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The silicon detector systems of the Compressed Baryonic Matter experiment

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The Compressed Baryonic Matter (CBM) experiment [1] is a fixed-target heavy-ion experiment that will operate at the international Facility for Antiproton and Ion Research (FAIR) [2] now under construction in Darmstadt, Germany. The experiment intends to study rare probes, which are emitted from heavy ion collisions with a beam energy of 4 to 45 AGeV. A focus is laid to the short lived open charm particles and to particles decaying into di-lepton pairs.
Handling the up to 10^7 Au+Au collisions/s required for generating those probes with sufficient statistics, as much as reaching the required sensitivity for observing them, forms a major challenge for the silicon detectors of the experiment. We present the concept and the development status of two central detectors of CBM, the CMOS pixel based micro vertex detector (MVD) and the micro-strip detector based silicon tracking system (STS).

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1. Introduction

The CBM experiment [1] is one of the core experiments of the future FAIR facility [2], which is currently being constructed at GSI Darmstadt. The fixed target experiment aims at exploring the phase diagram of hadronic matter in the region of highest net-baryon densities. To study its properties, this hot and dense hadronic matter is generated by means of heavy ion collisions with beam energies of up to 12 AGeV (provided by the future SIS-100 synchrotron) and up to 45 AGeV (provided by the future SIS-300 synchrotron). The collisions generate so-called hadronic fireballs, complex multi-body systems of particles, which are, among others, predicted to undergo phase transitions. Due to its short life time and small size, the fireball itself is not accessible for experimental methods and its complex properties have to be derived from its decay products. Insufficient knowledge on those end-states let room for a number of hypotheses, which differ substantially in the their assumptions on the properties of the fireball but show, within the uncertainties of existing data, similar end states.

CBM aims to enhance the understanding of the physics processes occurring in the fireball by excluding most of the hypotheses available today. To do so, the experiment will gain a wide number of additional physics constraints from measuring numerous particles, which are out of reach of other past and present experiments covering the FAIR energy range, and the hypotheses will be tested against this novel knowledge.

CBM is designed as a dedicated multi purpose detector, which includes in one setup a di-electron and a hadron spectrometer and in a second, slightly modified setup, a di-muon spectrometer. The technological requirements on CBM are derived from the wish to detect the rare open and hidden charm particles as well as rare light vector mesons decaying into di-leptons. In its hadron- and di-electron setup shown in Figure 1, CBM comprises a Micro Vertex Detector (MVD) and a Silicon Tracking System (STS), which are located in a 1 Tm magnetic field. A Ring Imaging CHerenkov detector (RICH) and a Transition Radiation Detector serve for the identification of slow and fast electrons respectively. Hadrons are identified by a time-of-flight system, which will likely base on a diamond start counter and a resistive plate chamber (RPC). The setup is completed by an electro-magnetic calorimeter and a Projectile Spectator Detector (PSD), which allows a determination of the collision plane. In the di-muon configuration, the RICH detector is moved out and replaced by an instrumented muon absorber.

The primary mission of the MVD of CBM is to reconstruct open charm particles by means of identifying their secondary decay vertices. Due to the small Lorentz boost and the short lifetimes of those particles ($c\tau \sim 100$ μm), a secondary vertex resolution of 50 μm along the beam axis is required. The STS is to measure the particles' momenta with a resolution of $\delta p/p \approx 1\%$.

CBM aims to freeze most of the technical specifications of the MVD and the STS in 2015 so that the mass production of components can be achieved until 2017. The both detectors shall be assembled by 2018 for subsequent commissioning in the CBM experiment.

2. Experimental conditions

In a fixed-target heavy-ion collision for the CBM physics program, e.g. gold ions impinging with projectile energies of 25 GeV per nucleon on a stationary gold foil of a few hundred micrometer thickness, typically up to 1000 charged particles are produced. Most of them enter the aperture of CBM, which ranges between polar angles of 2.5° to 25° and covers the forward hemisphere in the laboratory frame, i.e. from center-of-mass rapidity close to beam rapidity.

The trajectories and the momenta of the charged particles are reconstructed with the STS. This detector consists of 8 equi-distant layers, which employ double sided silicon strip sensors, and are installed between 30 and 100 cm downstream of the target. Once the tracks are found, they are extrapolated towards the MVD, which extends between 5 - 20 cm downstream the target.

