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Implementation of the cellular automaton method for track reconstruction in the inner tracking system of MPD at NICA

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A track reconstruction method based on a cellular automaton concept has been developed and implemented for the inner tracking system of the MPD experiment at NICA. The reconstruction algorithm is briefly described and some obtained results are presented.

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1. Introduction

The Nuclotron-based Ion Collider fAcility (NICA) [1] is a new accelerator complex being constructed at JINR, Dubna, Russia. NICA's aim is to provide collisions of heavy ions over a wide range of atomic masses, from Au+Au at $\sqrt{s} = 4 - 11$A GeV (for Au^{79+}) and an average luminosity $L = 10^{27}$ cm^{-2}s^{-1} to proton-proton collisions with $\sqrt{s_{pp}} = 20$ GeV and $L = 10^{32}$ cm^{-2}s^{-1}.

The main goal of studying heavy-ion collisions is to explore the properties of nuclear matter under extreme density and temperature conditions. In these conditions, hundreds of charged particles are produced, and extracting high-quality physics information requires reconstruction of particle tracks and determination of their parameters with high precision.

Reconstruction of events with high multiplicity is a challenge, which physicists had started to be facing relatively recently (within the last 10 years or so - experiments at RHIC and LHC colliders). In future experiments (CBM at FAIR and MPD at NICA), this problem will be even more difficult due to the fact that successful realization of the physics program will require reconstruction of particle tracks with very low momenta (of the order of hundreds of MeV/c and even less) and processing large amounts of experimental data.

In this paper a track reconstruction method based on a cellular automaton algorithm will be described and its implementation for the Inner Tracking System (ITS) of the MultiPurpose Detector (MPD) presented.

2. TPC and ITS - central tracking detectors of MPD

The general view of the MPD detector is presented in Fig. 1. Its detailed description can be found in Refs. [2, 3]. Its main tracker is the time projection chamber (TPC) supplemented by the inner tracker (IT). IT and TPC have to provide precise tracking, momentum determination and vertex reconstruction.

In MPD, the inner tracking system is considered as a second stage detector. It is intended to do the following:

- first, it will enhance track reconstruction capabilities of all other tracking subsystems - ITS will be able to improve tracking of particles with momentum less than 150 MeV/c;
- second, the tracker will improve the identification and reconstruction of rare events, e.g. production of hyperons with strangeness -2 and -3.

From Figs. 2 and 3 one can see that ITS and TPC have quite different geometries. In particular, ITS has only four layers with multiple overlaps of sensitive elements (Figs. 4, 5). On the contrary, TPC has a "simpler" structure and provides much larger number of coordinate measurements for a track (>50). Therefore, one should expect that the two detectors will require different approaches to optimal track reconstruction.

3. Track reconstruction techniques in MPD ITS: Kalman filter vs cellular automaton

The current approach to the problem of track reconstruction in MPD TPC is based on the method of the Kalman filter. This method provides means to find tracks and determine their param-

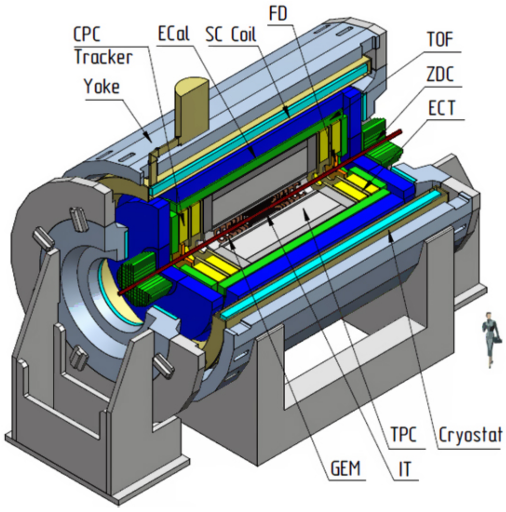

Figure 1: General view of the MPD detector. The detector includes the following subsystems: superconductor solenoid (SC Coil) and magnet yoke, time-projection chamber (TPC), inner tracking system (IT), time-of-flight counters (TOF), electromagnetic calorimeter (EMC), straw-tube endcap tracker (ECT), cathode pad chambers (CPC), gas electron multiplier detectors (GEM), fast forward detectors (FD) and zero degree calorimeter (ZDC).

