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TRD TRACKING USING THE CELLULAR AUTOMATON ALGORITHM FOR COMPRESSED BARYONIC MATTER EXPERIMENT

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The paper describes implementation details of the Cellular Automaton Algorithm (CAA) [I. Abt, D. Emeliyanov, I. Gorbounov, I. Kisel, *Nucl. Instrum. Methods Phys. Res.* **A490**, 546 (2002)] for reconstruction of the particles' tracks in Transition Radiation Detector (TRD), designed for Compressed Baryonic Experiment (CBM) which will operate at the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany. The application and performance of cellular automaton method for standalone track finding and first level event selection are presented.

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1. Introduction

The CBM experiment is dedicated to investigate the properties of highly compressed baryonic matter as it is produced in nucleus–nucleus (*e.g.* Au+Au) collisions from 15 to 45 A GeV. The scientific goal of the research program is to explore the QCD phase diagram of strongly interacting matter in the region of highest baryon densities and thus measurements of hadronic, leptonic and photonic observables at interaction rates up to 10 MHz. The current layout of specialized detectors is shown in Fig. 1. High-resolution silicon tracking system (STS) is placed in the field of a superconducting dipole magnet (field of 1 Tesla). Outside of the magnetic field, a Ring Imaging Cherenkov Detector (RICH) and three stations of Transition Radiation Detectors (TRD) will track and identify electrons in the momentum ranges relevant for low-mass vector meson and charmonium measurements. Hadron identification will be achieved by the Time-Of-Flight measurement (TOF) in an array of resistive plate chambers. The setup is completed by an Electromagnetic Calorimeter (ECAL) for identification of photons, electrons and muons. The alternative detector layout anticipates to replace RICH detector by muon detector system [1]. The experiment will operate at the future Facility for Antiproton and Ion Research in Darmstadt, Germany.

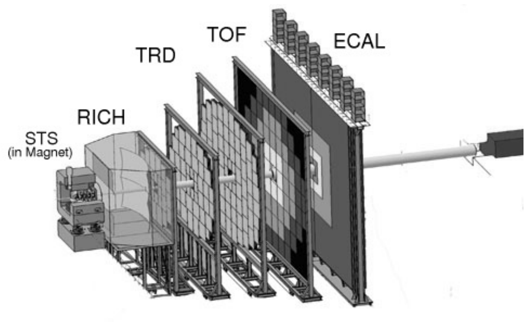

Fig. 1. The CBM detector layout [1].

The major experimental challenge is posed by extremely high reaction rates of up to 10^7 events/second. A typical central Au+Au collision in the CBM experiment will produce up to 700 tracks in the TRD detector. This huge amount of data requires high-speed data acquisition and an on-line event selection and background suppression methods. The standalone TRD cellular automaton tracking procedures are a part of a wider on-line background suppression issue. Thus track reconstruction procedures should be fast, efficient and reliable.

2. Cellular Automaton Algorithm for TRD

Cellular automata were proposed in forties of the 20th century by S. Ulam. At the same time, J. von Neumann who tried to develop hypothetical self-reproduction machine, realized that cellular automata which reflect the simplified physical model of the real world, is the solution of his search. In the early 1950s cellular automata were studied as a possible model for biological systems. At present, they are also quite numerous in the wide and fashionable domains such as artificial intelligence. The best-known example and implementation of cellular automata is "The Game of Life" devised by the British mathematician J.H. Conway in 1970. It is a non-player "game", needing no input from human players. Further evolution of the game is only determined by its initial state and conditions that give particular forms of repetitive or other behavior [8]. In "The Game of Life" one can imagine a world as a matrix of cells. Each cell has 8 neighboring cells, 4 adjacent orthogonally, 4 adjacent diagonally. Each cell may or may not be occupied by "life" and picture of the world changes in given time steps. In this world a very simple set of rules is implemented. At each time step, life persists in any location where it is also present in 2 or 3 of the 8 neighboring locations. Life in each cell with 4 or more neighbors dies from overcrowding, and life in cells with 1 or none dies from isolation. Life is born in any empty location for which there is life in 3 out of the 8 neighboring locations. It is important to understand that all births and deaths occur simultaneously in a given time step. One can notice that such game based on the cellular automata could be viewed as kind of parallel computers. And thus, being local and parallel, cellular automata avoid exhaustive combinatorial searches, even when implemented on conventional (single-processor) computers.

