outer detector layers will be reduced.

Acknowledgments

The reported study was supported by the Russian Science Foundation, project no. 23-12-00042, https://rscf.ru/en/project/23-12-00042/.

References

[1] NICA. [*WebLink*]
[2] Kh. Abraamyan et al., Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip. **628** (2011) 99-102. [*CrossRef*]
[3] V. Kekelidze et al., Nucl. Phys. A **967** (2017) 884-887. [*CrossRef*]
[4] G. Moore, D. Teaney, Phys. Rev. C **71** (2005) 064904. [*CrossRef*]
[5] H. van Hees, R. Rapp, Phys. Rev. C **71** (2005) 034907. [*CrossRef*]

[6] V. Zherebchevsky et al., Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip. **985** (2021) 164668. [*CrossRef*]
[7] V.I. Zherebchevsky et al., Bulletin of the Russian Academy of Sciences: Physics **86** (8) (2022) 948-955. [*CrossRef*]
[8] The ALICE Collaboration, J. Phys. G Nucl. Part. Phys. **41** (2014) 087002. [*CrossRef*]
[9] L. Musa, S. Beole, CERN Courier (2021). [*CrossRef*]
[10] The ALICE Collaboration, Tech.Rep. CERN-LHCC-2019-018. LHCC-I-034 (CERN, Geneva, 2019). [*CrossRef*]
[11] The ALICE ITS project, Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip. **1028** (2022) 166280. [*CrossRef*]
[12] K. Gudima, S. Mashnik, A. Sierk, User manual for the code LA QGSM, Report LA-UR-01-6804 (Los Alamos Natl. Labor., Los Alamos, 2001).
[13] A. Tawfik, E. Abbas, Phys. Part. Nuclei Lett. **12** (2015) 521-531. [*CrossRef*]
[14] MpdRoot Software. [*CrossRef*]
[15] Frühwirth R., Nucl. Instrum. Methods Phys. Res. A: Accel. Spectrom. Detect. Assoc. Equip. **262** (1987) 444-450. [*CrossRef*]
[16] Hoecker A. et al., arXiv (physics/0703039) (2009). [*CrossRef*]