FAST RECONSTRUCTION OF TRACKS IN THE INNER TRACKER OF THE CBM EXPERIMENT

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Abstract

Typical central Au-Au collision in the CBM experiment (GSI, Germany) will produce up to 700 tracks in the inner tracker. Large track multiplicities together with the presence of an inhomogeneous magnetic field make the reconstruction of events complicated.

A cellular automaton method is used to reconstruct tracks in the inner tracker. The cellular automaton algorithm creates short track segments (tracklets) in neighbouring detector planes and links them into tracks. Being essentially local and parallel the cellular automaton avoids exhaustive combinatorial search, even when implemented on conventional computers. Since the cellular automaton operates with highly structured information, the amount of data to be processed in the course of the track search is significantly reduced. The method employs a very simple track model which leads to utmost computational simplicity and a fast algorithm.

Efficiency of track reconstruction for particles detected in at least three stations is presented. Tracks of high momentum particles are reconstructed very well with efficiencies of about 98%, while multiple scattering in detector material leads to a lower reconstruction efficiency of slow particles.

CBM EXPERIMENT

The CBM Collaboration builds a dedicated heavy-ion experiment to investigate the properties of highly compressed baryonic matter as it is produced in nucleus-nucleus collisions at the Facility for Antiproton and Ion Research (FAIR) [1] in Darmstadt, Germany.

Overview

The scientific goal of the research program [2] is to explore the phase diagram of strongly interacting matter in the region of highest baryon densities. This approach is complementary to the activities at RHIC (Brookhaven) and ALICE (CERN-LHC) which concentrate on the region of high temperatures and very low net baryon densities. The territory of dense baryonic matter accessible in heavy-ion collisions is located between the line of chemical freeze-out and the hadronic/partonic phase boundary, as indicated by the hatched area in Figure 1. New states of matter beyond the deconfinement and chiral transition at high net baryon densities and moderate temperatures may be within reach of the experiment. The proposed experimental programme includes: the study of in-medium properties of hadrons; the search for the chiral and deconfinement phase transition at high baryon densities; the search for the critical point of strongly interacting matter; the study of the nuclear equation-of-state of baryonic matter at high densities (as it exists in the interior of neutron stars); the search for new states of matter at highest baryon densities.

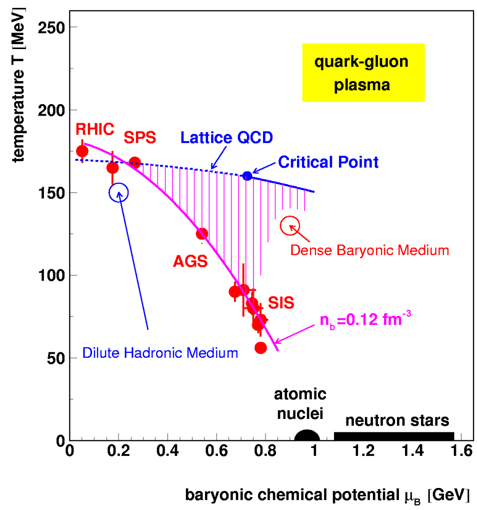

Figure 1: The phase diagram of strongly interacting matter.

The experiment aims at a comprehensive study of hadrons, electrons and photons emitted in heavy-ion collisions. Its main experimental objective is the measurement of extremely rare signals in an environment typical for heavy-ion collisions. This requires the collection of a huge number of events which can only be obtained by very high reaction rates and long data taking periods. Reaction rates are up to 10 MHz (minimum bias) which corresponds to a beam intensity of 10^9 beam particles per second on a 1% interaction target. The rare signals are embedded in a large background of charged particles.

Experimental Setup

The experimental setup has to fulfil the following requirements: identification of electrons which requires a pion suppression factor of the order of 10^4; identification of hadrons with large acceptance; determination of the primary and secondary vertices (accuracy ≈ 50 μm); high granularity of the detectors; fast detector response and read-out; very small detector dead time; high-speed

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trigger and data acquisition; radiation hard detectors and electronics; tolerance towards delta-electrons. Figure 2 depicts the present layout of the CBM experimental setup.

