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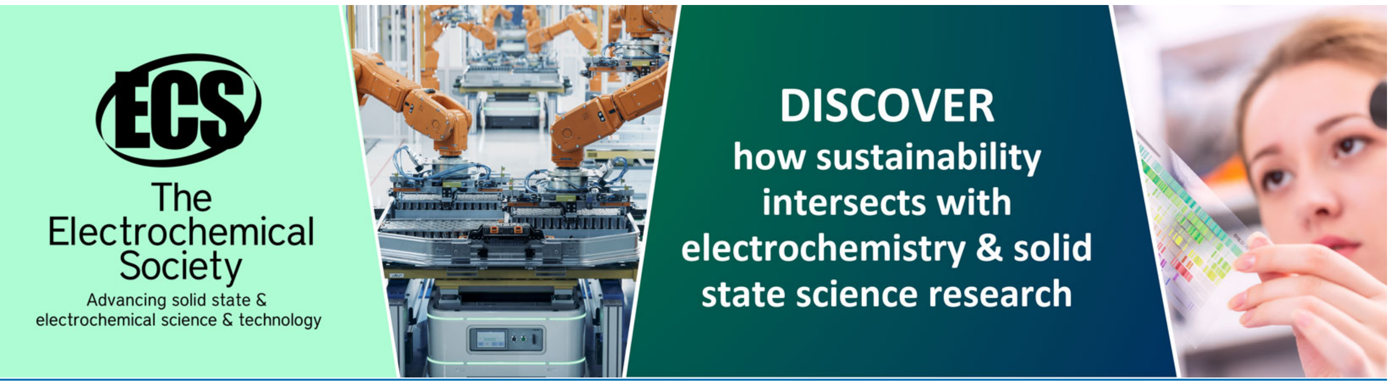

Track reconstruction algorithms for the CBM experiment at FAIR

Andrey Lebedev[1,2], Claudia Höhne[1], Ivan Kisel[1], Gennady Ososkov[2] for the CBM collaboration

[1] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[2] Laboratory of Information Technologies, Joint Institute for Nuclear Research, Dubna, Russia

E-mail: andrey.lebedev@gsi.de

Abstract. The Compressed Baryonic Matter (CBM) experiment at the future FAIR accelerator complex at Darmstadt is being designed for a comprehensive measurement of hadron and lepton production in heavy-ion collisions from 8-45 AGeV beam energy, producing events with large track multiplicity and high hit density. The setup consists of several detectors including as tracking detectors the silicon tracking system (STS), the muon detector (MUCH) or alternatively a set of Transition Radiation Detectors (TRD). In this contribution, the status of the track reconstruction software including track finding, fitting and propagation is presented for the MUCH and TRD detectors. The track propagation algorithm takes into account an inhomogeneous magnetic field and includes accurate calculation of multiple scattering and energy losses in the detector material. Track parameters and covariance matrices are estimated using the Kalman filter method and a Kalman filter modification by assigning weights to hits and using simulated annealing. Three different track finder algorithms based on track following have been developed which either allow for track branches, just select nearest hits or use the mentioned weighting method. The track reconstruction efficiency for central Au+Au collisions at 25 AGeV beam energy using events from the UrQMD model is at the level of 93-95% for both detectors.

1. The CBM experiment

The CBM experiment [1] is being designed to investigate high-energy nucleus-nucleus collisions at the future international FAIR project. The objective of high-energy heavy-ion collision experiments performed worldwide is to explore the phase diagram of matter governed by the laws of QCD. Of particular interest is the phase where a quark-gluon-plasma is formed. At very high beam energies - as provided by RHIC in Brookhaven and by LHC at CERN - matter is created at extremely high temperatures similar to the early universe. In heavy-ion collisions at FAIR beam energies (2-45 AGeV) nuclear matter is compressed to very high net-baryon densities such as in core collapse supernovae or in the interior of neutron stars. The CBM experiment offers the possibility to discover the most prominent landmarks of the QCD phase diagram expected to exist at high net baryon densities: the first order deconfinement phase transition and the critical endpoint. At these baryon densities also hadrons are expected to change their properties and chiral symmetry to be restored. Special focus is set on rare observables such as charm and dilepton production as those observables can give insight into the hot and dense medium created in heavy ion collisions [2].