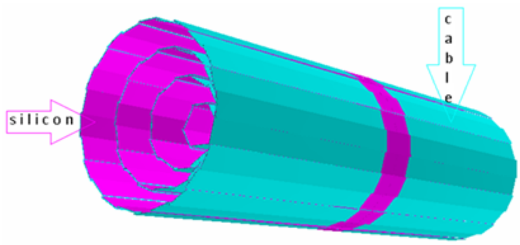

Figure 2: Layout of the ITS detector.

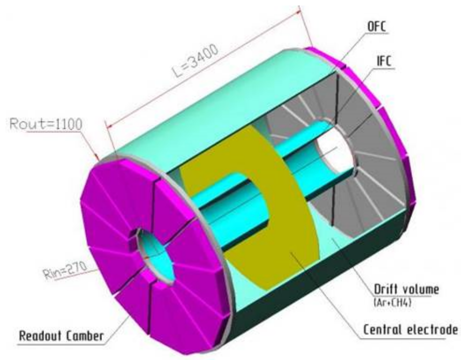

Figure 3: Layout of the TPC detector.

eters simultaneously [4]. The Kalman filter is a recursive filter, which evaluates the state of a linear dynamic system using a set of inaccurate measurements with the errors distributed according to the normal law. For the central tracking detector TPC with its relatively "simple" geometry, relatively low hit density and large number of track coordinate measurements with small distance between consecutive points, the Kalman filter is a natural choice of the reconstruction method. It produces very good results both in terms of the track reconstruction efficiency and momentum resolution (Fig. 6).

First attempts to extend the Kalman filter procedure to ITS using track extrapolation from TPC showed some deficiencies of the approach due to complexity of the ITS geometry and high hit density in the detector. Namely, the necessity to extrapolate tracks to complex detector surfaces and select hits in the configuration with relatively large amount of the active (silicon detectors) and

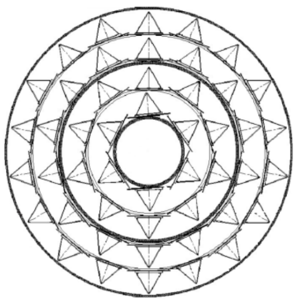

Figure 4: Transverse view (along the beam direction) of ITS.

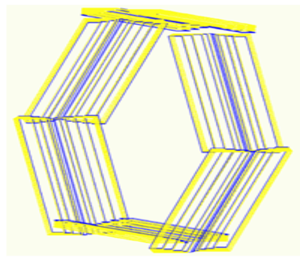

Figure 5: The layout of the innermost ITS layer.

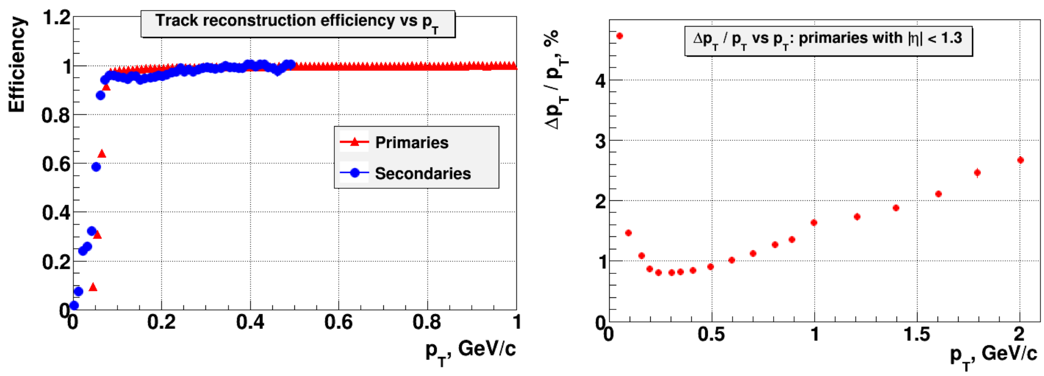

Figure 6: Left – track reconstruction efficiency as a function of track transverse momentum p_T for primary and secondary particles; right – relative transverse momentum resolution for primary tracks with pseudorapidity $|\eta| < 1.3$ reconstructed in TPC.

passive (readout cables) material made the core Kalman filter procedure rather inefficient with a subsequent loss of tracking quality.