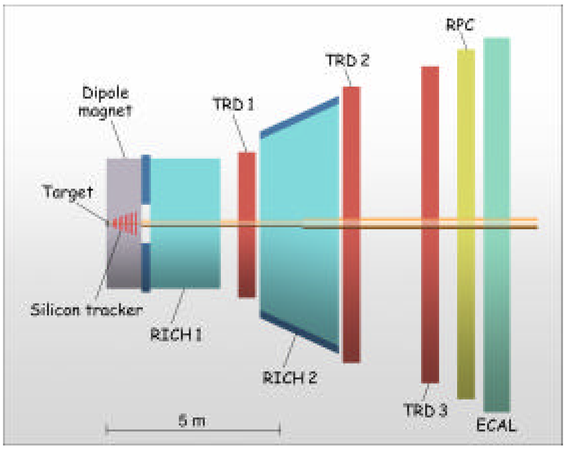

Figure 2: Geometry of the CBM experiment.

Inside the dipole magnet gap are the target and a 7 plane Silicon Tracking System (STS) consisting of pixel and strip detectors. The Ring Imaging Cherenkov detectors (RICH) have different radiators for the detection of electrons (first RICH) and mesons (second RICH). The Transition Radiation Detector (TRD) arrays measure electrons with momenta above 1GeV ($\gamma = 2000$). The TOF stop detector consists of Resistive Plate Chambers (RPC). The electromagnetic calorimeter (ECAL) measures electrons, photons and muons.

The CBM setup is optimized for heavy-ion collisions in the beam energy range from about 8 to 45 AGeV. Experiments on dilepton production at beam energies from 2 to about 8AGeV could be carried out with the HADES spectrometer if installed in front of the CBM target.

Event Reconstruction

Typical central Au-Au collision in the CBM experiment will produce up to 700 tracks in the inner tracker (Figure 3 gives an example of a reconstructed event). Large track multiplicities together with the presence of a non-homogeneous magnetic field make the reconstruction of events complicated. Therefore the collaboration performs an extensive analysis of different track recognition methods in order to better understand the geometry of the detector and to investigate specific features of accepted events.

One of the well-known methods, the Hough transform, is implemented in order to investigate its hardware applicability (e.g. FPGAs) in the Level-1 trigger. It uses a parametric description of a track by a set of its parameters. Once the track model and detector measurement model are given, all hits in the detector can be projected into the track parameter space creating a complex density distribution with many local maxima. In this case the track recognition becomes a search for the local maxima corresponding to tracks.

Conformal mapping is a mathematical technique used to convert (or map) one mathematical problem and solution into another, simpler one. The conformal mapping method is used to transform a complicated particle trajectory in a non-homogeneous magnetic field into a parabola. A fitting procedure based on the parabolic approximation has been developed. It takes into account multiple scattering in material and ionization losses.

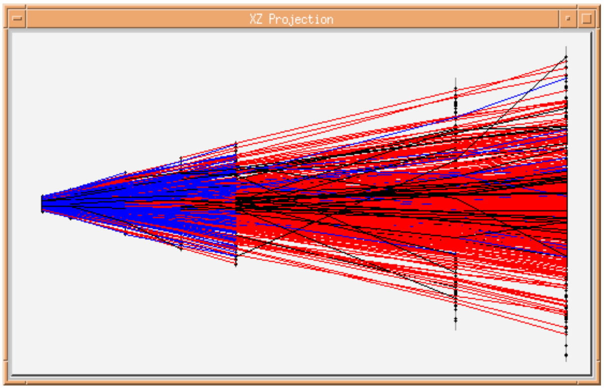

Figure 3: Reconstructed tracks in the Silicon Tracking System for a central Au-Au collision at 25 AGeV.

Here we describe another reconstruction procedure which is based on a cellular automaton method.

CELLULAR AUTOMATON METHOD

Algorithm

The cellular automaton method [3, 4, 5, 6] creates short track segments (tracklets) in neighbouring detector planes and strings them into tracks (Figure 4).

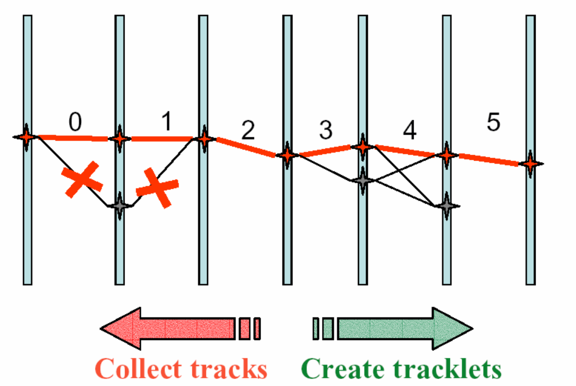

Figure 4: A simple illustration of the cellular automaton algorithm It creates tracklets, links and numbers them as possibly situated on the same trajectory, and collects tracklets into track candidates.

