Simulation and reconstruction of free-streaming data in CBM

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Abstract. The CBM experiment will investigate heavy-ion reactions at the FAIR facility at unprecedented interaction rates. This implies a novel read-out and data acquisition concept with self-triggered front-end electronics and free-streaming data. Event association must be performed in software on-line, and may require four-dimensional reconstruction routines. In order to study the problem of event association and to develop proper algorithms, simulations must be performed which go beyond the normal event-by-event processing as available from most experimental simulation frameworks. In this article, we discuss the challenges and concepts for the reconstruction of such free-streaming data and present first steps for a time-based simulation which is necessary for the development and validation of the reconstruction algorithms, and which requires modifications to the current software framework FAIRROOT as well as to the data model.

1. The CBM experiment

The Compressed Baryonic Matter Experiment (CBM) is a heavy-ion experiment to be operated at the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt, Germany [1,2,3], from 2018 on [4,5]. Its physics aim is the investigation of strongly interacting matter at extreme net-baryon densities as obtained in nuclear collisions in the beam energy range 10 - 45 A GeV. The core of CBM is a large-acceptance spectrometer, realised by a silicon tracking system located in the field of a superconducting dipole magnet. Upstream of this main tracking system there are detectors for the identification of electrons (RICH, TRD), hadrons (TOF) and neutral particles (ECAL). Alternatively to the electron detectors, an active absorber system will be used to measure muon pairs. The planned experimental setups for the measurement of hadrons and electrons and for the measurement of muons are shown in Figure 1.

The physics programme of CBM comprises the measurement of yields, spectral distributions, correlations and fluctuations of the particles produced in the heavy-ion reactions. This includes the bulk hadrons as well as very rare probes like multi-strange hyperons or charmed hadrons which are close to the production threshold at CBM energies. To study the feasibility of the measurement of this variables, simulations are performed within the software framework FAIRROOT [6,7] which is based on ROOT [8]. The simulations include detailed detector geometries with passive materials, supports and front-end electronics, advanced detector response models comprising charge propagation and discretisation on the read-out planes, and full reconstruction of space points, tracks and vertices. Using this framework, the feasibility to measure the major observables was demonstrated [9,10,11].
Figure 1. Left: Setup of the CBM experiment for electron and hadron measurements. The beam enters from the left. From left to right: Superconducting magnet hosting the target, the micro-vertex detector (MVD) and the silicon tracking system (STS), ring-imaging cherenkov detector (RICH), three stations of transition radiation detectors (TRD), time-of-flight wall (TOF) and electro-magnetic calorimeter (ECAL). The forward calorimeter (PSD) at the end of the setup serves for event characterisation (centrality, event plane). Right: CBM setup for muon measurements. The RICH detector is replaced by an active absorber system (MUCH). Only one TRD station is used for tracking between MUCH and TOF.

The expected multiplicities of the rare probes like charmed hadrons are of the order of $10^{-6}$ per collision, which have to be detected among a background of several hundreds of charged tracks per event (see Figure 2). CBM is thus being designed to cope with very high interaction rates of up to 10 MHz, a requirement which puts strong constraints on the technology of detectors and read-out electronics, but also on the data processing. In fact, the latter will be one of the limiting factors for the tolerable event rate. At the maximal rate, we expect a raw data flow of about 1 TB per second from the front-end electronics through the data acquisition system. This rate has to be reduced on-line to the targeted archival rate of about 1 GB/s, thus by three orders of magnitude. As in most cases no easy trigger signatures exist, the data reduction requires on-line event reconstruction and selection. A focus of CBM is therefore the development of fast reconstruction algorithms fully exploiting the parallelism features offered by modern computer architectures.

Event reconstruction in CBM starts, after cluster and hit finding in the various sub-detector systems, with track finding in the main tracker (STS). An approach based on the Cellular Automaton has proven to be both fast and efficient [12], as well as scalable when being executed on many-core architectures [13]. The current reconstruction time is about 16 ms per minimum bias event (Au+Au at 25 A GeV beam energy) on an Intel X5550 (2x4 cores, 2.67 GHz).

The track parameters are reconstructed using the Kalman filter algorithm, taking into account propagation in a non-homogeneous magnetic field and multiple scattering and energy loss in the detector materials. The Kalman filter serves also for track propagation throughout the detector system, and is thus inherently used by the track finding algorithms. Hence, optimisation of this algorithm with respect to speed is also mandatory; including the use of SIMD and multi-threading, the execution time could be reduced by many orders of magnitude [14].

Track finding in the downstream detectors (TRD and/or MUCH) is performed with a track following method, using the tracks already found in the STS as seeds [15, 16]. Rings in the...
Figure 2. Typical event in the CBM experiment: simulation of a central Au+Au collision at 25A GeV beam momentum in the main tracking system. About 600 charged tracks per event in the acceptance have to be reconstructed on-line in order to select events with e.g. displaced vertices from open charm decays.

RICH detector are found by an algorithm based on the Hough transform [17]. Found rings as well as TOF hits are attributed to tracks based on proximity.

In summary, the developed reconstruction routines allow the reconstruction of events in CBM with high efficiency and accuracy, and are suitable to cope with the extreme environment in terms of track multiplicity and event rate.