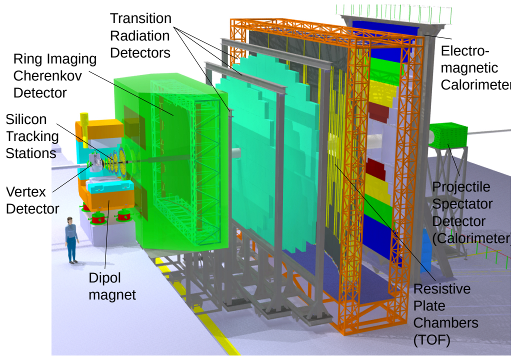

Figure 1: The CBM experiment in the hadron- and di-electron configuration.

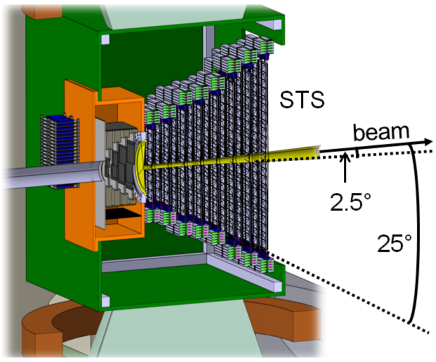

Figure 2: Engineering study of the MVD and the STS installed in the dipole magnet of CBM.

During heavy ion runs, the silicon detectors are exposed to a high amount of δ - electrons, which are knocked out of the target by the primary beam. Despite many electrons are deflected out of the detector acceptance by the magnetic field, they dominate the occupancy of the MVD. This load limits the maximum collision rate compatible with using the MVD to $\sim 10^5$ Au-Au collisions/s. Moreover, the δ-electrons generate a relatively high ionizing radiation dose (~ 3 Mrad/year for the MVD). Besides this dose, the MVD has to stand 10^{13} n_{eq}/cm^2 per year[1]. In case the proton beam is used, only few δ-electrons are emitted and the rate capability allows to measure the primary hadrons from $\sim 10^7$ p-A collisions per second. As the rate capability of the detector is now exploited by hadrons instead of light electrons, the expected non-ionizing radiation dose increases by a small factor as compared to the A-A scenario.

The STS is substantially less exposed to radiation and δ-electrons but unlike the MVD[2], it has to handle the full CBM collision rate of up to 10^7 Au+Au collisions/s. Depending on the detailed physics program, it has therefore to tolerate 10^{14} n_{eq}/cm^2 per year. Both, the STS and the MVD will be explicitly designed to allow for an easy access and repair. We foresee a regular, typically yearly, replacement of the few most irradiated sensors of the MVD.

[1]Assuming $5 \cdot 10^6$s (~ 2 months) beam on target per year, 10^5 Au-Au collisions/s, no explicit security margin.

[2]So far, one cannot compromise the excellent vertex resolution needed for open charm reconstruction with the 10 MHz Au+Au collision rate foreseen for CBM. Until this is solved by means of technological upgrades, we intend to move out the MVD whenever no vertex information but highest beam intensities are required.

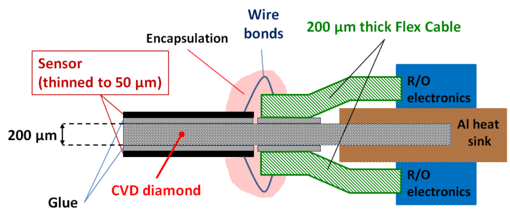

Figure 3: Simplified cross section of a MVD station and the MVD prototype. In the final MVD, the sensors will be staggered (not shown).

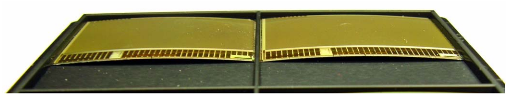

Figure 4: Thinned MIMOSA-26AHR sensors.

3. The Micro Vertex Detector of CBM

3.1 Detector concept

The MVD [3] is composed of four equi-distant silicon pixel layers located 5-20 cm from the target. The envisaged secondary vertex resolution of ~ 50 µm along the beam axis requires a material budget of $\lesssim 0.3$ X_0 and a spatial resolution of $\lesssim 5$ µm in the first station. As a vacuum window would spoil the vertex resolution, the MVD is located in the target vacuum (see Figure 2).

The fixed target geometry of CBM allows to move a maximum of material and functionality out of the geometrical acceptance of the experiment. Along this line, the sensors will be mounted on highly heat conductive carbon materials. Those supports will also transport the up to ~ 1 W/cm^2 of dissipated power of the sensors to liquid cooled heat sinks installed outside the detector acceptance. For the first two detector stations, the support will be made from a $\sim 150-200$ µm thin layer of stiff and highly heat conductive CVD diamond. The more downstream stations will most likely be made from thermal pyrolytic graphite (TPG), which is wrapped in a thin layer of carbon fiber. The poor mechanical properties of this cheaper solution call for a higher thickness of the support, which is required in any case to obtain the cooling power needed for cooling the more sizable stations.

