Development of a Vector Finder toolkit for track reconstruction at NICA experiments: current status and future prospects

D. Zinchenko[a1], *A. Zinchenko*[a], *R. Zinchenko*[b] *E. Nikonov*[a]

[a] Joint Institute for Nuclear Research, Joliot-Curie 6, Dubna 141980, Moscow region, Russia

[b] Moscow State University, Physics Department, Leninskie Gory 1, Moscow 119991, Russia

The MPD (MultiPurpose Detector) and BM@N (Baryonic Matter at Nuclotron) setups at the NICA complex are intended to carry out experiments with heavy ions in the collider and fixed-target modes, respectively. To extract quality physics information from their data it is required to develop and implement efficient and reliable event reconstruction methods in the conditions of high particle multiplicity.

A unified approach to the task of track reconstruction in these two experiments was proposed and implemented as a Vector Finder software toolkit. The current status of this project is described in this paper and its basic performance numbers are demonstrated for simulated event samples. Possible future improvements of the method are also presented.

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Introduction

The Nuclotron-Based Ion Collider Facility (NICA) is currently under construction at the Joint Institute for Nuclear Research (JINR) in Russia. Its main experiments dedicated to studies of heavy-ion interactions, Multi Purpose Detector (MPD) and Baryonic Matter at Nuclotron (BM@N), are expected to strengthen the experimental investigation of the high-density baryonic matter produced in heavy-ion collisions in the energy range of several GeV, i.e. $\sqrt{s_{NN}}$ = 4 - 11 GeV for MPD and $\sqrt{s_{NN}}$ = 2.3 - 3.3 GeV for BM@N.

Obtaining quality physics results from experimental data requires adequate tools for data processing - in particular, reliable and efficient methods of track reconstruction in high-multiplicity environment of heavy-ion interactions. One of the proposed approaches to this task - a Vector Finder toolkit [1] - was originally developed and implemented for the MPD upgrade program, which included the installation of the Inner Tracking System (ITS) based on the next-generation silicon pixel detectors known as Monolithic Active Pixel Sensors (MAPS) between the beam pipe and the Time Projection Chamber (TPC). Such a detector will increase the research potential of the experiment for both the high-luminosity proton–proton and high-multiplicity

[1]E-mail: zinchenk1994@gmail.com

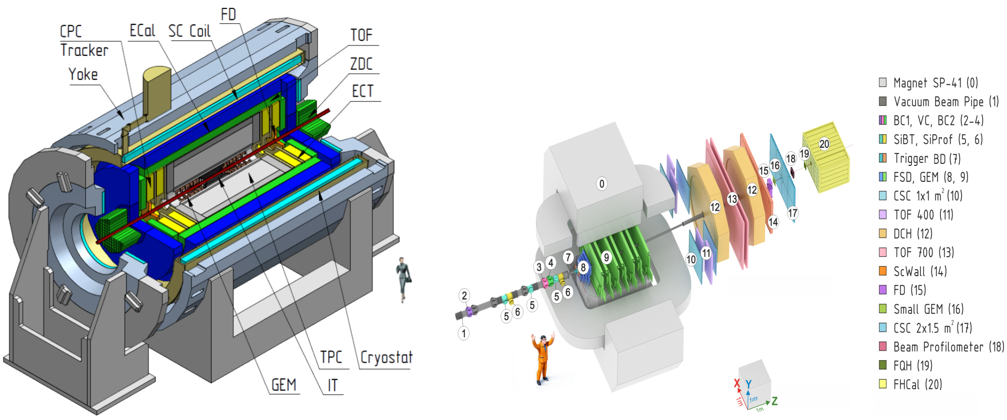

Fig. 1. MultiPurpose Detector and Baryonic Matter at Nuclotron - detectors for heavy-ion interaction studies at NICA.

nucleus–nucleus collisions. The main purpose of the ITS is to improve the quality and precision of tracks, primary and secondary vertex reconstruction in the MPD in the region close to the interaction point.

ITS studies showed that a Kalman filter - based approach used for track finding in the TPC, did not efficiently handle such ITS features as high coordinate resolution and a small number of measurements per track (5 as compared with 53 in the TPC). That is why it was decided to develop another approach for track finding in the ITS of MPD, which was implemented as a Vector Finder toolkit.

