Track based alignment procedure for the CBM silicon tracking detector

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Abstract. The CBM (Compressed Baryonic Matter) experiment at FAIR is being designed for the study of the QCD phase diagram in the region of the high baryon chemical potential at relatively moderate temperatures. The Silicon Tracking System (STS) is the central detector for momentum reconstruction of the produced charged particles in the CBM experiment. It consists of 8 layers of altogether \( \sim 900 \) double sided silicon micro strip sensors. Limited mechanical precision (> 100\( \mu \)m) during the mounting, temperature differences during the experiment, influence of the applied magnetic field result in misalignment to the detector component positions. Therefore, the intrinsic spatial resolution (\( \sim 20 \mu \text{m} \)) of the detector components has to be recovered by a track based alignment method. In this conference paper, the current status of implementation of the alignment algorithm is presented. For this work, the GBL (General broken line) track refit model is employed to create the necessary input data structure to provide the input to the standalone PEDE part of the \( \chi^2 \) minimization based MILLEPEDE II alignment algorithm.

1. Introduction
The Facility for Antiproton and Ion Research (FAIR) currently under construction in Darmstadt (Germany), will offer the opportunity to study nuclear collision at extreme interaction rates. The FAIR Modularized Start Version (MSV) comprises the SIS100 ring which will provide energies for gold beam upto 11AGeV (\( \sqrt{S_{NN}} = 4.9 \text{ GeV} \)), nuclei with \( Z/A = 0.5 \) upto 15AGeV, protons upto 29 GeV.

The research program on dense QCD matter at FAIR will be performed by the experiments CBM and HADES.

The CBM is a fixed target experiment designed to run at extremely high interaction rates up to 10MHz, facilitated by fast and radiation hard detectors, fast and self-triggered read-out electronics, a high speed data acquisition system and online event selection based on full track. The CBM research program addresses fundamental aspects of QCD such as the equation-of-state of highly compressed baryonic matter, the deconfinement phase transition and its critical endpoint, chiral symmetry restoration at high baryon densities, and the in-medium properties of hadrons.

To achieve such a physics program, various types of detectors are designated to identify both hadrons and leptons and to detect rare probes in a heavy-ion environment.

STS detector is the heart of the CBM experiment to reconstruction the momentum of the produced charged particles and to identify them from their bending to the applied magnetic field (1T). So, the precise knowledge of the STS detector component co-ordinates on the different
hierarchy levels are crucial for correct momentum reconstruction. Any form of misalignment will lead to degradation of the track reconstruction quality, resulting in wrong physics analysis. In this paper, effects of misalignment on physics analysis and current state of track based alignment algorithm are discussed with examples.

2. Silicon Tracking System
The Silicon Tracking System (STS) [1] will be located inside a superconducting dipole magnet, comprising of 8 tracking stations between 30 cm and 1m downstream of the target with an individual gap of 10cm respectively (Fig. 1), covering the aperture between the polar angles $2.5^\circ < \theta < 25^\circ$. The task of the detector is to reconstruct the track of all the charged particles flying through the detector after the beam-target interactions and to determine their momenta. The double-sided microstrip sensors with a stereo angle of $\pm 7.5^\circ$ between the front and back side strips having a strip pitch of $58 \mu m$, make the building blocks of the STS, which provide a single-hit resolution of around $\sim 20 \mu m$ and required momentum resolution of $\Delta P/P < 2\%$ for the particles with momentum above 1 GeV/c.

A Sensor with a very thin micro cables (flat) at the back forms a module and the modules will be arranged on the carbon fiber supporting structure, forming ladders, and further half-stations which will be mechanically and electrically integrated into tracking stations (Fig. 2).

Using the above mentioned hierachial geometry scheme, the track reconstruction algorithms will provide the trajectory finding efficiency exceeding 90% above the momentum of 1 GeV/c.

But the alignment uncertainties of the CBM-STS detector, with such an excellent intrinsic spatial resolution, affect the performance of the track reconstruction, resulting in wrong physics analysis. The basic sources of these uncertainties are the limited mechanical mounting precision($\sim 100 \mu m$) during the assembly of the detector, deformations of the detector elements due to the temperature effects, and(or) influence of the applied magnetic field; so, during the experiment, the spatial resolution of the STS cannot be rescued just relying on the mechanical mounting or the detector geometry itsel-f. Therefore, the idea is to use one track based alignment methods (relying solely on the tracks) to determine the exact silicon sensor positions ($\sim 10 \mu m$). To achieve such a goal, one alignment algorithm is developed for the CBM experiment, combining the GBL [2] and the MILLEPEDE II [3]. But before discussing the track based alignment algorithm further, in the next section, the effects of the misalignment on the track reconstruction are discussed with some misalignment scenario examples.
3. Effects of the misalignment

3.1. Misalignment Scenarios

For this paper, three misalignment scenarios are introduced in the STS geometry on hierarchial basis (i.e., to the sensors, ladders, and then to the stations). A virtual technique is used for applying the misalignment, i.e., according to the misalignment scenarios, the transformations is applied on the STS hits at the time of track reconstruction without modifying the ideal geometry (Scenario_0).

The applied misalignment scenarios are detailed in the following table.

Table 1. Look up table for the applied misalignment scenarios.

| Element | Sensor | Ladder | Station |
|---------|--------|--------|---------|
| X       | 10 µm  | 50 µm  | 200 µm  |
| Y       | 10 µm  | 50 µm  | 200 µm  |
| α       | 50 µrad| 250 µrad| 1000 µrad|
| β       | 50 µrad| 250 µrad| 1000 µrad|
| γ       | 50 µrad| 250 µrad| 1000 µrad|

All the transformations (translations and rotations) are applied to the detector elements as per the above data table. All the above data (taken as the standard deviation of a Gaussian distribution of mean 0) are diced to make the transformations random.