So, ITS features require to develop and implement a method that would allow to cope with high multiplicity of tracks affected by a multiple scattering inside a complex detector geometry. As one of the possibilities one can take the one proposed in the cellular automaton (CA) method.

Cellular automata are dynamic systems that evolve in a discrete, usually two-dimensional space consisting of cells. In application to ITS tracking, one can take as a cell a track segment connecting pairs of detector hits on two consecutive layers. The cell can have two states: 1 if the segment is considered as a part of the track, and 0 if the segment connects the points which do not lie on the same track.

Within this scheme, the task of track reconstruction in MPD ITS should consist of three main steps:

- formation of tracks - segments;
- construction of tracks - candidates;
- track fitting;

and be realized within the MPDRoot software framework [5] (Fig. 7). It is the first two steps that can be handled by the CA approach, the last one being the “standard” task for the Kalman filter.

Thus, one can propose the following CA procedure:

- start from track-segments built from ITS hits from sequential detector layers. Possible combinatorics can be reduced by applying some a priori physics cuts, e.g. segment angles should be consistent with ion collision topology;
- combine “neighbor” segments to build candidate tracks, where the “neighborhood” is defined by the requirements to share a middle point and have close enough angles (again consistent with event topology);
- evaluate the track state vector parameters to apply the Kalman filter;
- evaluate the initail covariance matrix of these parameters.

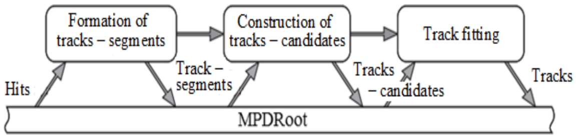

Figure 7: Track reconstruction steps.

4. CA implementation for ITS

As mentioned above, to reduce possible hit combinations the CA procedure should use some a priori information. For instance, one can introduce some angular acceptance windows (“cuts”) on the transverse (*dangt*) and longitudinal angle (*dangl*) of track segments. A schematic representation of the angles is shown in Fig. 8. The main difference between these angles is that the particle track in the longitudinal plane is described by a straight line, while in the transverse plane by a circular arc due to deflection in the magnetic field. Therefore, for the 4-layer detector one can build 3 longitudinal angles (between consecuitive segments) and 2 transverse angles, since the transverse angle is in fact an angular difference of the deflection angles.

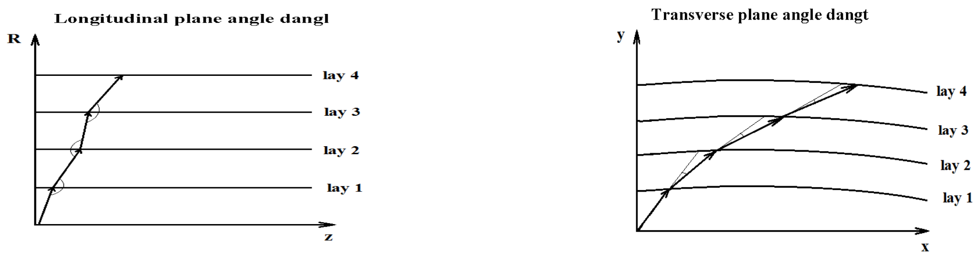

Figure 8: Left - schematic representation of the angle *dangl* in the longitudinal plane; right - schematic representation of the angle *dangt* in the transverse plane.

The numerical estimates of the acceptance cuts can be obtained from the angular distributions of *dangt* and *dangl* for samples of tracks with fixed transverse momentum p_T to obtain the dependences of their RMS (root mean square) on p_T. Figures 9 and 10 show histograms of the angles *dangl* and *dangt* for $p_T = 0.05$ GeV/c, the spread of angles for a fixed p_T being due to the effect of coordinate reconstruction errors and multiple scattering of particles in the detector material. One should also add here that the estimation procedure went from the innermost to the outermost layer with a sequential averaging of the angles to obtaine more and more accurate values from one layer to another (hence more narrow distributions for the layers with larger numbers in Figs. 9, 10). The obtained dependences of the distribution σ (standard deviation of the Gaussian fit) on p_T can be seen in Fig. 11 for layers 2-4 (*dangl*) and layers 3,4 (*dangt*).