The "Game of Life" inspired us to make use of cellular automaton algorithms for track finding in TRD. By analogy to the game, in track finding procedure the initial state consists of interaction points in each TRD layer, instead of occupied/unoccupied cells. In a given time step, two points from two adjoining layers can create Space Point (SP, Fig. 2). At this stage the rules which are in force have geometrical nature (Fig. 3). The process can be carried out simultaneously for 6 double layers (two double layers in each TRD station; see Fig. 2; detailed description can be found below). In the next time step, so-called segments are created from SPs simultaneously in 3 TRD stations. At this stage also geometrical rules are in force which either allow or deny to create a segment from two SPs. These rules are the same for all TRD stations, but it should be mentioned that they differ from rules at previous stage. The last step is beyond CA and results in selection of ap-

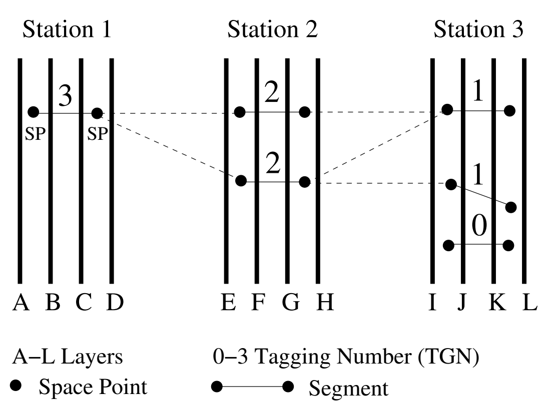

Fig. 2. TRD detector layout scheme with marked space points (SP), segments connecting SP, tagging number ascribed to given segment and 3 track candidates. Read in text for detail.

propriate segments which are the elements of a given track. Such algorithm employs a very simple track model where the track consists of three segments, each of them composed from four hits in consecutive detector layers. This leads to utmost computational simplicity and a fast algorithm. Since cellular automata operate with highly structured information, the amount of data to be processed in the course of the track search is significantly reduced.

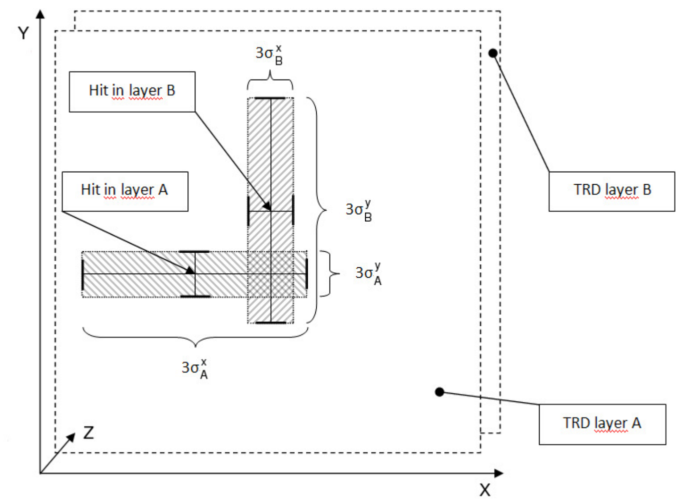

Fig. 3. The space point creation scheme. If the rectangles, created by 3σ X–Y area of two considered hits are partially overlapped, the space point is created. At this stage, one hit can be a constituent of multiple space points.

Now, a track reconstruction procedure, based on a cellular automaton method, used for finding and reconstructing tracks in the standalone TRD tracker will be described. To study the detector response, 10^4 Au (25 A GeV)+Au central UrQMD [2] and PLUTO [3] events have been used. The PLUTO event generator was used to simulate the J/ψ decay to e^+e^- pair, which was treated as a proper signal in the environment of background which consists of electrons, positrons, protons and pions as a product of the reactions occurring inside the detector materials and a product of the UrQMD generator. The detectors layout was implemented in development of CBMROOT software package [4].