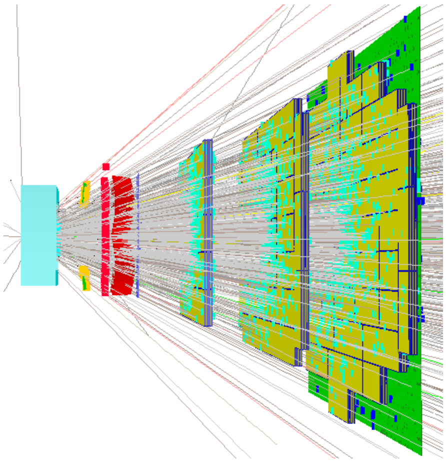

Figure 1. Example of a typical CBM event in the CBM detector, i.e. tracks of a central Au-Au collision at 25 *A*GeV beam energy. About 800 charged particles are detected in the CBM acceptance. Only primary particles are shown.

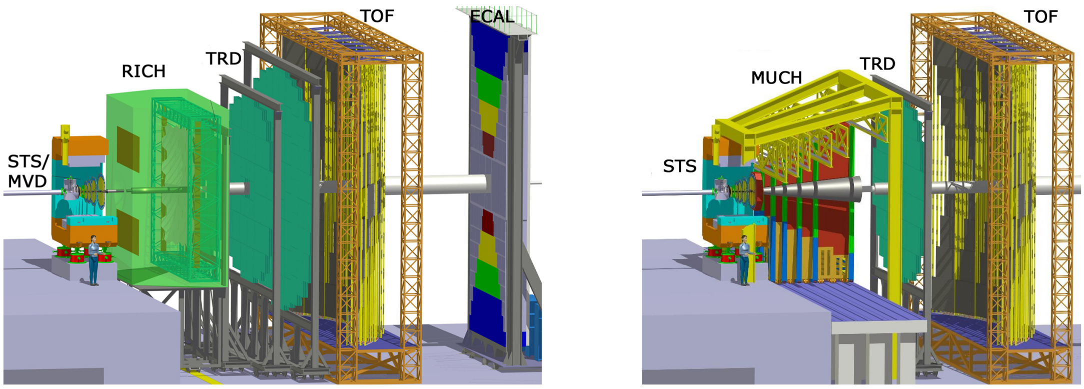

Figure 2. Sketch of the CBM detector: setup for electron [left] and muon [right] identification.

The experimental task of CBM is a comprehensive measurement of hadron and lepton production in *pp*, *pA* and *AA* collisions from 8-45 *A*GeV beam energy. The experimental challenge is to select rare events in nucleus-nucleus collisions with charged particle multiplicities of about 800 per central event (see Figure 1) at reaction rates of up to 10 MHz.

Two different CBM detector setups are investigated, one for electron and one for muon measurements. The CBM experimental setup comprises the following detector components (see Figure 2):

- *Silicon Tracking System (STS)* located inside a large acceptance dipole magnet for track and vertex reconstruction and momentum determination.
- *MUon CHamber absorber system (MUCH)* for muon identification in case of muon measurements or, alternativly
- *Ring Imaging CHerenkov detector (RICH)* for electron identification in case of electron measurements.
- *Transition Radiation Detectors (TRD)* for global track reconstruction and electron identification.
- *Resistive Plate Chambers (RPC)* provide a time-of-flight measurement needed for hadron identification.
- *Electromagnetic Calorimeter (ECAL)* for the measurement of photons and neutral particles.