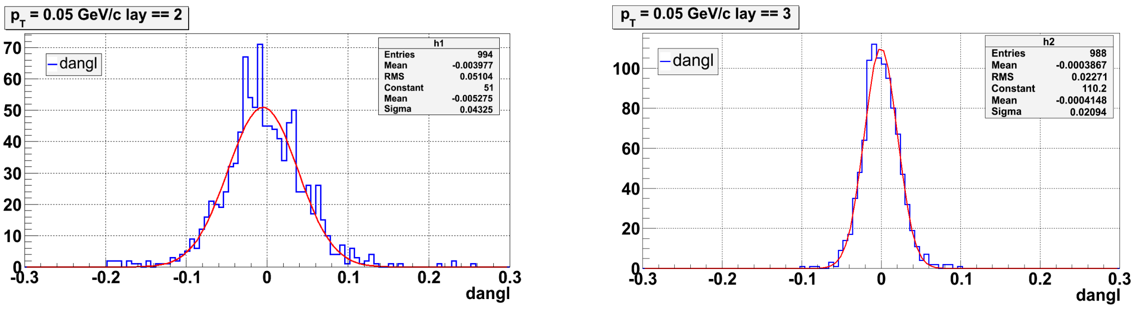

Figure 9: Distribution of *dangl* for layer 2 (left) and layer 3 (right) for $p_T = 0.05$ GeV/c.

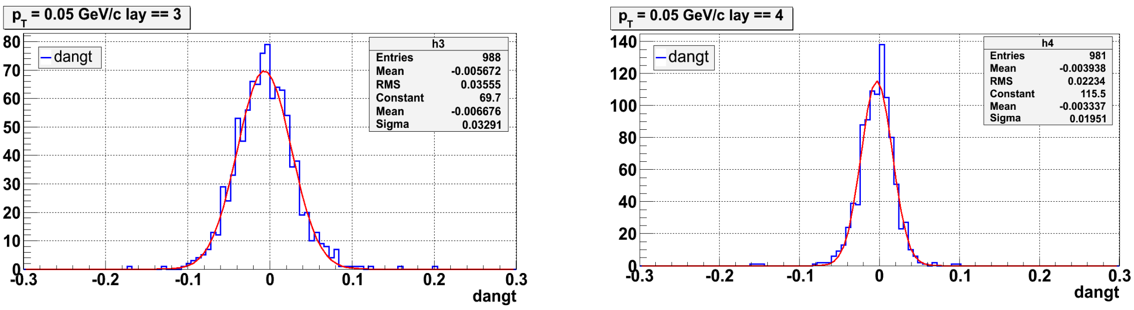

Figure 10: Distribution of *dangt* for layer 3 (left) and layer 4 (right) for $p_T = 0.05$ GeV/c.

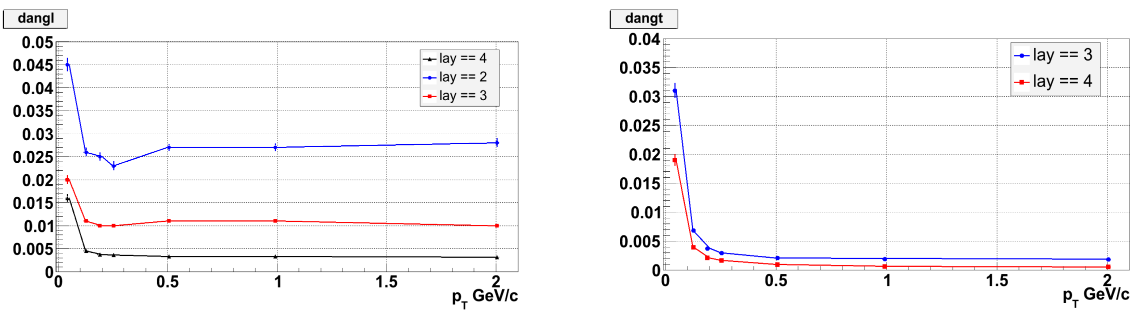

Figure 11: Left - *dangl* sigma dependence on p_T (layers 2-4); right - *dangt* sigma dependence on p_T (layers 3,4).