Vector Finder implementation showed significant improvement of track reconstruction quality on simulated data [2], so it was decided to adapt the same approach to the ongoing fixed-target experiment of NICA, BM@N, which had its first physics run in December 2022 - January 2023. This decision required further toolkit development for handling different detector geometry, larger number of detector stations and higher ghost hit rate.

The current status of the toolkit algorithms for the two heavy-ion NICA experiments and their performance results are described below.

MPD and BM@N detectors

The MPD detector at the NICA collider has been designed to detect hadrons, electrons and photons over a large phase-space at the high event rate of 7 kHz achieved at NICA for Au + Au collisions at the designed luminosity of $L = 10^{27} \mathrm{cm}^{-2}\mathrm{s}^{-1}$. As can be seen in Fig. 1 (left), it is a typical collider detector where all the subdetectors are located inside a superconducting solenoid, which produces a magnetic field along the beam axis with a nominal strength of 0.5 T. A detailed description of the detector components can be found in [3]. Here only the tracking subdetectors relevant for the current study are presented.

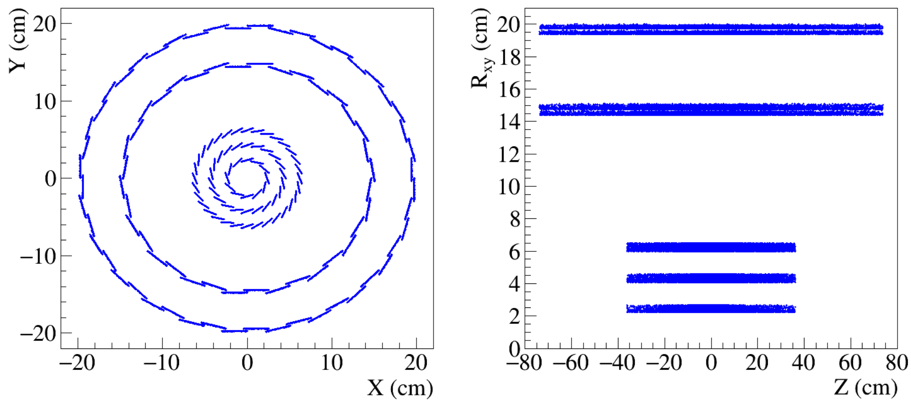

Fig. 2. Monte-Carlo points produced in the Inner Tracking System of MPD in different projections.

The TPC is the main tracking subdetector for the reconstruction of charged particle trajectories over the pseudorapidity range of $|\eta| < 1.5$. It provides the momentum measurement for charged particles with a precision better than 3.5% at a transverse momentum p_T below 2 GeV/c and particle identification via the specific energy loss measurement (dE/dx) in the TPC gas with a resolution better than 8%.

The future Inner Tracker (IT) system, made of 5 layers of silicon pixel detectors, is intended for very accurate determination of the position of primary and secondary vertices and improvement of the track reconstruction performance for low-p_T tracks. These goals are achieved because of higher acceptance of the ITS in pseudorapidity ($|\eta| < 2.0$) and transverse momentum of tracks resulting from its close proximity to the beam line (3 cm instead of 40 cm in the TPC) and excellent spatial resolution (< 10 μm in each direction as compared with 0.5 mm and 1 mm in transverse and longitudinal directions, respectively, for the TPC). One of the proposed ITS configurations and its dimensions can be better evaluated from Fig. 2, where coordinates of the points produced by particles during Monte Carlo simulation are shown in two projections.

The current layout of the BM@N setup is presented in Fig. 1 (right). It is a typical fixed-target detector described in more detail in Ref. [4]. Tracks of charged particles are reconstructed with the hybrid tracking system consisting of 4 stations of double-sided microstrip silicon sensors (Forward Silicon) downstream from the target, and a set of 7 planes of GEM (gaseous electron multiplier) detectors with two-coordinate strip readout mounted downstream from the silicon stations. The Forward Silicon subsystem contains 6, 10, 14 and 18 modules in stations 1-4, respectively, arranged into pairs of half-stations below and above the beam line at a distance of ~10 cm between stations. The central tracker configuration can be better understood from Fig. 3, where Monte Carlo simulated points are plotted in two projections.

