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A precision device needs precise simulation: Software description of the CBM Silicon Tracking System

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Abstract. Precise modelling of detectors in simulations is the key to the understanding of their performance, which, in turn, is a prerequisite for the proper design choice and, later, for the achievement of valid physics results. In this report, we describe the implementation of the Silicon Tracking System (STS), the main tracking device of the CBM experiment, in the CBM software environment. The STS makes uses of double-sided silicon micro-strip sensors with double metal layers. We present a description of transport and detector response simulation, including all relevant physical effects like charge creation and drift, charge collection, cross-talk and digitization. Of particular importance and novelty is the description of the time behaviour of the detector, since its readout will not be externally triggered but continuous. We also cover some aspects of local reconstruction, which in the CBM case has to be performed in real-time and thus requires high-speed algorithms.

1. Introduction

The Compressed Baryonic Matter (CBM) experiment at the Facility for Anti-proton and Ion Research, currently under construction in Darmstadt, Germany, is designed to explore the phase diagram of strongly interacting matter at high net baryon densities by studying nucleus-nucleus collisions in the energy range $2A$ to $45A$ GeV. In such collisions, up to 700 charged particles are to be expected in the detector acceptance. A key feature of CBM is the very high interaction rate capability of up to 10 million collisions per second, which will make the experiment sensitive to extremely rare probes. Because of the high interaction rates and mostly complex trigger signatures, no hardware trigger will be employed; instead, CBM will have free-streaming front-end electronics and online data selection exclusively based on event reconstruction in real-time in software.

The Silicon Tracking System (STS) is the core detector of CBM [1]. Its task is the reconstruction of the tracks of the particles produced in the collisions and the determination of their momenta. The requirements to the STS are high track reconstruction efficiency ($> 95\%$ for momenta above 1 GeV), good momentum resolution ($\approx 1.5\%$ for $p > 1$ GeV), high hit rate capability (up to 20 MHz/cm^2, and high radiation tolerance (up to $10^{14}\,\mathrm{n_{1\,MeV\,eq}/cm^2}$). The design choice for the STS is the construction from double-sided microstrip silicon sensors with

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7.5^{o} stereo-angle between strips at the front and the back side, the self-triggered fast read-out electronics being placed outside of the acceptance.

In order to exploit the full capacity and precision of the STS system, precise simulation and efficient reconstruction algorithms are required. A particular feature of the simulation is to model the free-streaming readout. Instead of triggered events, so-called time slices have to be filled, which represents all detector raw data within a given time interval. A time slice usually comprises many simulated events (O(1000) - O(100000)). All reconstruction algorithms have to operate on such time slices as raw data input format.

In the following, we discuss first the detector response model used in the simulations, and then describe the current status of the local reconstruction software (cluster and hit finding).

2. Detector response model

A realistic detector response model is required to understand the detector performance and to get reliable physical results from simulations. The model has to describe both the processes occurring in the silicon detectors when a charged particle passes through (analog response), and the behaviour of the read-out ASIC (digital response).

The analog response model implemented for the STS comprises the following processes:

- The incident particle loses energy by creating electron-hole pairs along its trajectory inside the sensor. This energy loss is non-uniform. To model this, we divide the particle trajectory into thin layers ($\sim\ 3\,\mu$m – about 100 layers for a perpendicular track) and estimate the energy loss in each layer using the Urban model [2]. The energy loss is converted into charge using the ionisation energy of Silicon.
- Since the sensor is over-depleted, the created charges drift to the read-out planes in the planar electric bias field (this approximation is valid in 90 % of the sensor volume).
- Since the STS is placed in a magnetic dipole field, the drifting charge carriers experience a deflection perpendicular to the drift direction ("Lorentz shift").
- Thermal diffusion leads to a transversal increase of the charge cloud with time.
- The integration time of the readout ASIC is larger than the drift time of both electrons and holes. The charge projection on the read-out place can thus be described by a Gaussian. It is discretised by integration over each read-out strip.
- A fraction of the charge in each read-out strip is re-distributed to both the left and right neighbour strip ("cross-talk"). This fraction is calculated from the inter-strip capcitance C_{is} and the coupling capacitance C_{c} through

$$Q_{\mathrm{crosstalk}} = \frac{Q_{\mathrm{strip}} C_{\mathrm{is}}}{2C_{\mathrm{is}} + C_{\mathrm{c}}} \ .$$

The above described processes are calculated for each incident particle independently. The interference of tracks is taken into account before digitisation when two tracks deliver charge into a given read-out strip within the dead time of the ASIC. This can happen for two tracks of the same event, but also for tracks from different events, provided the time separation of the events is small enough.

The digital response simulation converts the resulting analog charge above threshold into a signal ("digi"), taking into account the dynamic range and the number of ADC channels (32 in our case) of the readout ASIC. The digis are then delivered to the software representation of the DAQ, which combines data streams from all sub-detectors into time slices.