Once the a priori information is obtained, the CA procedure proceeds as follows:

- segments between hits on layers 1 and 2 are created. Here a physics cut has been applied (pseudorapidity limit $|\eta| < 2$);
- track segments are extended to the layer 3 if the respective longitudinal angle is within the largest acceptance window;
- two segments, built from hits from the first three layers of the detector give a p_T - estimate from the transverse angle between the segments;
- for the given p_T, it is checked whether the longitudinal angle is within the allowed range;
- the procedure is repeated for the next layer using the information about the angles from previous layers (by averaging).

To speed up the processing, the CA procedure works in three passes - the first one to search for tracks with p_T >0.4 GeV/c, the second with p_T >0.2 GeV/c, and the third with p_T >0.05 GeV/c for the remaining hits. When all valid track-candidates are built, their initial track parameters and error matrices are evaluated. They are stored for the subsequent use in the Kalman filter.

5. Some results of CA-based tracking in ITS

To evaluate the cellular automaton performance, the UrQMD generator[6] of central Au-Au interactions with $\sqrt{s}$ = 9A GeV with an average multiplicity of about 1000 charged particles in the detector acceptance was used.

To check the ouput of the CA procedure (before applying the Kalman filter), the normalized parameter residuals (pulls) demonstrating the correctness of the estimates of the track parameter errors were calculated:

$$pull_x = \frac{(x_{rec} - x_{MC})}{\sigma_x}, \tag{5.1}$$

where x_{rec} is the reconstructed track parameter value, x_{MC} is the true (Monte Carlo) value of the track parameter and σ_x is the computed value of the track covariance matrix element. Assuming a correct estimate of the covariance matrix, the distribution of the normalized residuals should be described by the normal distribution with a mean of 0 and variance close to 1. Figure 12 shows distributions of pulls for 4 track parameters $rphi, posz, ang, theta$ (transverse position, longitudinal position, azimuthal angle and polar angle).

Figure 13 shows the relative momentum resolution for the primary and secondary tracks defined as:

$$\frac{dp_T}{p_T} = \frac{(p_T^{rec} - p_T^{MC})}{p_T^{MC}}. \tag{5.2}$$

It should be noted that ITS alone (i.e. without TPC) is not intended to measure particle momenta (except for very low p_T). The results in Fig. 13 are shown just to demonstrate that the Kalman fitter for ITS tracks works correctly.

As mentioned above, one of the motivations of this work was to try to overcome some deficiencies of the ITS track finder based on the TPC inward track extrapolation. Some indication of

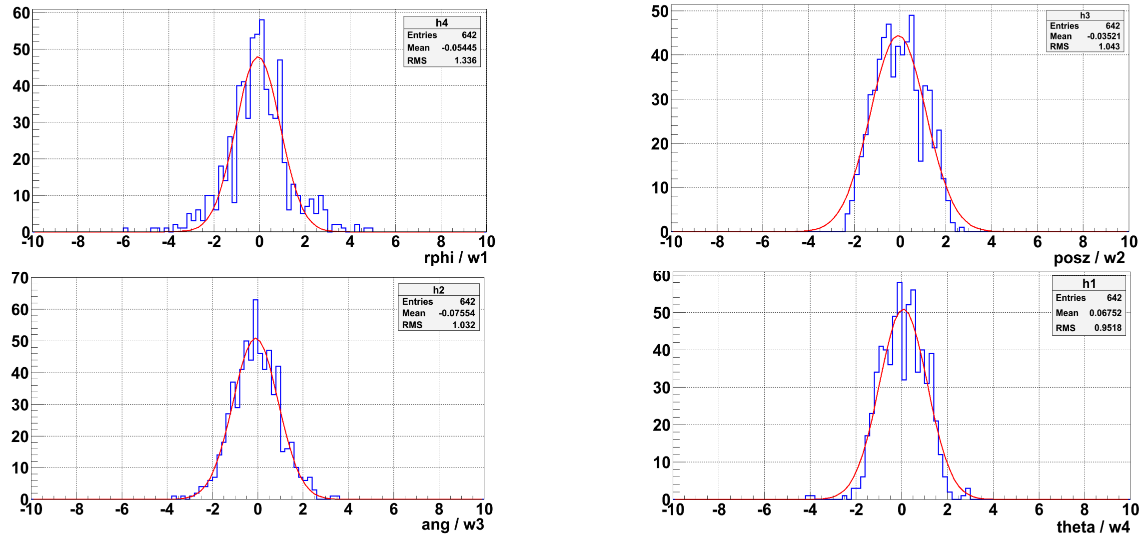

Figure 12: Distributions of pulls. Here $rphi, posz, ang, theta$ are the true errors, $w1, w2, w3, w4$ are the calculated ones.

