The Silicon Tracking System of the CBM Experiment at FAIR

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Abstract. The Compressed Baryonic Matter (CBM) experiment at the future Facility for Antiproton and Ion Research (FAIR) aims to study the properties of nuclear matter at high net-baryon densities and moderate temperatures.

The Silicon Tracking System (STS) is the key detector to reconstruct with a high efficiency up to 1000 charged particle trajectories created in heavy-ion collisions at interaction rates of up to 10 MHz. It will determine the momentum of the particles with a momentum resolution $\Delta p/p \approx 1-2\%$ which requires ultra-low detector material budget of 0.3-1% $X_0$ per layer. The detector comprise eight layers of double-sided silicon micro-strip sensors and will be placed inside the 1 Tm superconducting magnet which limits the space available, which in turn requires advanced cooling approaches and mechanical design with precise tracking layers alignment. The micro-strip sensors have to be radiation hard and checked for their quality optically and electrically before the assembly.

This contribution gives an overview of the STS and presents the status of its component quality control and assembly procedures.

1. CBM experiment at FAIR
The Facility for Antiproton and Ion Research will expand the well established infrastructure of the GSI heavy-ion research center. It will provide the unique research opportunities in the fields of nuclear, hadron, atomic and plasma physics.

The CBM experiment [1] aims to perform both integral and differential systematic measurements of bulk as well as rare particles produced in nuclear collisions with unprecedented precision and statistics. The collisions of nucleus-nucleus and proton-nucleus systems, with a reference measurements from proton-proton collision, at unique interaction rates of $10^7$ and $10^9$ interactions per second will be conducted at different beam energies (c.f. Fig. 1, left panel). These interaction rates open access to the rare probe measurements, such as multi-strange hyperons, hypernuclei, particles with charm quarks and vector mesons decaying into lepton pairs (c.f. Fig. 1, right panel). The CBM experiment will run in a self-triggered, so called free streaming, data taking mode without hierarchical hardware trigger system.

2. Silicon Tracking System
The Silicon Tracking System (STS) is the core detector of the CBM. It is located in the dipole magnet and provides track reconstruction and momentum determination of charged particles from beam-target interactions [2]. The detection of rare probes requires the STS to be capable...
Figure 1. A comparison of interaction rates and center of mass collision energies of high energy physics experiments (left panel). Particle yields depending on the collision energy for central Au+Au and Pb+Pb collisions (right panel).

measuring Au+Au collisions at interaction rates up to 10 MHz. The track multiplicities reach up to 700 per central Au+Au collision in the aperture of $2.5^\circ < \theta < 25^\circ$.

The STS comprise 8 tracking layers from 30 to 100 cm downstream the target. It occupies a volume of about 2 m$^3$ with the thermal enclosure. The sensors will be kept at temperatures below -5 C$^\circ$ in a dry nitrogen atmosphere to prevent thermal runaway and condensation. The STS will be placed inside 1 Tm superconducting dipole magnet. A schematic view of the STS detector without thermal enclosure and services is shown in Fig. 2 (left panel).

Figure 2. View of the STS detector without thermal enclosure and services (left panel), an arrangement of sensors forming half of a detection layer (middle panel) and the sensor modules on the carbon ladders with front-end electronic boxes on the top and bottom ends of the ladder.

The basic building block of the STS is a module, which consists of a double-sided silicon micro-strip sensor and a bundle of ultra-light multi-layer micro-cables which connect the sensor to the front-end electronics (FEE). The micro-cables have a length of up to 50 cm, which is needed to mount the FEE outside of the detector’s acceptance. Altogether, about 900 modules, mounted onto the carbon fiber ladders, are arranged to form eight tracking layers.