The considered TRD detector is composed of 3 stations. Each of them consists of 4 layers and each layer gives coordinates in two-dimensional space: XZ and YZ plane [1], where Z coordinate corresponds to beam direction. It is assumed that every TRD layer has ideal detection efficiency, *i.e.* every charged particle that crosses an active volume generates a signal. The registered and digitized signal is called a particle hit. Every hit posesses information about its spatial coordinates and energy deposited by a particle. During the experiment, when a single Au+Au collision occurs, the TRD detectors will register about 700 hits in the first sensitive layer. Due to physical limitations of a detector and the shape of an individual chamber, a single layer can precisely determine only one of the plane coordinates (X or Y), whereas a second value has large uncertainty. Every even layer measures precisely one coordinate (for instance X), while every odd layer determines the other coordinate (Y). By combining hits in neighboring detector layers the particle track is created. The presented procedure consists of four parts as follows:

(1) Creation of space points (SP) (Fig. 3). The point in the 3-dimensional space is a structure created by a combination of hits from two adjoining even–odd detector layers. Since the Z positions of the detectors are known, measured X and Y coordinates are sufficient to create one SP. This process is constrained with a geometrical restriction. The standard deviations of X_A and Y_A in odd layer (A) are σ_A^x and σ_A^y, respectively, whereas σ for X_B and Y_B in even layer are σ_B^x and σ_B^y. Each hit from an odd layer $A(X, Y, Z)$ is projected onto an even layer along vector passing through target $T(0, 0, 0)$ and hit A. In Z position of an even layer we are looking for overlapping of rectangular region $A \pm 3\sigma_A^x \times A \pm 3\sigma_A^y$ and $B \pm 3\sigma_B^x \times B \pm 3\sigma_B^y$. If these regions overlap the SP object is created with hits from odd–even layers.

(2) Segment creation part (Fig. 2). By combining two SPs from two neighboring pairs of detector layers in one station, the segment structure is constructed. In this case geometrical restriction similar to the one used in space point creation process is in force. Every segment contains the information from all four layers of a single detector station. The process of creation of segments is simultaneous and independent for all three stations. The final track candidate consists of three segments from successive stations. The next steps of algorithm lead to a selection of appropriate segments which are the elements of the given track.

(3) Tagging procedure. In this step, a so-called Tagging Number (TGN) is assigned to every created segment. Initially, a TGN value equal to 0 is assigned to each segment. This procedure starts to operate on segments from the third station and goes upstream according to the beam direction. For each segment from the third station the algorithm looks for a segments from the second station, which can be a part of the same long track. In order to decrease plausible, but unrealistic

possibilities of selection, the geometrical restriction is applied. In the case of success the TGN value of a segment from the third station is set to 1 (in case it is equal to zero) and automatically TGN value of given segment from the second station is set to 2 (increased by one with relation to TGN of segments from its right side). Identical procedure is applied to a pair of the second and first TRD stations. Therefore, one can notice that at the end each segment from the first station which has TGN value equal to 3 has at least one segment candidate from the second station for building the long three-segment track. Thus, it can be concluded that given segment from the second station, which has TGN value equal to 2, is also connected to at least one segment from the station number three.

(4) The long track creation process. The long track is created by merging three segments, each from individual station. The creation process is started from segments which have TGN value equal to 3. They are merged together with those with the TGN value equal to 2. Then each segment with TGN value equal to 2 is merged with those with the value equal to 1 (Fig. 2). For every long track candidate, built in this way, the χ^2 value is calculated. The χ^2 is a criterion of competition between tracks and is calculated by application of Kalman filter procedure [5,6]. In the next step the tracks are sorted according to the χ^2 value. The first track from the top of the stack (with lowest χ^2) is classified as a "track candidate". After that, all hits which belong to this track are marked as "used", and therefore do not participate in further processing. If any of the next tracks at the stack uses the hit marked as "used" is classified as a "fake track". When all track candidates are processed the procedure described above can be repeated with less restrictive geometrical conditions and with remaining unused hits.