Both the Forward Silicon and the GEM stations are installed inside a large aperture dipole magnet with a gap height of 1 m, providing a vertical

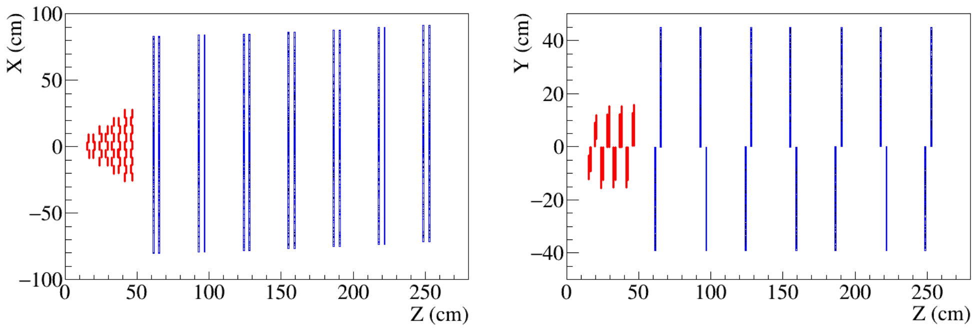

Fig. 3. Monte-Carlo points produced in tracking detectors of BM@N in different projections.

magnetic field with a maximum value of 1.0 T and a field integral along the central tracker of ∼2 T·m. For different beam ions and energies, the magnetic field value is adjusted to steer the beam particles through the vacuum beam pipe.

Vector Finder track reconstruction algorithm

Despite the differences between the two detector configurations coming from the beam interaction regime (collider versus fixed target), the track reconstruction environments are quite similar in both cases. Namely, there is a bending plane perpendicular to the magnetic field direction, where track projections are close to circle arcs. In the longitudinal projection with respect to the magnetic field direction tracks can be considered as straight lines. Therefore, one can define two sets of acceptance criteria to preselect hit combinations possibly belonging to particle tracks. Below, the track reconstruction method is presented for the BM@N central tracker with additional comments for the MPD ITS where needed.

The reconstruction procedure begins from building vectors connecting hits on two detector layers, where a hit is a reconstructed point on a detector layer (station). Two hits can make a vector if they satisfy the acceptance criterion on the difference of tangents of their angular positions along the field direction. This difference should be quite small. Hits on a vector together with the mean interaction point also define a momentum estimate which can be used to reject combinations with too high curvature of the track candidate or to implement the reconstruction procedure in several passes to speed up the processing. Within such a procedure, tracks with high momentum and large number of hits are reconstructed in the first pass. Hits, attached to the found tracks, are excluded from further processing. For each subsequent pass, looser criteria are used to accept softer and shorter tracks. It should be noted here that the interaction point is well constrained in the case of the fixed-target configuration, where it is defined by the transverse beam size and the target position, while it is widely distributed along the beam direction in the collider. However, its position can be determined with sufficient accuracy by trigger detectors or evaluated from hit pair combinations before track reconstruction.

At the next stage, bivectors (hit triplets) are built by combining two vectors sharing the same hit which is the terminal hit of the first vector and the initial one of the second vector. In order to be combined, both vectors should have consistent curvature (or inverse momentum) estimates. In addition, they should have similar slope parameters in the non-bending hyperplane, defined by the bivector projection onto the bending plane and the magnetic field direction. This is checked by the linear fit in this hyperplane, and the fit χ^2 is used as the acceptance cut. Moreover, in order to further reduce the combinatorics, the number of bivectors built from one vector can be restricted to a certain number N_3, i.e. up to N_3 bivectors with the lowest χ^2 are kept with the others being rejected.

The collections of vectors and bivectors are further used to build tracks with the following procedure. Starting from a bivector on the first station (layer), the track candidate is extended by adding a vector to its end according to the following scheme: if, for example, the starting bivector bv_{123} contains hits from detector layers 1, 2 and 3, the vector v_{34} is attached to it if there is a bivector bv_{234} in the bivector collection. The track extension procedure is repeated until no more vectors are attached. Track candidates with 4 hits are fitted with a Kalman filter procedure and its χ^2 is used as a stopping criterion of the extension process. For survived 4-hit tracks, for every additional hit the χ^2-value is updated with the Kalman hit filtering function to decide on further extension. After all track candidates are processed, the ones with a sufficient number of hits are passed through the clone removal procedure, which finds track pairs with more than one shared hit and removes the track with a lower quality.

