Abstract. Development of fast and efficient event reconstruction algorithms is an important and challenging task in the Compressed Baryonic Matter (CBM) experiment at the future FAIR facility. The event reconstruction algorithms have to process terabytes of input data produced in particle collisions. In this contribution, several event reconstruction algorithms are presented. Optimization of the algorithms in the following CBM detectors are discussed: Ring Imaging Cherenkov (RICH) detector, Transition Radiation Detectors (TRD) and Muon Chamber (MUCH). The ring reconstruction algorithm in the RICH is discussed. In TRD and MUCH track reconstruction algorithms are based on track following and Kalman Filter methods. All algorithms were significantly optimized to achieve maximum speed up and minimum memory consumption. Obtained results showed that a significant speed up factor for all algorithms was achieved and the reconstruction efficiency stays at high level.

1. Introduction
The Compressed Baryonic Matter (CBM) experiment [1] will be a dedicated setup for the measurement of fixed target heavy ion collisions at the future FAIR accelerator in Darmstadt. It is being designed for the investigation of the properties of highly compressed baryonic matter [2]. A key item of the CBM physics program is the precise measurement of low-mass vector mesons and $J/\psi$ in their leptonic decay channel.

The CBM experiment will be run in 2 different modes: electron and muon. Figure 1 and Figure 2 show the CBM experimental setups with electron detectors and the muon detection system, respectively. Electron identification will be performed by Ring Imaging Cherenkov detector (RICH) and Transition Radiation Detectors (TRD). Time-of-flight detector (TOF) also can be used for identification of low momenta electrons ($p < 1.5 GeV/c$). Muon identification will be performed by Muon Chamber detector (MUCH). Also this setup includes TRD detector as a last tracking station for MUCH and TOF for rejection of remaining protons.

2. Challenges for the event reconstruction
The event reconstruction is an important part of many high energy physics experiments.

The main challenge of the event reconstruction in the CBM experiment results from the large multiplicity of particles produced in heavy-ion collisions. For example, around 800 particles are
produced in central Au+Au collisions at 25A GeV beam energy. This high charged particles multiplicity leads to a high track and ring density in the detectors.

In order to produce high-statistics data even for the particles with the lowest production cross sections, the CBM experiment is designed to run at reaction rates up to 10 MHz. A huge amount of data will be collected, in order to process them event reconstruction algorithms have to be extremely fast. Therefore, the speed of the tracking algorithm is extremely important for any analysis of data in CBM.

Other challenges for the track reconstruction algorithm include: large material budget, especially in the MUCH detector which includes few meters of iron; complex detector structure with overlapping sensors and different Z positions of sensors; dead zones of detectors. All these peculiarities have to be taken into account by tracking algorithm. For the ring reconstruction algorithm challenges are: the different number of hits per ring (from 5 to 50) which causes hard to reconstruct rings with small number of hits; ring distortions due to multiple scattering, the residual magnetic field and detector granularity.
3. Event reconstruction in TRD and MUCH detectors

The Transition Radiation Detector (TRD) will serve for particle tracking and for the identification of electrons and positrons with $p > 1.5 \text{ GeV/c}$. It consists of 10 detector layers located at approximately 4.5 m to 9 m downstream of the target. The total active detector area is about $600 \text{ m}^2$. The readout will be realized in rectangular pads giving a resolution of 300 - 500 $\mu\text{m}$ across and 3 - 30 mm along the pad. Every second TRD layer is rotated by 90° in order to get good spatial resolution for both $X$ and $Y$ coordinates. The pion suppression factor obtained with 9 TRD detector hits is estimated to be above 100 at an electron efficiency of 90%.

The muon identification will be performed by Muon Chamber System (MUCH). The CBM concept is to track the particles through a hadron absorber system, and to perform a momentum-dependent muon identification. This concept is realized by segmenting the hadron absorber in several layers, and placing triplets of tracking detector planes in the gaps between the absorber layers. The actual design of the muon detector system consists of 6 hadron absorber layers (iron plates of $3 \times 20; 30; 35; 100 \text{ cm}$ thickness) and 18 gaseous tracking chambers located in triplets behind each iron slab. In total, the muon chambers cover an active area of about $70 \text{ m}^2$ subdivided into about half a million channels.

3.1. Track reconstruction in TRD and MUCH detectors

The developed track reconstruction algorithm in TRD and MUCH [3, 4, 5, 9] is based on track following method using reconstructed tracks in the STS as seeds. The track following is based on the standard Kalman filter technique and is used for the estimation of track parameters and trajectory recognition. Main logical components are track propagation, track finding, track fitting and finally a selection of good tracks. Each of the steps will be described in the following in some more detail.