1.1. The CBM muon identification system
The CBM muon detector will be used for the detection of vector mesons (ρ, ω, ϕ, J/ψ) via their decay into $\mu^+\mu^-$ pairs. The muon detection system is located downstream of the STS. Muon identification by absorber technique, in which hadrons are absorbed but μ^+ and μ^- not, is used. The current design of the muon system consists of 5-6 hadron absorber layers made of iron of variable thickness, and of 2-3 tracking detectors in between each of the gaps. The detailed layout of the detector is still under discussion. For the MUCH stations in the high track density region pad layout is forseen based on Gas Electron Multiplier (GEM) chamber technology. For the later detector stations in MUCH where track densities are low, straw tube chambers or Multi-Wire Proportional Chambers (MWPCs) are under discussion. For the measurement of muons from low-mass vector mesons (ρ, ω, ϕ), the total iron absorber thickness is 125 cm (7.5 λ_I, where λ_I is a nuclear interaction length), whereas for muons from charmonia, 1 m of iron is added (total thickness of 13.4 λ_I).

1.2. The CBM Transition Radiation Detector
The TRD will be used for track reconstruction and electron identification. Together with the RICH detector it has to provide efficient electron identification. The TRD is located between the RICH and TOF detector. The currently forseen layout consists of 12 identical layers, grouped in 3 stations. Each layer is formed of a radiator and a MWPC readout with a total thickness of 6 cm. Stations are placed at 5 m, 7 m and 9 m downstream the target. A pad layout based on MWPC chamber technology is forseen. The pad orientation changes by 90 degrees from layer to layer. The pad size varies from 0.03 cm to 0.05 cm across the pad and from 0.27 cm to 3.3 cm along the pad.

2. Track reconstruction
Track reconstruction in the TRD and MUCH system is based on track following using reconstructed tracks in the STS as seeds. In the STS track reconstruction is based on the cellular automaton method [3] and provides initial track parameters as starting point for the following track prolongation. This track following is based on the standard Kalman filter technique as proposed in [4] and is used for the estimation of track parameters and trajectory recognition in TRD and MUCH. Tracks are prolongated subsequently from one detector station to the next adding additional hits in each detector. 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.

2.1. Track propagation
The track propagation is the main part of this track reconstruction method. The algorithm calculates the average trajectory and its errors in a covariance matrix while taking into account three main processes which may change the trajectory, i.e. energy loss, multiple scattering and the influence of a magnetic field. The track propagation itself is logically again separated into three main components: track extrapolation, geometrical navigation in the detector material, and the calculation of effects such as multiple scattering or energy loss while passing the detector material. The track propagation algorithm controls these components while propagating a track from one detector station to the next.

The routine for track extrapolation calculates the further trajectory according to the equation of motion. If the track passes a field free region a straight line is used for extrapolation and the transport matrix calculation. If passing a magnetic field the equation of motion for a charged particle is solved applying the 4^{th} order Runge-Kutta method. The transport matrix is calculated by integrating the derivatives in parallel.

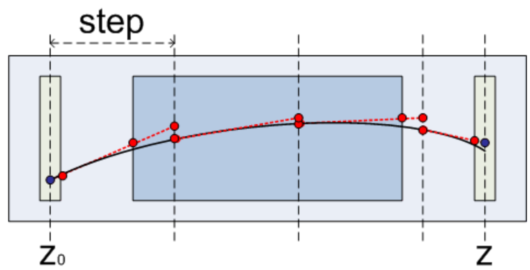

Figure 3. Sketch of the track propagation algorithm. Dotted lines show the straight line geometrical navigation through the detector material; solid lines show the extrapolation including magnetic field and material effects. Track parameters are calculated at each dot.