As can be understood from the method description, the track reconstruction procedure is strongly based on a priori constraints defined by the detector configuration. The constraints allow reducing the combinatorics and can be obtained from a Monte Carlo simulation of the setup with a particle transport code (e.g.Geant3 or Geant4) and analysis of sets of hits from the same particles on different detector stations. For example, one can see in Fig. 4 (left) the inverse value of the momentum projection $1/p_{xz}$ on the bending plane XZ as a function of $\Delta\tan(X/Z) \equiv \Delta T_x$, where ΔT_x is a difference of tangents of vector initial and terminal hit angular positions in XZ-plane and the momentum is calculated using the mean position of the beam-target interaction region as the third point. The results were obtained for BM@N detector simulated response to minimum bias Xe + CsI interactions at $\sqrt{s_{NN}} = 3.296$ GeV (kinetic energy of Xe beam of 3.9 GeV), produced with the DCM-SMM event generator [5]. The distributions are fitted by the 4-th degree polynomials and the fit parameters are stored in a lookup table to define the acceptance windows in ΔT_x for different reconstruction passes with different cut-off values of $1/p_{xz}$ as shown on the plot by the dashed line. The lookup table contains such parameters for all station pairs, which are allowed to form a vector, and different values of the initial

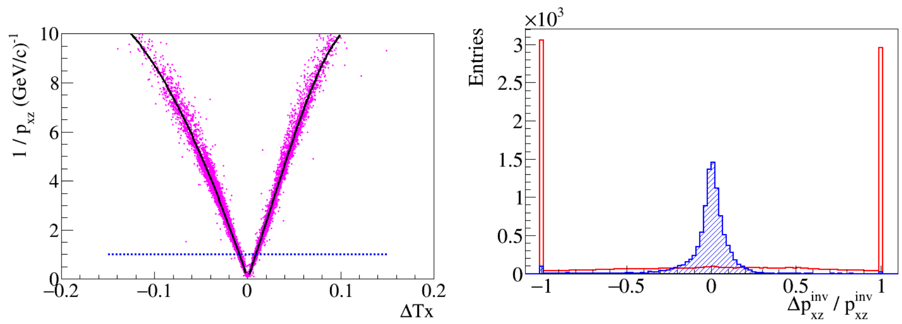

Fig. 4. Left) inverse momentum $1/p_{xz}$ as a function of the difference ΔT_x of tangents of vector initial and terminal hit angular positions in XZ-plane $T_x^{init} \equiv \tan(X^{init}/Z^{init})$ for initial and terminal stations 2 and 3 and $T_x^{init} = -0.05$; right) difference of inverse track momentum estimates from two vectors in a bivector starting from station 3. Blue and red histograms represent correct and wrong vector combinations, respectively. Red histogram is scaled by a factor of $1/200$.

point $T_x^{init} \equiv \tan(X^{init}/Z^{init})$, which are stored as binned data. Figure 4 (right) shows the difference of inverse track momentum estimates from two vectors in a bivector for the hits from the same particle and wrong combinations. One can see that distributions for correct vectors are peaked at zero and can be used to apply some constraints on this variable.

Results

Performance of Vector Finder for MPD was tested on a sample of UrQMD generated events of central Au+Au collisions at $\sqrt{s_{NN}} = 9$ GeV. The events were passed through the detector setup within the MpdRoot software framework using the Geant3 transport package to simulate the effect of the material and magnetic field. Figure 5 shows track reconstruction efficiency as a function of the transverse momentum p_T and pseudorapidity η. The efficiency is close to 1 in the full acceptance region of the detector. It should be noted here that the probability to reconstruct fake tracks (fake rate) is very low due to high granularity of the ITS pixel sensors.

For BM@N, Vector Finder was tested on a sample of Xe + CsI minimum bias interactions at $\sqrt{s_{NN}} = 3.296$ GeV, produced with the DCM-SMM event generator. Figure 6 shows reconstruction efficiency as a function of the transverse momentum and pseudorapidity as well as ghost rate. While the efficiency also achieves high values, ghost rate becomes a significant challenge for this setup due to high track density in the fixed-target regime and high ghost hit rate in the detectors with double-sided strip readout.