Scenario_1: transformed data are applied at the local sensor level of the ideal geometry (Scenario_0).

Scenario_2: in addition to the sensor level modifications, transformed data are applied to the local ladder level.

Scenario_3: in addition to the last two scenarios, transformed data are applied to the local station level.

Important assumption: Z-value is kept constant throughout, as the projection is always taken to the X-Y plane.

3.2. Misalignment results

The investigation of the effects of the misalignment of the STS on primary track properties is done using 1000 UqQMD events under the SIS100 energy. The track reconstruction is performed in several steps; track seeding from the STS hits, trajectory building using the combinatorial cellular automaton, track fitting and smoothing using the Kalman filter. The error on the hit position in the track fit is obtained by combining the spatial resolution of the detector with the applied misalignment uncertainty.

The effects of the STS misalignment result in deterioration of the momentum resolution (Fig. 3). The standard rules for matching the reconstructed track with the MC track are realized. The effect is shown for the primary track efficiency (quality of matching of the reconstructed tracks with the MC tracks) plotted against momentum (Fig. 4). The primary vertex resolution (Fig. 5) and the reconstructed invariant lambda mass (Fig. 6) based on decay topology are also tested. The obtained results are clearly indicating the direct influence on the track and the primary vertex reconstruction and emphasize the necessity of the precise alignment of the STS detector to achieve such a high spatial resolution.
4. Track based alignment method
The alignment of a large detector in particle physics requires the determination of a large number of the alignment parameters, typically of the order of 100 to 1000, but sometimes above 10000. The alignment parameters are defined by the accurate space coordinates and orientation of the detector components. For this purpose usually the special alignment measurements are combined with the data of the particle reactions, typically the tracks from the physics interactions and from the cosmics. An efficient and fast method is an overall least square fit (to avoid any local fit biasness), with all the global (DOF of the detector components) and local parameters (track parameters), perhaps from thousands of events, determined simultaneously. The Millepede II is such a 2nd generation (subsequent to the Millepede I) algorithm that uses the special structure of the least squares matrices for a simultaneous fit.

4.1. General Broken Lines
In most of the experiments including CBM, Kalman Filter [4] track fit is used as a default track reconstruction fit as it is less computationally expensive than the standard least square fit and it facilitates an easy treatment of the multiple scattering in the form of process noise. However, the computation of the global covariance matrix in the common Kalman track fit is not complete: The correlations between track parameters at different position along the track are not calculated; although the computation of the global covariance matrix is a natural part of the least-squares estimator track fit. Consequently, the result of the common Kalman track fit cannot directly be used in a closed-form alignment (global) procedure (special treatment is needed, further look at [5]). The GBL (Fig. 7) defines a track model based on a special kind of
least-squares estimator with a proper description of the multiple scattering leading to a system of linear equations with a special structure of the corresponding matrix allowing for a fast solution with the computing time depending linearly on the number of measurements. The calculation of the full covariance matrix along the trajectory enables the application to track based alignment and calibration of any large detector with a global method using the Millepede-II later on.

4.2. Realignment results

One toy misalignment scenario is proposed to testify the newly built track based alignment algorithm for the next generation unit based STS geometry, where 8 stations are placed within 9 units and each unit is divided into two half mechanical units (misalignment hierarchy). Half unit no. 1 and 18 are kept fixed (for global referencing purposes) and others are randomly displaced using the virtual method by taking $\sigma_x = 150 \mu m$, $\sigma_y = 150 \mu m$ for the translations along the X & Y axes and $\sigma_\gamma = 2.5$ mrad for the rotation with respect to the Z-axis, using a Gaussian dist. of mean 0 and Z values are fixed like before.

For this purpose, 100000 single muon events are simulated with a fixed momentum of 2 GeV/c and without any magnetic field. Those muon tracks are then reconstructed and fitted with the help of the ideal track finder and the Kalman filter. Then the GBL track refit is applied using the Kalman track seed to construct the necessary input for the MILLEPEDE II and on the final step Pede is used to calculate the misalignment corrections (Fig. 8). The realignment results are given below:

Figure 7. GBL scheme.  
Figure 8. Flow diagram.  

![Figure 9. Residual dist. in X dir.](image)  
![Figure 10. Residual dist. in Y dir.](image)


5. Conclusion
The simple toy misalignment scenario is tackled quite well and the alignment algorithm is ready to apply for the other active hierarchies i.e. on the ladder and sensor level. But for now, one box generator is in use to produce the single muon events (even without any magnetic field, i.e. straight tracks are in use), so, the track occupancies on some of the edge ladders (so are the corresponding sensors within) are 0 and without a minimum no of inputs, no detector components can be realigned. So, the realistic interaction models (like UrQMD) and the cosmic air shower will be used to solve the present problem (work in progress).

Another important feature will be introduced i.e. the algorithm should be smart enough to decide whether it needs one single step (present implementation) or iterative steps to achieve the desired corrections for the more realistic and adaptive misalignment scenarios (work in progress).

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6. References
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Figure 11. Translational and rotational corrections on the Half unit level with the accuracy: $\Delta X < 5 \mu m$, $\Delta Y < 5 \mu m$, $\Delta \gamma < 50 \mu rad$