2.1. Silicon micro-strip sensors
STS employs state of the art double-sided micro-strip silicon sensors based on the p$^+$-n-n$^+$ technology. The silicon sensors have a thickness of about 300 µm, 20 µm strip size and 58 µm
strip pitch. Depending on the sensor position, different-sized sensors will be used. The sensor sizes are $22 \times 62 \, \text{mm}^2$, $42 \times 62 \, \text{mm}^2$, $62 \times 62 \, \text{mm}^2$ and $124 \times 62 \, \text{mm}^2$ with 1024 strips each. Additionally the smaller sensors with fewer strips, so-called “baby” sensors, will be used to cover gaps close to the beam pipe. The sensors provide the spatial resolution of about 25 $\mu$m.

The strips are parallel to the edges on the n-side and inclined by 7.5$^\circ$ on the p-side. This allows to have both read-out planes oriented in the same direction unlike to the designs where the strips are perpendicular. The p-side corner strips are interconnected with the second metal layer lines. The implant strips are read out by the AC coupled aluminum read-out strips.

Figure 3. A photograph of prototype silicon sensors. Four major sensor sizes are shown.

The sensors are produced by two manufacturers: CiS Forschungsinstitut für Mikrosensorik GmbH located in Erfurt, Germany and Hamamatsu Photonics K.K. located in Hamamatsu, Japan. After the procurement, the sensors are checked for their quality optically and electrically.

The optical inspection is done in highly automated fashion employing a custom-built setup (c.f. Fig. 5, left panel) with motorized linear stages, zoom and focus. It allows to check for visible defects such as surface scratches, read-out strips and other electrical elements integrity [3]. This is done by performing a scan over the sensor’s surface and collecting the microscopic photographs of the regions of interest. For a typical $62 \times 62 \, \text{mm}^2$ sensor 910 images are collected per side. The images are processed online and stored on disk for offline analysis. The analysis chain is based on machine vision algorithms (MVA) such as geometrical and color transformations, filtering, pattern and texture matching, as well as advanced morphology. Having enhanced certain features in the microscopic image of a sensor by applying a combination of the above algorithms, the size and shape parameters of the defects found can be determined.

The methods based on MVAs provide a powerful set of defect detection algorithms. However, they are configuration dependent, i.e. provide insufficient result if not properly adjusted. For advanced defect analysis, the neural network techniques are applied. They allow to automatically detect the defect presence, its location and classify it [4].

Figure 4. Different object classes located and classified with neural networks: dust grain, scratch, AC and DC pads and bias resistors.
Additionally, metrology procedures can be performed to qualify the sensor cutting edge and parallelism, its warp and thickness. These metrics are important for the ladder assembly procedures.

**Figure 5.** Optical (left panel) and electrical (right panel) quality assurance setups for the CBM silicon micro-strip sensors in the University of Tübingen.

The electrical characterization of the silicon sensor is an essential step to qualify the sensor performance. All sensors received during the preproduction stage have to be tested at the quality assurance centers. During the production stage a fraction of up to 10% of the sensors chosen randomly and those identified as faulty by an optical inspection have to be checked. Additionally 1% of the sensors, which corresponds to a single sensor from the batch, have to be tested in depth to verify the manufacturer data.

The basic tests are performed on all received sensors allowing to estimate the sensor quality. These tests include measurement of current-voltage (I-V) and capacitance-voltage (C-V) characteristics of a sensor. From these measurements the full depletion voltage and breakdown voltage of the sensor can be extracted. Fig. 6 shows the I-V and C-V characteristics of the prototype sensors.

**Figure 6.** The I-V (left panel) and C-V (right panel) characteristics of the prototype sensors measured during the electrical characterization at the University of Tübingen [5].

During the subset tests (up to 10% of all sensor) the per-strip electrical measurements are conducted including the sensor’s strip integrity and uniformity of the electrical properties. In this inspection the sensor is checked for the pinholes\(^1\), measurements of the strip leakage currents and the coupling capacitances are performed.

\(^1\) A short in the coupling capacitor between implant strip and read-out strip
The in-depth tests are performed on a smaller fraction of the sensors allow to characterize their more complex properties. These tests include the measurement of the interstrip capacitance, total strip capacitance, polysilicon resistance and coupling capacitor breakdown.