Being essentially local and parallel cellular automata avoid exhaustive combinatorial searches, even when implemented on conventional computers. 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. Usually cellular automata employ a very simple track model which leads to utmost computational simplicity and a fast algorithm. Having an inhomogeneous magnetic field we use a straight line track model in the non-bending projection and a local parabolic approximation in the bending projection.

Performance Evaluation

For evaluation purposes all simulated and reconstructed tracks are subdivided into several categories: a “reference set” of tracks, an “all set”, an “extra set”, and clone and ghost tracks.

By definition, a track from the all set of tracks should intersect the sensitive regions of at least 3 stations. A reference track should have a momentum greater than 1 GeV/c in addition.

The reference set of tracks can also include tracks of particular physics interest:

- secondary tracks from interesting decays;
- primary tracks coming from the target region.

In addition to these tracks the so-called extra set of tracks, containing low-momentum tracks, is also considered.

A reconstructed track is assigned to a generated particle, if at least 70% of its hits have been caused by this particle. A generated particle is regarded as found, if it has been assigned to at least one reconstructed track. If the particle is found more than once, all additionally reconstructed tracks are regarded as clones. A reconstructed track is called a ghost, if it is not assigned to any generated particle (70% criteria).

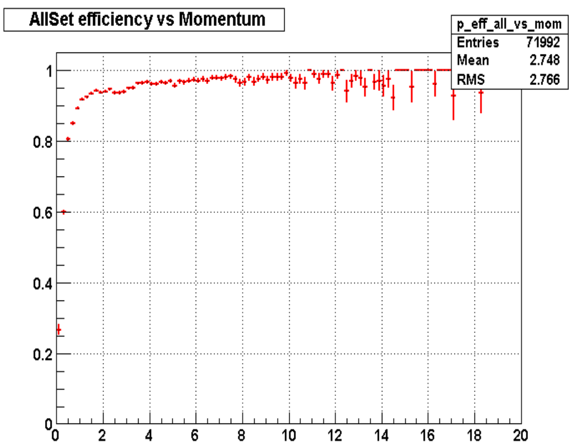

Figure 5: Track reconstruction efficiency as function of momentum in GeV/c.

Efficiency of track reconstruction for particles detected in at least three stations is presented in Figure 5. Tracks of high momentum particles are reconstructed very well with efficiencies of about 98%, while multiple scattering in detector material leads to a lower reconstruction efficiency of slow particles.

Table 1 gives efficiencies for all sets of tracks. One can see that reconstruction efficiency for reference primary tracks is more than 98%, while the efficiency of all reference tracks is slightly lower because of the presence of secondary tracks originating far downstream from the target region. Total efficiency for all tracks with a large fraction of soft secondary tracks is 90%. Clone rate is not a problem for the algorithm. Ghost level is at 5%.

Table 1: Efficiency of track reconstruction

Track category	**Efficiency, %**
Reference primary	98.36
Reference tracks	94.85
All tracks	90.09
Clone	0.11
Ghost	5.18
Tracks/event	**648**

Table 2 presents time consumptions for each stage of the algorithm. The first two steps (fetching and sorting data) are specific to the current format of simulated data and will be eliminated soon. The most time consuming part, creating and linking tracklets, takes 115 ms caused by intensive access to hits. Being algorithmically and arithmetically very simple this step together with the next one, creating track candidates, can be implemented in hardware, increasing the speed of the algorithm up to a few orders of magnitude (see next subsection). Only the last stage of track finding, selection of tracks, needs to be running on a CPU because of final track fitting, which is mathematically much more complicated.

Table 2: Timing of reconstruction steps

Reconstruction step	**Time, ms**
Fetch MC data	63.3
Local copy and sort	12.4
Create and link tracklets	115.7
Create track candidates	53.5
Select tracks	2.6

Our Experience (HERA-B and LHCb)

A cellular automaton based package CATS [5, 6, 7] is the default reconstruction package of the HERA-B experiment at DESY. The CATS package was extensively tested on simulated and real data using two other HERA-B track reconstruction packages as references: RANGER based on the Kalman filter method and TEMA based on the Hough transform method. Table 3 presents efficiencies and resolutions for all three packages on realistic Monte Carlo data in the pattern tracker of HERA-B. The number of interactions per event is one $J/\psi \to \mu^+\mu^-$ event and two superimposed Poisson distributed inelastic events with the aim to represent the track multiplicity in the triggered data of 2000.