2. Reconstruction of free-streaming data

The huge data rates and the absence of simple trigger primitives in CBM exclude conventional, latency-limited trigger architectures. Instead, CBM will have to deal with complicated trigger patterns like e.g. the displaced vertices of open charm decays, which require partial event reconstruction and thus the processing of a major part of the raw event data. To cope with this conditions, CBM employs a new data acquisition concept with autonomous, self-triggered front-end electronics which will asynchronously deliver time-stamped data messages on activation of the respective detector channel. All data messages will be shipped through fast, optical links to a readout buffer, the size of which is adjusted to the L1 decision time. The data are then passed via a high-throughput event building network to a large computer farm (first-level event selector, FLES), where online event selection is performed [18]. The data acquisition concept is schematically depicted in Figure 3.

As a consequence of this readout concept, the association of detector signals to a physical event is no longer given a priori by a hardware trigger. This association is, however, a prerequisite of the current reconstruction algorithms, which were developed and validated on event-by-event simulated data. It must thus be either performed in software by the data acquisition system or the FLES prior to the reconstruction chain, or the reconstruction algorithms must be modified in order process not event-associated data.

In principle, there are two limiting cases. If the average time separation of events is large compared to the time span of hits within one event, the event association can be performed based
Figure 3. Concept of the CBM data acquisition chain in comparison to a conventional one. All raw data flow asynchronously from the self-triggered front-end electronics to a readout buffer. Event selection is performed online in the FLES computer farm.

on the hit time information only. This situation will be present for running modes with moderate interaction rates, like for the measurement of bulk observables, where no trigger signature is available or no trigger is required. In this case, a simple sorting algorithm running prior to the reconstruction chain is called for; the event-based reconstruction can then be used as before.

If, on the other hand, the average time between subsequent events is of the same order as the time difference of hits within one event (high event rates), the disentangling of hits from different events becomes nontrivial, as demonstrated in Figure 4 for an interaction rate of 10 MHz. In this case, both time and coordinate information of the hits have to be used in order to associate hits to physical events, in other words, event reconstruction becomes four-dimensional. Formally, this implies to add the time coordinate to the state vector of a track:

\[(x, y, dx/dz, dy/dz, q/p) \rightarrow (x, y, dx/dz, dy/dz, q/p, t)\]  \hspace{1cm} (1)

and to perform hit-to-track association (or tracklet-to-tracklet in the case of the Cellular Automaton) by proximity not only in phase space but also in time. Events will be separated after track finding based on the reconstruction of their primary vertex, where many tracks will intersect, again both in coordinate space and in time.

Another consequence is that a set of data corresponding to several or many physical events has to be dispatched to one processing node. An exploratory study showed that the Cellular Automaton track finder is able to operate on an overlay of up to 20 minimum bias events without serious degradation in speed [13]. For further insight into the problem and development of proper algorithms, realistic input data from simulations are required.
3. Time-based simulation

It is thus indispensable to simulate the free-streaming data as expected to be delivered from the DAQ system of the running experiment. However, the current framework, as most HEP software frameworks, is fully oriented on event-by-event processing. The simulation and reconstruction of a continuous data stream hence requires modifications to the framework and, possibly, to the data model in general, which currently is based on TClonesArrays as branches of a ROOT tree.

As a first step towards a time-based simulation, the (event-based) Monte-Carlo data are prepared in a suitable way for the digitisers to operate on a data stream. A dedicated task class (CbmMCStreamer) calculates the absolute hit time, taking the MC hit time (w.r.t. the event) and a model of the time structure of the beam, and delivers a continuous, time-sorted stream of MC hits to the digitisers. In this process, the association of MC hits to events is destroyed. Persistency is still obtained by using the ROOT tree concept, but now a tree entry does not correspond any longer to one physical event, but to an (arbitrary) time slice ("epoch"). It should be noted that the epoch on the MC level need not coincide with any time scale defined by the read-out and DAQ system, but in first place just serves to discretise a continuous data stream in order to keep as close as possible to the current data model. As one (output) epoch does not coincide with one (input) event, a dedicated, "asynchronous" mode of the Run Manager was implemented, in which the filling of the output tree is not triggered, as usual, by the end of the processing of one input event. Instead, the streamer task itself decides on the end of the epoch and triggers the output accordingly. Border effects like events split between two epochs are treated correctly by appropriate buffering in the streamer task.

With this rather simple preparatory work, it is now possible to implement a time-based detector response, taking into account the anticipated timing behaviour of detectors and read-out electronics like e.g. time resolutions and channel dead times. This requires intelligent bookkeeping of the history of each channel, i.e. time and charge deposit of the last hit. Furthermore, work on proper algorithms for event association and, if required, four-dimensional track reconstruction can be started.
For a full validation of the read-out and data acquisition concept of CBM, however, a complete simulation of the raw data stream from front-ends through DAQ to the first-level event selector is aimed for. Such a simulation will probably go beyond the current, ROOT-based data model, but will be oriented as closely as possible to the data format to be used for the real data stream, which will diminish the “traditional” difference between online and offline software.

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