2.2. Module assembly
A sensor module consists of a double-sided silicon micro-strip sensor connected with a bundle of micro-cables to a read-out chips on the FEE board from each side. The read-out chips are custom developed in AGH Krakow and have 128 read-out channels which amplify the input analog signal and convert it to a digital with a 5-bit ADC (c.f. Fig. 7).

Figure 7. A prototype module (without cables shielded) with a sensor connected to the FEE with micro cables (left panel). STS-XYTER read-out chip (right panel).

The module assembly is a complex multi-step procedure and involves a set of custom developed jigs and fixtures which allow to handle the components. To equip a full module, 16 micro-cables and read-out chips are required. The micro-cables are TAB-bonded to the sensor and the chip from both ends. The chips are then die- and wire-bonded to the FEE board and covered with a glob top for protection. After equipping the module with all cables, they are shielded from both sides with layers of aluminum, polyimide and foamed polystyrol.

2.3. Ladder assembly
The ladder assembly requires high-precision jigs and fixtures for the best sensor mounting and positioning accuracy. The carbon fiber frame is fixed in the jig, then the so called L-legs are glued to them. The L-legs are made of fiberglass and carry the sensors above the ladder. After gluing the L-Legs to the ladder, a sensor module is grabbed by the sensor holder tool and sucked to it by applying an under-pressure. The sensor module with the holder structure is then laid over the L-Legs, pushed against the ladder tool edge to align it, and glued to the L-Legs. The module front end boards are then mounted to the FEE board holding and cooling box. The carbon fiber ladder is populated with sensor modules and cooling boxes are attached to the fixtures.

Figure 8. A prototype ladder with 5 sensor modules (left panel) and reconstructed sensor positions (right panel).

Figure 8 shows a prototype ladder equipped with 5 sensor modules. The modules are staggered in the Z-direction and the cable bundles are located below the next overlapping sensor.
The machine vision and 3D contactless metrology algorithms described in [3, 6] are applied to reconstruct the 3D positioning of the sensor on the ladder and assure the positioning precision.

3. Status and Summary
The silicon micro-strip sensor development was concluded and first shipments of sensors are expected from mid-2019. The quality assurance centers have developed highly involved quality assurance procedures and methods and ready to receive the sensors.

The module and ladder assembly equipment and procedures were developed and established. They were tried out on prototype components and the system integration concepts were elaborated. The prototype detector (mSTS, c.f. 9) with limited amount of modules was assembled and its performance is currently under investigation in the mCBM demonstrator experiment at SIS18 facility in GSI, Darmstadt. The pilot version of the demonstrator with one sensor ladder equipped has launched in December 2018. Its configuration will extend gradually in the year 2019 to its final version with 2 detection layers equipped with 3 ladders each. The demonstrator project is as well of extreme importance to try out the read-out of the modules, data collection and transport to the computing nodes.

Figure 9. A conceptual view of the mSTS detector of the mCBM@SIS18 demonstrator experiment.

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References
[1] Senger P, Friman B, Höhne C, Knoll J, Leupold S, Randrup J and Rapp R 2011 The CBM Physics Book, Compressed Baryonic Matter in Laboratory Experiments (Verlag Berlin Heidelberg: Springer)
[2] Heuser J, Müller W, Pugatch V, Senger P, Schmidt C J, Sturm C and Frankenfeld U 2013 Technical Design Report for the CBM Silicon Tracking System (STS) Preprint GSI-2013-05499
[3] Lavrik E 2017 Development of quality assurance procedures and methods for the CBM Silicon Tracking System PhD Thesis http://dx.doi.org/10.15496/publikation-20433
[4] Lavrik E, Panasenko I and Schmidt H R 2018 Accepted for publication in Nucl. Inst. Meth. A. Preprint 1807.00211
[5] Panasenko I, Lavrik E, Lymanets A and Schmidt H R 2016 J. Phys.: Conf. Ser. 742 012037
[6] Lavrik E, Panasenko I, Schmidt H R, Mehta S and Frankenfeld U 2018 Preprint 1812.00917