Track measurement in the high multiplicity environment at the CBM Experiment

Pradeep Ghosh¹,², for the CBM Collaboration
¹Goethe University, Max-von-Laue-Straße 1, D-60438 Frankfurt am Main
²GSI Helmholtz Center for Heavy Ion Research GmbH, Planckstraße 1, D-64291 Darmstadt
E-mail: Pr.Ghosh@gsi.de

Abstract. In the Compressed Baryonic Matter (CBM) Experiment at FAIR, the Silicon Tracking System (STS) will perform track reconstruction and momentum determination of the charged particles created in interactions of heavy-ion beams with nuclear targets. The STS will consist of 8 tracking layers located at distances between 30 cm and 100 cm downstream of the target inside the 1 Tm magnetic dipole field. An ultra-low material budget is required to achieve momentum resolution of the order of \( \Delta p/p = 1\% \). Therefore, the front-end electronics is placed outside the physics aperture. The active volume of the STS is built from 300 \( \mu \)m thick double-sided silicon microstrip sensors mounted onto lightweight carbon fiber support ladders. The sensors will be read out through ultra-thin micro-cables with fast self-triggering electronics at the periphery of the stations where also other infrastructure such as cooling can be placed. In this paper, the development status of the detector system, highlighting the overview of the STS layout, tracking algorithm and performance simulations are presented.

1. The CBM experiment

The Compressed Baryonic Matter Experiment (CBM) [1] is one of the four major experiments that are planned to be performed at the Facility for Anti-proton and Ion Research (FAIR)[2] at Darmstadt, Germany. The CBM experiment aims to explore the phase diagram of nuclear matter [3]. The CBM experiment at FAIR is a fixed target heavy-ion experiment which includes a Micro Vertex Detector (MVD), a Silicon Tracking System (STS), a Ring Imaging Cherenkov Detector (RICH), a Muon Chamber System (MUCH), a Transition Radiation Detector (TRD), a Time-of-Flight detection system (TOF) using resistive plate chambers, a Shashlik type Electromagnetic Calorimeter (ECAL) and a Projectile Spectator Detector (PSD) [4]. The experimental strategy is to perform systematic and multi-differential measurements of all particles produced in nuclear collisions with unprecedented precision and statistics. The CBM detector will identify hadrons and leptons in nuclear collisions with up to 1000 charged particles in CBM acceptance at collision rates up to 10 MHz. The experiment will be optimized in particular for the detection of rare probes, like hadronic decays of D mesons and leptonic decays of light vector mesons, that can yield information on the dense phase of the collisions. The challenge is to accomplish in this environment high-resolution charged particle tracking, momentum measurement and secondary vertex selection with a silicon tracking (STS) and vertex detection system (MVD), the central component of the CBM detector. The system requirements include a very low material budget, radiation tolerant sensors with high spatial resolution, and a fast readout to cope with free streaming data.
2. The Silicon Tracking System

The Silicon Tracking System (STS) is the core of the CBM experiment. It is located in the field of a large aperture dipole magnet. The main task of the STS is to provide track reconstruction and momentum information of the charged particles. The multiplicity of the charged particles is up to 700 per event covering the polar angles $2.5^\circ < \Theta < 25^\circ$.

![Conceptual design of STS with ladder structure and modules](image1)

![Engineering model of STS (Green) + MVD (Orange, see section 5)](image2)

Figure 1. (a) Conceptual design of STS with ladder structure and modules. (b) Engineering model of STS (Green) + MVD (Orange, see section 5)

The STS will comprise of 8 stations in ladder structure having silicon microstrip detectors [see Fig. 1(a)]. The 8 STS stations will be located downstream from the target at a distance of 30 cm to 100 cm. The required momentum resolution is of the order of 1% and single hit spatial resolution is of the order of 25 $\mu$m. This performance requires an ultra low material budget, achieved by micro-thin cables which connect the sensors to the front-end electronics located outside the active area of the detector. The conceptual and engineering design of the stations is shown in Fig.1(a) and Fig.1(b). In total 1220 sensors of three sizes will be connected to more than 14000 read-out ASICs and about 2.1 million channels are to be read. The STS consists of total 106 ladders of 8 different types. Each Ladder consists of different modules, the STS comprises about 900 modules of 25 different types. The active volume of the STS is built employing 300 $\mu$m thick double-sided silicon microstrip sensors mounted onto lightweight carbon fiber support ladders and read over ultra-light micro thin cables. STS is designed for hit finder efficiency close to 100% and track reconstruction $\geq 95\%$ for momenta $\geq 1$ GeV/c. The double sided micro-strip sensors are 300 $\mu$m thick and radiation hard upto a fluence of $1\times10^{14}$ $n_{eq}/cm^2$ compatible to CBM physics program for SIS100/300 at FAIR.