The implementation of the detector response model is done in a modular way such that each individual process can be activated or de-activated. This allows to study the influence of the processes on the reconstruction results separately. As an example, we compare in Fig. 1

two model variants: the "simple" model assumes a uniform energy loss (no fluctuations) and includes only the Lorentz shift in the magnetic field. The "realistic" model includes all effects mentioned above, i.e., energy loss fluctuations, Lorentz shift, thermal diffusion and cross-talk. The comparison is done for minimum-bias Au+Au collisions at 10A GeV generated by the UrQMD transport model.

The left-hand panel of Fig. 1 demonstrate a modest increase in cluster size in the realistic model, which is mainly caused by cross-talk; under our experimental conditions, thermal diffusion plays a minor role. The most noticeable effect is the decrease in coordinate resolution as seen in the centre panel. This, however, does not translate into a significant decrease in momentum resolution (right-hand panel) since the latter is dominated by small-angle scattering.

The detector response model was validated against data from in-beam detector tests [3]. The main validation criterion is the cluster size distribution as function of the incident track angle with respect to the sensor surface. A good correspondence of simulated and measured data was found.

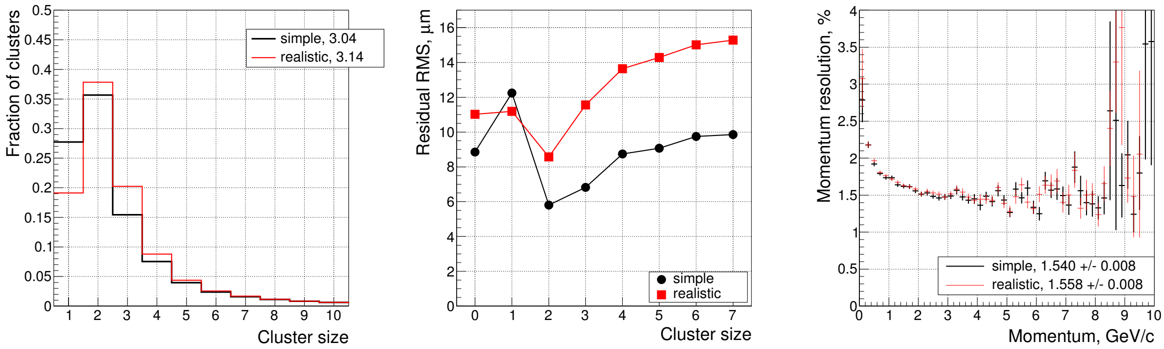

Figure 1. Comparison of reconstruction performance using the simple (black) and the realistic (red) detector response models (see text), obtained from the simulation of minimum-bias Au+Au events at 10A GeV. *Left:* Cluster size distribution with mean cluster size given in the legend. *Middle:* RMS of the residual distribution for the x-coordinate (for the sensor side where strips are perpendicular to the x-axis) for different cluster sizes. $x = 0$ means all clusters. *Right:* Relative momentum resolution as function of particle momentum. The legend gives the average for fast tracks ($p > 1\,\mathrm{GeV}$) in %.

3. Cluster reconstruction

The first step in the local reconstruction of STS data is cluster finding. A cluster is a set of digis corresponding to neighbouring strips which simultaneously deliver signals. "Simultaneously" here means within a time interval defined by the single-channel time resolution of about 5 ns. In order to account for inactive channels, e.g. due to failures during production or integration of the devices, the cluster finder can allow single-strip gaps in a cluster, if the missing strip corresponds to a dead channel.

In the ideal case, a cluster corresponds to a single track having traversed the sensor. In a high-track density environment, however, two clusters can merge into one if two tracks pass the sensor in close vicinity. For minimum-bias Au+Au collisions at 10A GeV, the cluster finding efficiency is about 99%.

Once a cluster is found, one-dimensional position information (perpendicular to the strip orientation) is obtained from its centre position. The latter is determined from the measured charges by a cluster position finding algorithm. Commonly, the centre-of-gravity method is used for this task, defining the cluster position by

$$x_{\text{rec}} = \frac{\sum_i x_i q_i}{\sum_i q_i}, \tag{1}$$

where q_i is the measured charge in strip i, x_i the strip centre coordinate, and i runs over all strips in the cluster. However, this definition in general leads to a bias of the reconstructed coordinate. Therefore, we use an alternative, unbiased approach which is motivated by minimizing the position residuals in the case of an "ideal" detector (uniform energy loss). This algorithm defines the cluster position as

$$x_{\text{rec, 2-strip}} = \frac{1}{2}(x_1 + x_2) + \frac{1}{3}\frac{q_2 - q_1}{\max(q_1, q_2)}. \tag{2}$$

for 2-strip clusters and

$$x_{\text{rec, n-strip}} = \frac{1}{2}(x_1 + x_n) + \frac{1}{2}\frac{\min(q_n, q) - \min(q_1, q)}{q}, \quad q = \frac{1}{n-2}\sum_{k=2}^{n-1} q_k. \tag{3}$$

for n-strip clusters (n $>$ 2). Eq. (3) is exact for a homogeneous charge distribution. The charge averaging and min-functions in (3) suppress fluctuations arising due to noise, non-uniformity of the energy loss, etc. For clusters with one strip only, the strip centre coordinate is chosen as cluster position.