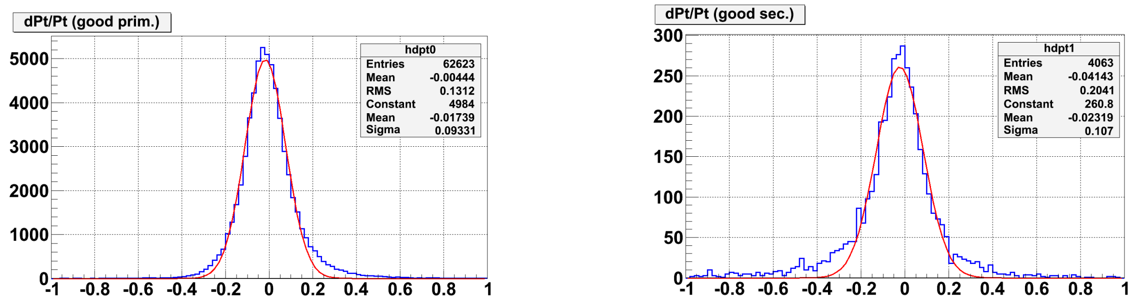

Figure 13: Left - the relative momentum resolution for primary tracks; right - the relative momentum resolution for secondary tracks.

CA-based approach advantages can be observed in Fig. 14, where the distribution of the squared values of hit deviations from the track normalized to the hit error (χ^2 / hit) and primary track reconstruction efficiency are shown for the both methods. One can see that the CA-based version gives somewhat better track quality (lower χ^2 / hit) and higher efficiency for very low p_T.

6. Conclusions

The cellular automaton algorithm has been developed and implemented for track reconstruction in MPD ITS within the MpdRoot framework.

First results of its operation obtained for simulated high-multiplicity events of central Au-Au interactions at $\sqrt{s} = 9$A GeV look promising.

Further work is needed on the algorithm optimization as well as on its development into a common ITS-TPC method.

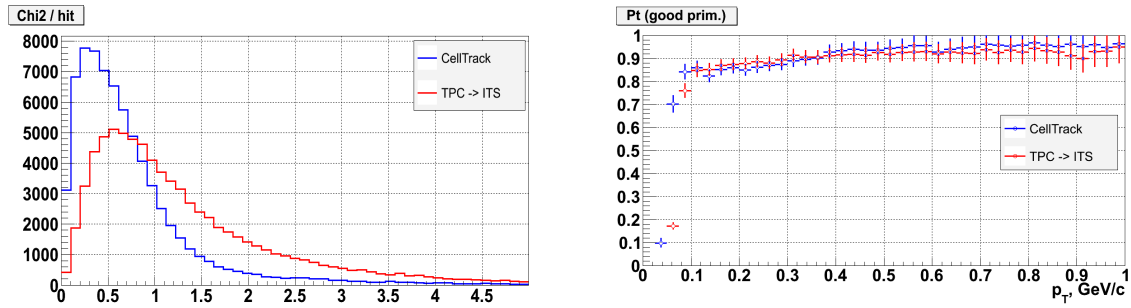

Figure 14: Left - distribution of χ^2 / hit; right - primary track finding efficiency vs p_T. Here "*CellTrack*" are the tracks found by the CA algorithm and fitted by the Kalman filter. "$TPC \rightarrow ITS$" - tracks were found in TPC using the Kalman filter and extrapolated to ITS.

References

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[4] R. Fruehwirth, *Application of Kalman filtering to track and vertex fitting*, *Nucl. Instr. and Meth. A*, **262**, 444 (1987).

[5] http://mpd.jinr.ru/.

[6] http://urqmd.org/.