3. Hit reconstruction in STS

Simulations have been performed that include the complete chain of physical processes caused by the charged particles traversing the detector: from charge separation in bulk silicon to digitization as an output. The first step of STS hit reconstruction is performed by the cluster finder algorithms. A cluster is a group of adjacent fired strips in a sensor with a common time stamp. A constant signal threshold is applied for every channel. The total charge of a cluster is defined as the sum of the single strip signals. The cluster position is given by the center-of-gravity method [5]. The cluster size distribution itself is presented in the Fig.2 for a threshold of 4000 electrons set in the read-out electronics. Due to inclination angles of tracks caused by the outwards bending magnetic field the cluster size increases towards the large polar angles.
Figure 2. (a) Cluster size distribution in the microstrip sensors of STS station 4 for a threshold of 4000 electrons applied in the read-out electronics. (b) Distribution of cluster sizes for the entire STS.

4. Track reconstruction

The track finding in the STS detector system which is operated in an inhomogeneous magnetic field is based on the Cellular Automaton (CA) method [6]. Subsequent track and vertex fitting makes use of the Kalman Filter (KF). At first a set of track segments (tracklets) from hits on the neighbouring stations is created using the algorithms. A set of cuts which reflects the geometrical acceptance of tracks in STS (for e.g., forward tracks with minimum 4 hits and momenta exceeding 100 MeV/c), is applied to create tracks with enough hits to be reconstructed. Then the Kalman Filter based track fitting procedure is used and a $\chi^2$ fit is calculated to combine and reject tracks accordingly. The propagation of the tracks in an inhomogeneous magnetic field is described by a complex formula [7]. An example of UrQMD generated central Au+Au collisions at 25 AGeV projectile energy reconstructed with the STS is visualized in Fig. 3. The reference primary tracks (tracks from the particle produced close to interaction point)

Figure 3. Display of reconstructed tracks from a central Au+Au collision at 25 AGeV projectile energy, shown in three different projections.
are reconstructed with efficiencies up to 96% depending on the particles momentum and the reconstruction efficiency of the secondary tracks (tracks from the decayed products) reaches up to 90% shown in Fig.4(a). The momentum resolution obtained for primary tracks is shown in Fig.4(b).

![Figure 4](image-url)  
(a) Track reconstruction efficiency and (b) momentum resolution in the STS as a function of the momentum for all tracks in central Au+Au at 25 AGeV projectile energy.

5. Particle identification

An important task of the STS is to precisely reconstruct weak decay topologies in order to measure strange and multi-strange hyperons. For this purpose, a dedicated software package (KF Particle) based on the Kalman Filter procedure was developed which reconstructs secondary vertices of track pairs or track multiplets with as high precision allowed by the high granularity of the STS. Geometrical (distance of closest approach) and topological (back-pointing of the mother track to the collision vertex) cuts allow to substantially reduce the random combinatorial background from primary tracks. The procedure can be repeated to reconstruct entire decay chains. In Fig. 5 simulated invariant-mass spectra for the decays are shown for $\Lambda\rightarrow p\pi^-$, and $\Omega^-\rightarrow \Lambda K^-$ from $1\times10^6$ fully reconstructed central Au+Au collisions events at 25 AGeV. In both cases, a clear separation of signal from combinatorial background is obtained; the experiment is even sensitive to the rare $\Omega^-$ close to its production threshold. The same measurement technique will be applied for D mesons, but is much more challenging because of their extremely low multiplicities in the order of $10^{-5}$ per collision and short decay lengths ($c\tau = 312$ $\mu$m for $D^0$ and 123 $\mu$m for $D^0$). The STS detector alone is not capable of resolving displaced vertices on this scale. For the measurement of open charm, it will thus be operated together with a dedicated Micro Vertex Detector (MVD), built from silicon pixel sensors and located between the target and the STS (see Fig. 1(b)). Tracks are first reconstructed in the STS and then extrapolated towards the MVD, where the corresponding high-precision pixel hits are associated. The combined MVD+STS system allows a reconstruction of displaced vertices with a precision of about 50 $\mu$m efficiently along the beam direction. This is sufficient to reconstruct the decays $D^0\rightarrow K^-\pi^+$ and $D^+\rightarrow K^-\pi^+\pi^+$ and their charge conjugates as shown in Fig. 6. Detailed results concerning the tracking efficiencies and the physics performance concerning the CBM physics case could be found in the STS technical design report [4].
Figure 5. Invariant mass spectra for the hyperon decays: $\Lambda \to p\pi^-$ (left) and $\Omega^- \to \Lambda K^-$ (right) central Au+Au collisions at 25 AGeV. $p, \pi^-, K^-$ were identified by the TOF detector (time resolution is assumed to be 80 ps). The simulated statistics results to $1 \times 10^6$ events at 25 AGeV.

Figure 6. Invariant-mass spectra for the decays $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$ and their charge conjugates for $10^{10}$ and $10^9$ central Au+Au collisions at 25 AGeV.

6. Conclusion
The results of the simulations indicate that the STS is capable of handling high multiplicity of tracks in the CBM collision environment. The physics performance studies yield that the STS can reconstruct rare probes with good detection efficiency. The track reconstruction algorithms are in continuous development and we expect even better results in future.

References
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