The unbiased algorithm yields better position resolution for an ideal detector with uniform energy loss of the incident particle. When including non-ideal effects into the detector response simulation, the performances of two algorithms become comparable (see Table 1). In terms of computational efficiency, the unbiased algorithm has less operations, since is does not involve a loop over all strips in the cluster. Furthermore, it allows an a-priori estimate of the position error [3].

Table 1. Position resolution (RMS of the residual distribution) for the centre-of-gravity and the unbiased cluster position finding algorithm obtained with the most realistic detector response simulation and the STS geometry. The results were obtained from 500 simulated minimum bias Au+Au events at 10 AGeV.

	Residuals, μm, $\pm\,0.1\,\mu$m	
Cluster size	Unbiased	Centre-Of-Gravity
1	14.2	14.3
2	10.3	10.2
3	13.3	13.6
all	14.5	15.1

4. Hit reconstruction

A hit is a combination of two clusters from opposite sides of the sensor, both clusters being simultaneous within the given time resolution. The hit coordinates are obtained by intersecting

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the two lines drawn through the cluster centres parallel to the strips. A common feature of the strip geometry is the appearance of fake (combinatorial) hits once a sensor is hit by more than one track (see Fig. 2). The number of fake hits for n particles traversing a sensor is $(n^2-n)\tan\alpha$, where α is the stereo angle (the relative angle between strips on the front and on the back side). A smaller stereo angle thus comes with a smaller amount of fake hits, but also with worse spatial resolution in one coordinate. For the CBM-STS, a stereo angle of 7.5° was chosen as compromise between fake hit rate and spatial resolution. In Au+Au collisions, a typical value for the fraction of fake hits is 45%.

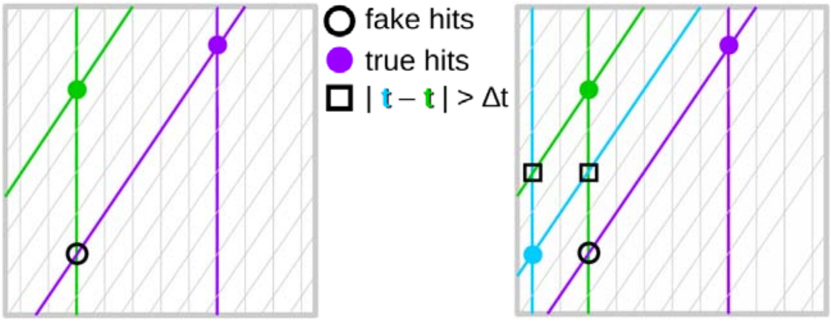

Figure 2. Hits in double-sided silicon sensors. The vertical grey lines show strips on one side of the sensor, the inclined lines those on the other side (the stereo-angle is not to scale for visibility). *Left* panel: event-based hit finder. Two incident particles penetrate the sensor within the same event. One particle fires green strips, another — violet strips. Two true hits (shown with filled dots) and one fake hit (empty dot) appear. *Right* panel: time-based hit finder. Three particles pass through the sensor within one time slice. "Green" and "violet" particles penetrate the sensor within the time resolution, resulting in the fake hit (round empty dot). "Blue" particle passage is time resolved — two additional fake hits (empty squared dots) do not appear.

5. Performance

Since the cluster and hit finding algorithms of CBM must be suitable to be applied in real-time, computing speed is a crucial performance figure. Both have to operate on time slices representing a large number of events, where the association of data to events is not given. For comparison, we have also implemented event-based versions of both algorithms, which operate on data from a single event and do not consider the timing information of the raw data.

Table 2 shows a comparison of the event-by-event case and the time-based case with 100 events per time slice. The tests were done on minimum-bias Au+Au events at 10A GeV. We find for both cases almost identical efficiency and fake hit rate. The speed of the hit finder does not depend strongly on the number of events in the time slice, while that of the cluster finder does. Further code optimization of the latter is needed to enable it to operate on large input data chunks. However, the numbers in Table 2 were obtained with non-parallelized code. Substantial speed-up will be obtained by the obvious sensor-wise parallelization.

6. Conclusion

The Compressed Baryonic Matter experiment will probe strongly interacting matter at extreme baryonic densities. Its ambitious physics programme requires very high interaction rate and no hardware trigger, which in turn requires the time coordinate to be included into the reconstruction. In this report, we presented the time-based simulation and reconstruction software for the Silicon Tracking System. The time-based cluster and hit finders show the same reconstruction quality as their event-based equivalents. The computational performance

Table 2. Performance of the time-based cluster and hit finders in comparison with the event-based ones. Event-based: 1000 minimum bias events Au+Au at 10 AGeV. Time-based: minimum bias events Au+Au at 10 AGeV, 10 μs time slice size, 10 MHz interaction rate.

	Event-based	Time-based
Cluster finder:		
Real time per event [ms]	4.8	22.2
Hit finder:		
Real time per event [ms]	3.5	3.6
Efficiency	98 %	97 %
True hits	55 %	53 %

of the hit finder meets the design requirements. Further speed-up of the algorithms will be possible via data-level parallelization.

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