In order to include the influence of the material along the trajectory, a routine based on the ROOT geometry package [5] searches for intersections of the prolongated track with detectors or passive material. For simplicity and speed of the routine this search is done along a straight line, although the track model in the magnetic field differs from a straight line. Therefore, the track propagation is done in several steps between detector stations marked as Z_0 and Z in Figure 3. In each of the steps (indicated as dotted line), the precise trajectory (solid line) is calculated after the straight line extrapolation, then including the full influence of the traversed material. At every intersection point and after every step track parameters are updated (dots). 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), bremsstrahlung (Bethe-Heitler formula) and direct pair production (estimated using table values). 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, the gaussian approximation using the Highland formula is used to estimate the average scattering angle.

A detailed description of the developed track propagation can be found in [7].

2.2. Track finding

In the track finding algorithm hits are attached to the propagated track at each detector station using three different methods. Either just the nearest hit is attached to the track, or a weighting method including all surrounding hits is used, or all hits within a certain environment are included. For the first two methods, only one track is further propagated, the last 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 validation gate is defined based on the residual vector r (distance between fitted track and the hit) and the residual covariance matrix R. In the context of Kalman-based tracking filters, a validation gate can be expressed as $v = rR^{-1}r^T < d$. The cut value d is chosen such that a defined probability of rejecting the correct hit is achieved, here this probability is chosen to be 0.001. Values for d can be taken from χ^2 tables in dependence on the number of effective degrees of freedom. Here the effective degree of freedom is 1 for a straw tube detector hits and 2 for pixel hits from pads in a GEM detector. The algorithm takes into account possibly missing hits due to detector inefficiencies.

The three 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 χ^2 value is calculated for each track branch and unlikely ones are rejected. For the other two methods no track branches are created.

The "nearest neighbor" method attaches the hit with the smallest v, if lying in the validation region at all. In the "weighting method" all hits within the validation gates of all stations are assigned to the track. Then an iterative hit selection and track fitting procedure starts. In this procedure weights are assigned to each hit in the validation gate and a weighted mean of these hits is calculated. The weight is proportional to the multivariate Gaussian function and includes a temperature parameter T. The method uses simulated annealing to recalculate those weights in each iteration. Finally, the hit with the highest weight from each station is selected.

2.3. Track selection

After track finding, this routine shall reject so called clone and ghost tracks but keep the correctly found tracks with high efficiency. Two tracks are called clone tracks if they consist of a very similar set of hits, i.e. the track is essentially found twice. Ghost tracks are tracks that consist of a random set of hits. The selection algorithm works in two steps. First tracks are sorted by their quality which is defined by the track length and χ^2. Then, starting from the highest quality tracks all hits belonging to the track are checked. In particular, the number of hits shared with other tracks is calculated and the track is rejected if this number is larger than 2 out of 12 for TRD and 11-15 for MUCH, respectively.

3. Performance of the tracking algorithms

In order to test the track reconstruction algorithms, central Au+Au collisions at 25 AGeV beam energy were simulated with UrQMD [8]. These events were used to estimate the background in which the interesting signal, i.e. electrons or muons from the primary vertex were embedded. In order to enhance statistics 5 primary μ^+ (e^+) and 5 primary μ^- (e^-) were embedded in each event. Compared to the overall multiplicity of charged tracks in the acceptance (appr. 800) they do not distort the overall situation. GEANT3 [6] was used for transport through the CBM detector setup as described in section 1. Hits were calculated from the MC information as realistic as currently possible. In the MUCH detector a pad layout as from GEM detectors or signals as from straw tubes were implemented, the latter only for the last two absorber gaps and after the last absorber. For TRD a pad layout for MWPCs as described in section 1.2 was used.

The above described tracking routine was then tested on this dataset. A TRD track was accepted if having at least 8 hits out of 12. The resulting efficiency is shown in fig. 4. The momentum integrated value is 94.7% for all tracks, and 91.0% for electron, i.e. signal tracks. The efficiency loss for electrons compared to all tracks is probably due to the more complicated energy loss of electrons in particular in the TRD. From all reconstructed tracks 6% are ghost tracks.