Some additional quality assessment of reconstruction performance can be done using Fig. 7 which shows invariant masses of track pairs with opposite charges under the hypotheses of the proton and π^- meson for Λ hyperon and π^+ and π^- for K_s^0 meson reconstruction according to the approach from Ref. [6]. The results were produced for a set of 950 thousand events of Xe + CsI interactions obtained during the first physics run of BM@N with Xe

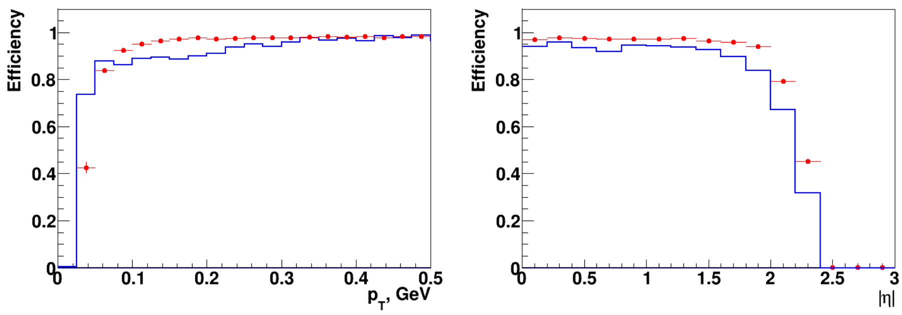

Fig. 5. (Left) track reconstruction efficiency in the MPS ITS as a function of transverse momentum for primary and secondary tracks produced with $|\eta| < 1.2$; (right) reconstruction efficiency as a function of $|\eta|$ for primary and secondary tracks with $p_T > 0.1$ GeV/c. Red color is for primaries, blue one for secondaries.

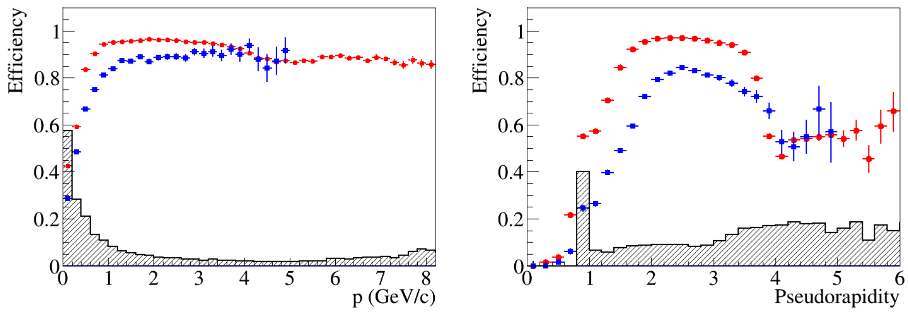

Fig. 6. Track reconstruction efficiency in the BM@N central tracker for primary (red circles) and secondary (blue squares) and ghost rate (hatched histogram) as functions of: left) momentum, right) pseudorapidity.

beam kinetic energy of 3.8 GeV and demonstrate clear peaks at right mass values.

Summary and future steps

The Vector Finder track reconstruction toolkit has been developed and implemented for NICA experiments MPD and BM@N. It was tested for simulated event samples of heavy-ion interactions and demonstrated good performance results. Its application for track reconstruction in the first physics run of the BM@N experiment has confirmed high performance level also for real data.

As a next step, it is planned to apply multivariate analysis methods based on machine learning techniques to better define track selection criteria, which is especially important for the BM@N experiment where a relatively high fake track rate was observed.

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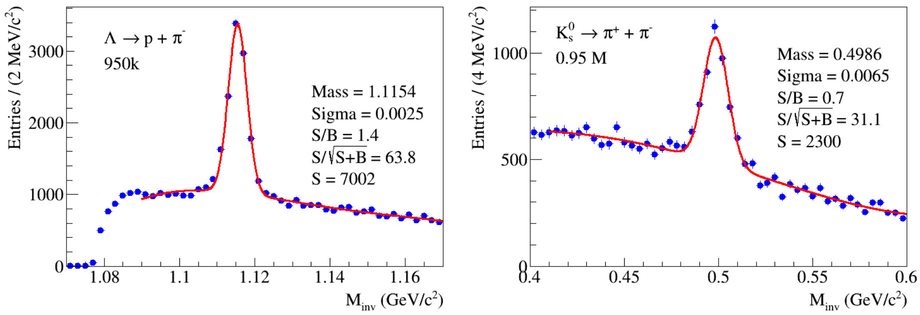

Fig. 7. Reconstructed invariant mass of Λ hyperon and K_s^0 meson obtained with a set of 950 thousand events of Xe + CsI interactions collected during the first physics run of BM@N with Xe beam kinetic energy of 3.8 GeV.

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