The track propagation algorithm estimates the trajectory and its errors in a covariance matrix while taking into account three physics processes which influence the trajectory, i.e. energy loss, multiple scattering and the influence of a magnetic field. The influence of the material on the track momentum is taken into account by calculating the expected average energy loss due to ionization (Bethe-Bloch formula) and bremsstrahlung (Bethe-Heitler formula). The influence on the error, i.e. the covariance matrix due to multiple scattering is included by adding process noise in the track propagation. Here, a gaussian approximation using the Highland formula is used to estimate the average scattering angle. The propagation of the trajectory is done according to the equation of motion. If the track passes a magnetic field the equation of motion for a charged particle is solved applying the 4th order Runge-Kutta method. If passing a field free region a straight line is used for propagation and the transport matrix calculation.

In the track finding algorithm hits are attached to the propagated track at each detector station using two different methods. Either just the nearest hit is attached to the track, or all hits within a certain environment are included. For the first method, only one track is further propagated, the branching method allows for several track branches to be followed, one for each attached hit. Common techniques to these methods are the above described track following, the Kalman Filter and the calculation of the validation region for hits.

Assignment of new hits is done step by step at each detector station. After the track propagation to the next station possible hits are attached and track parameters are updated by the Kalman Filter. For the attachment of hits a validation gate is calculated in order to allow for a high degree of confidence in the hit-to-track assignment. The algorithm takes into account possibly missing hits due to detector inefficiencies, dead zones in the detector, inefficiency of hit finder algorithm etc.
The two methods which can be chosen for hit assignment to tracks differ in the way how a situation is dealt with in which several hits lie within the validation gate. In case of the branching method, a new track branch is created for each hit lying within the validation gate. Since the number of branches can grow exponentially, the $\chi^2$ value is calculated for each track branch and unlikely ones are rejected. Also for each input track seeds number of created branches is calculated and if it exceeds the limit than the tracking continues using nearest neighbor approach. For the second method no track branches are created. The nearest neighbor method attaches the nearest hit, if lying in the validation region at all.

After track finding tracks are selected based on the quality criterion and the number of shared hits between tracks.

3.2. Optimization of the tracking algorithm.

The main disadvantage of above described tracking algorithm is relatively slow calculation time. The implementation of the vectorized version of the algorithm would be very challenging or even impossible. On the other hand the algorithm is general and universal, it can be applied for different geometry configurations without modifications. Below two possibilities of how one can improve calculation time of the algorithm are discussed, namely, approximation of the magnetic field and simplification of geometry.

3.2.1. Magnetic field approximation. The track fit based on Kalman Filter is intensively used in the track reconstruction algorithm. Kalman filter intensively uses track propagation algorithm. Therefore, its speed is very critical for the overall track reconstruction performance. Profiling the track propagation procedure it was found that one of the bottle neck is the access to the field map. The reason is that for the application in CBM the algorithm uses a 70 MB large field map, therefore permanently accesses the main memory. And moreover it uses 3-dimensional spline approximation to calculate the field values.

The magnetic field of the CBM magnet is quite smooth and in some regions can be locally approximated by polynomials. However, detailed studies of such approach showed that for the magnetic field after the STS detector polynomial approximation is not accurate enough due to large fluctuations of the field. A new algorithm for the field approximation was implemented. Outside the magnet a 2D grid slice for each magnetic field component in ($X$, $Y$) is built. Such approach allows for a faster access and a lower memory consumption in comparison to storage of the full magnetic field map. However, it is less general and has to be tuned to a particular geometry. The drawback of such approach is that the access to the grid cannot be effectively vectorized.

3.2.2. Geometry representation in tracking. The standard track propagator uses a geometry navigation based on the ROOT geometry package. It is a very precise method for geometry navigation, however it is not efficient in terms of calculation speed. First, because it uses the detailed Monte-Carlo detector geometry, currently consisting of 800000 volumes. Second, because this algorithm is rather general and not optimized for the CBM setup. Thus, a simplified detector geometry description and an optimized geometry navigation algorithm are needed.

FAIRROOT contains a tool which allows to estimate the detector material budget by using special geantino particles. Using this tool the material budget for detector stations and material between stations in the silicon equivalent were approximated. It is easy to retrieve the material budget in a particular detector station by $X$ and $Y$ coordinates. The material estimation is used in the track propagation algorithm.

As it was mentioned optimization requires implementation which is not as general as for initial version. Here we will explain how described optimization was implemented to improve the speed for the TRD tracking algorithm. In order to propagate track to the first TRD detector
station in the presence of stray magnetic field and the RICH detector a special virtual stations
are used. These stations store information about the approximated material budget and the
magnetic field. A track is propagated between virtual stations using Runge-Kutta algorithm.
In the TRD detector each station contains information about material and hits. Hit-to-track
attachment is based on the nearest hit approach.