Table 3: Efficiencies and resolutions of CATS, RANGER and TEMA reconstruction packages

	CATS	RANGER	TEMA
Ref. J/ψ, %	97.4	93.6	90.8
Ref. prim., %	96.2	91.5	87.4
Ref. set, %	92.3	84.6	82.7
All tracks, %	55.6	40.0	44.8
Extra set, %	33.3	13.0	21.7
Clone, %	2.1	2.5	0.8
Ghost, %	14.0	17.2	17.1
Tracks/event	**59**	**42**	**47**
x, μm	246	322	291
y, mm	3.7	5.0	4.1
t_x, mrad	0.62	0.71	0.76
t_y, mrad	4.73	6.96	5.39
Hits/track	**31**	**26**	**31**

CATS has a higher efficiency, the effect becomes even more pronounced for soft (extra) tracks. In addition, it finds more tracks and produces less ghosts. Finally, CATS collects more hits per track, resulting in a significantly better estimate of track parameters.

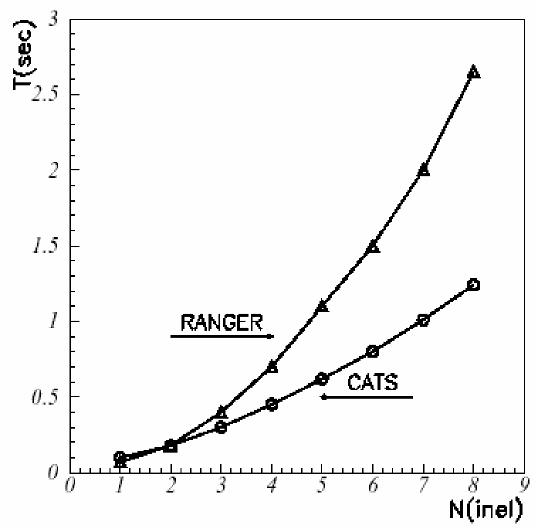

Figure 6: Mean computing time per event versus number of superimposed inelastic interactions.

CATS and RANGER were also tested on different numbers of superimposed inelastic interactions exactly mixed, with the number of tracks rising from 40 for one interaction up to 320 for eight (Figure 6). A PC with dual 500 MHz Pentium III processors was used in this test. For CATS, the CPU time shows only a very moderate increase, corresponding to an almost constant time requirement per track.

The result of efficiency studies on real data is that CATS finds 10-18% more *J/y* than RANGER and TEMA, depending on the applied cuts. CATS also produces better signal to background ratios and significantly narrower *J/y*-peaks. In addition, CATS has demonstrated higher efficiency for K^0_S signal, it finds 20% more K^0_S events than RANGER and TEMA.

A cellular automaton based tracking algorithm [8, 9] for the LHCb Level-1 trigger has been implemented for PCs and has a reconstruction efficiency of 97% for daughter tracks from *B*-mesons.

The reconstruction algorithm takes about 5 ms per event on a 1 GHz Pentium III processor. The 2D tracking part of the algorithm is highly combinatoric and takes about 75% of the total reconstruction time. Therefore, a hardware implementation of the 2D tracking has been investigated using an FPGA co-processor. There were 8 processing units programmed in an FPGA running in parallel. The FPGA uses the same algorithm as the CPU but simplified with respect to FPGA features. It makes a full tracklet search and introduces relations between tracklets to make their gathering into full tracks by the CPU easier. At the same time it filters data suppressing detector noise and hits from tracks out of geometrical acceptance. The FPGA based reconstruction algorithm requires on average 15 μs per event.

SUMMARY

The algorithm based on the cellular automaton method is developed for the reconstruction of tracks in the inner tracker of the CBM experiment. Comprehensive tests of the algorithm have shown high reconstruction efficiency and low ghost rate. The algorithm has a reasonable behaviour of the CPU time consumption and robustness with respect to large track multiplicities. It is also possible to implement the most time consuming combinatorial part of the algorithm in hardware, for instance FPGAs, thus speeding the algorithm up to a few orders of magnitude. Having experience in the HERA-B and LHCb experiments we expect that the cellular automaton algorithm will work reliably with more realistic simulated and real data of the CBM experiment.

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