3. Benchmark of TRD tracker

The algorithm described in the previous section gives promising results with regard to speed and efficiency. After processing 10^4 Au(25 A GeV)+Au merged central and mbias UrQMD events with PLUTO-generated J/ψ electron–positron decay in each, on average 550 tracks per event, with 12 registered in TRD hits, (53 tracks per event for mbias data) were reconstructed. As central and mbias reactions we consider processes with the impact parameter $b = 0$ and $0 \leq b \leq 100$ fm, respectively. For central events the efficiency of correctly reconstructed tracks is about 86% for particles with momentum below 1 GeV/c and is equal to 93% for particles with momentum above 1 GeV/c. In Fig. 4 the reconstruction efficiency as a function of momentum is shown. Proposed for the CBM event selection bases on detection events with e^+e^- pair from J/ψ decay. Due to the fact that the invariant mass of charmonium is equal to 3.096 GeV/c^2, the most crucial thing is high detection efficiency of high momentum particles (above 1 GeV/c).

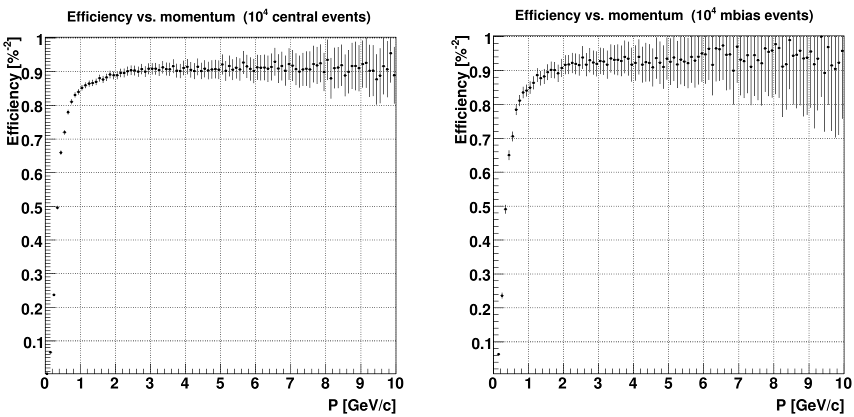

Fig. 4. Track reconstruction efficiency as a function of ideal momentum at central and mbias Au+Au 25 A GeV reaction.

4. Application of TRD tracker

The standalone TRD tracking procedure has been developed for CBM experiment having in mind the low-level on-line event selection. It has been created to reduce the amount of data that do not contain interesting signal, *i.e.* electrons and positrons from the J/ψ decay. The J/ψ meson is produced with multiplicity about 1.5×10^{-5} in 25 A GeV Au+Au ion collision, and the e^+e^- branching ratio is about 5.9%, thus the high beam intensity is required to chance to detect J/ψ meson. Thus, the huge bulk of background data should be efficiently suppressed allowing to pass remaining information to the mass storage system. Reconstruction of the electron and positron tracks from discussed J/ψ decays and calculation of their momenta vectors results in reconstruction of J/ψ mass. The full event selection is done as follows (described for one event):

(1) Reconstruction of all tracks. For each reconstructed particle track the initial momentum vector is estimated as well as the particle charge.

(2) Charged particle identification. The considered 12-layer TRD detector possesses identification power of 99% of high-energy electrons, *i.e.* electrons are distinguished from pions with 99% of success.

(3) Transversal momentum cut. The threshold equals 1 GeV/c and all particles with lower transversal momentum are rejected from further considerations.

(4) If there are at least two particles of unlike charge in the entire event left, the combinatorics phase begins. Every positive particle that survived the cuts is combined with every negative one, and the invariant mass for each pair is calculated. If at least one pair contributes with a mass from the region $M\langle 2.5, 3.5\rangle$ GeV, the whole event is accepted and passed for mass storage system or processed further with a higher level selection. The algorithm passes 1 per background events, while 50% of signal survives.

The average processing time of an event is about 0.5 and 0.1 seconds for central and mbias events, respectively. The procedure was tested using the standard PC computer with 2 multithread, 3 GHz Pentium 4 processors and 1 GB of RAM. As parallel processing is one of the key features of the algorithm, it is ready to be implemented in the multi-core environment, such as nVidia Tesla systems, where one processor (which contains 128 independent cores), can be assigned to multiple events at the same time. The expected speed gain is at least a factor of 1000. Alternatively, further improvements of timing performance of the Cellular Automaton and Kalman filter algorithms can be achieved using the SIMD instruction set [7] in multi-processor PC-compatible computer farm.

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