![Figure 3](image3.png)  
Figure 3. Magnetic field approximated as grid slice in (X,Y).

![Figure 4](image4.png)  
Figure 4. Material approximation in silicon equivalent.

4. Event reconstruction in the RICH detector
The RICH detector is designed to provide identification of electrons and positrons and
suppression of pions in the momentum range below 10 GeV/c [6, 7]. This will be achieved
using a gaseous RICH detector built in a standard projective geometry with focusing mirror
elements and a photon detector. The detector will be positioned behind the dipole magnet
about 1.6 m downstream of the target. It will consist of a 1.7 m long CO$_2$ gas radiator and
two arrays of mirrors and photon detector planes. The mirror plane is split horizontally into
two arrays of spherical glass mirrors, 4x1.5 m each. The 72 mirror tiles have a curvature of 3 m
radius, a thickness of 6 mm. Rings of Cherenkov radiation will be projected onto two photon
detector planes 2x0.6 m each. The design of the photon detector plane is based on MAPMTs
(e.g. H8500 from Hamamatsu). In-beam tests with a prototype RICH of real-size length showed
that 22 photons are measured per electron ring. On the order of 75 rings are seen in central
Au+Au collisions at 25AGeV beam energy.

4.1. Ring reconstruction in the RICH detector
The developed ring recognition algorithm [8, 9, 10] is a standalone two step process, i.e the
input data is only an array of RICH hits and no track information is used in this step. First,
a local search of ring-candidates is performed which is based on the Hough Transform method
(HT) [11]. For a ring search hit triplets are combined and the corresponding ring parameters
are calculated as each combination of three hits defines a ring. The main disadvantage is that
in its straight-forward realization for a multi-parametric curve recognition the HT requires very
large combinatorics which makes it intrinsically slow. The method can be optimized by making
use of the limited maximum radius $R_{\text{max}}$ for Cherenkov rings in the CBM-RICH detector.
Thus, instead of combining all possible hit triplets in the whole photon detector plane, only hits
within a local area around a possible ring candidate are combined. Then ring center and radius
are calculated using HT equations from every triplet of selected hits and the corresponding
Hough histograms (ring center, radius) are filled. Strong peaks in the Hough histograms should correspond to the expected ring center and radius. If the peak is higher than a prescribed cut this ring-candidate is accepted and shifted to the ring-candidate array, otherwise rejected.

The above described local ring-candidate search algorithm does find not only correct rings but also wrong rings which are formed by random combinations of hits. The selection of good rings from the array of found ring-candidates is based on the ring quality calculated by an artificial neural network.

5. Results
The results presented in this section are based on studies performed for central Au+Au UrQMD [12] collisions at 25 AGeV beam energy.

Figure 5 (left) shows the track reconstruction efficiency in dependence on momentum in the TRD detector. Results are presented for 2 different approaches: nearest neighbor (nn) and branching. The branching tracking performance is slightly better (91.9%) in comparison to the nearest neighbor approach (90.1%), however the nearest neighbor algorithm is faster and easier to implement. The calculation time of the initial implementation is about 2500 $\mu$s per event for the branching algorithm and 1300 $\mu$s per event for the nn algorithm for one CPU core. A speed up factor of 14 was achieved for the fast version (90 $\mu$s per event) in comparison to the initial version of the algorithm.

The track reconstruction efficiency in dependence on momentum in the MUCH detector is shown in Figure 5 (right). Results are presented for nn and branching algorithms. Results are also presented for single $J/\psi$ decaying into $e^\pm$ without background and embedded into UrQMD events. Both tracking approaches show the same performance.

Figure 5. Track reconstruction efficiency in dependence on momentum in the TRD detector (left) and in the MUCH detector (right). nn - nearest neighbor algorithm, branch - branching algorithm.

Figure 6 shows the ring reconstruction efficiency for embedded primary $e^\pm$ in dependence on momentum. Primary $e^\pm$ were embedded in UrQMD events in order to enhance statistics. Results are shown for two sets of rings: rings from primary $e^\pm$ with at least 7 hits (red) and rings from for primary reference $e^\pm$ which have more than 15 hits in the ring and a momentum larger than 1 GeV/c (blue). The efficiency integrated over the momentum range 0 - 12 GeV/c is 91% for primary $e^\pm$ and 95.7% for primary reference $e^\pm$. The calculation time of the fast version of the algorithm is at the order of 45 $\mu$s per event for one CPU core.
6. Summary
Event reconstruction algorithms in the RICH, TRD and MUCH detectors were discussed. Although standard reconstruction algorithms are slower, but they are more general and do not depend strongly on detector geometry. Development of fast algorithms leads to implementation which strongly depends on a certain geometry but they are needed to run the online event reconstruction.

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