For the MUCH detector the reconstructed track was required to pass through the whole iron absorber of 2.25 m length. This is the condition which would be used for J/ψ reconstruction. Efficiencies from the three described tracking methods are shown in fig. 5 (left) and found to be very similar. Momentum integrated values are listed in table 1. The track finding method employing branching has the highest efficiency, however is also the slowest method. Efficiencies for the weighting approach are only lower by 1.5% but require less time. The simplest and fastest method in which just the closest hit is attached shows only a drop of 2.5% compared to the branching method. Furthermore, two different MUCH setups were compared using the track finding method with the nearest hit for both cases: the first had GEM detectors with pad readout only ("GEM"), in the second the last three detector stations were replaced by straw tubes ("GEM+straw"). The straw tubes were arranged in 6 layers in groups of two and with tilting angles of $\pm 45°$. Results are shown in fig.5 (right) and table 1. This modified, but simpler setup with less electronic channels results in an efficiency drop of appr. 3%. The fraction of ghost tracks is low in all cases.

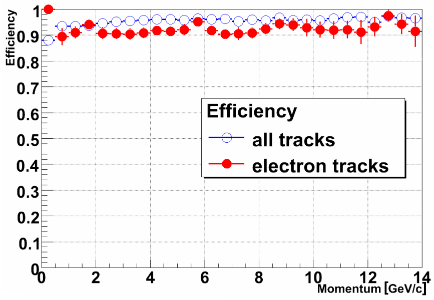

Figure 4. TRD track finding efficiency in dependence on momentum for central Au+Au collisions at 25 AGeV beam energy (UrQMD).

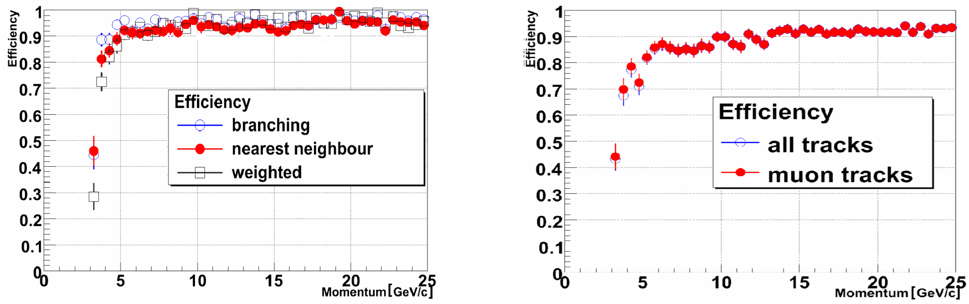

Figure 5. MUCH track finding efficiency in dependence on momentum for central Au+Au collisions at 25 AGeV beam energy (UrQMD). Three tracking methods (branching, nearest neighbor and weighting) are compared for a pad layout for all MUCH chambers [left]. The efficiency for nearest neighbor tracking is shown in case of straw tube detectors in the 3 last MUCH stations [right].

	GEM			GEM+straw
	Branching	Nearest Neighbor	Weighting	Nearest Neighbour
all	94.4%	91.9%	93.0%	89.2%
muons	94.7%	92.3%	93.4%	89.5%
ghosts	0.5%	1.1%	1.1%	1.6%

Table 1. MUCH track finding efficiency. Comparison of three methods for "GEM" layout (first 3 columns) and MUCH nearest neighbor track finding efficiency for the "GEM+straw" layout (last column).

4. Summary

Efficient and fast track reconstruction algorithms are a key ingredient to the CBM experiment. Based on track reconstruction in the silicon tracking system inside a dipole magnet, three track following methods for different detector setups were implemented. All methods are based on track following, the use of a Kalman filter and the calculation of a validation region. However, the discussed methods differ in the way hits are attached to the track. All three methods show efficiency above 90%. Further investigations and developments in particular in order to speed up the algorithms are ongoing. Overall, these tracking routines show, that the physics performance anticipated by the CBM detectors can be met with the current layout.

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