The MVD will be equipped with the ultra light and granular CMOS Monolithic Active Pixel Sensors (MAPS) provided by the PICSEL group of the IPHC Strasbourg [4]. MAPS are subdivided into an active pixel matrix and a passive area hosting analog and digital control and data sparsification circuits. To obtain a detector with a close to 100% fill factor, we will install two layers of sensors per station and the active surface of one layer will cover the passive surface of the opposite one.

The sensors will most likely be read out by means of thin flex print cables. To reduce the material budget of the particularly thin first detector stations, we are studying the option of putting the necessary metal traces directly on the CVD-diamond. This might be done by means of metal deposition and lithographic edging. The task is eased by the fact that the small number of sensors forming the first station may be controlled via one single metal layer.

3.2 Status of the sensor R&D

MAPS were chosen as a sensor technology because they show decisive advantages in terms of good spatial resolution, ultra-light material budget and low power consumption. The R&D on adapting the radiation tolerance and time resolution of the sensors to the needs of CBM is performed in synergy with the STAR-HFT [5] and the ALICE-ITS [6].

The sensors for the CBM-MVD will follow the concept of MIMOSA-26AHR [7]. This sensor hosts an active pixel matrix of ~ 2 cm^2, which is composed of 1152 columns with 576 pixels each. The matrix is read out with a column parallel rolling shutter within 115.5 µs. Zero suppression is done on the chip and the digital data obtained is shipped out via two 80 Mbps links. Slow control is performed by means of a JTAG interface. The pixel pitch of 18.4 µm $\times$ 18.4 µm allows for a spatial resolution of 3.5 µm and the sensor is routinely thinned to 50 µm. A satisfactory tolerance to bulk damage ($\gtrsim 10^{13}$ n_{eq}/cm^2) was reached[3].

The read-out speed and and the tolerance of MIMOSA-26AHR to ionizing radiation do not yet match the requirements of CBM. Therefore, the architecture is being migrated from the previously used 0.35 µm CMOS process to an intrinsically more radiation tolerant 0.18 µm process. First prototypes manufactured in this process tolerated up to ~ 10 Mrad [8]. This fits our needs but remains to be reproduced with sensors hosting the full analog and digital read-out chain.

Independently of the feature size of the process, the read-out speed of the sensors is limited by the high capacity of the read-out buses of the columns. To bypass the limited readout frequency of the buses, the PICSEL group enlarged the pixel size to 33×22 µm^2. This accelerates the readout by reducing the number of pixels per column and the the spatial resolution of the sensors remains at an acceptable value of ~ 5 µm. Moreover, the higher packing density of the 0.18 µm process is exploited by adding one parallel read-out bus and one parallel discriminator block to each column. Both measures reduce the read-out time to ~ 30 µs. An alternative approach exploits the novel option to use full CMOS on the pixels manufactured with the 0.18 µm process. This allows for discriminating the analog signals already on the pixel and to send digital data through the readout buses. This reduces the energy consumption of the sensor and accelerates the readout to ~ 10 µs.

Both technological options would satisfy the needs of CBM. Test results from first prototypes suggest that using two discriminators per column is possible without adding a relevant amount of read-out noise. The in-pixel discriminators do still exhibit a slightly too high noise of 29e. The origin of this noise is understood and will be eliminated in a next generation of prototype, which is expected for middle 2014 [9].

3.3 The MVD prototype

To validate our detector concept, we designed a detector prototype [10] based on MIMOSA-26AHR. This sensor is considered as a representative precursor of the final sensor in terms of engineering aspects like the mechanical properties, the electronic interface and the power dissipation. After thinning the sensor to 50 µm, it is flexible and, due to inner stress, slightly bended. To handle the sensors, we developed customized positioning tools and vacuum holders, which allowed us to glue two sensors to each side of a 200 µm thick CVD-diamond (see Figure 5). The Flex Print Cables (FPC) used for steering and the read-out of the sensors were also glued to the holder. Hereafter, they were connected by means of wire bonding. Over all, 18 thinned MIMOSA-

[3] The sensor irradiated to 10^{13} n_{eq}/cm^2 showed a dark occupancy of few 10^{-5} and a detection efficiency of $\sim 99.8\%$ for 120 GeV/c pions [7]. There are strong arguments for a higher radiation tolerance, but no explicit beam tests were carried out as the requirements were met. The latter do not include explicit security margins but they are derived from the doses expected for the the most irradiated sensor, which is easy accessible and covers an explicit hot spot. In case of an unexpected burn out, it may be exchanged previous to the scheduled, yearly replacement of the most irradiated sensors.

Figure 5: A single sided core module of the prototype comprising two sensors and an FPC glued on a CVD diamond.

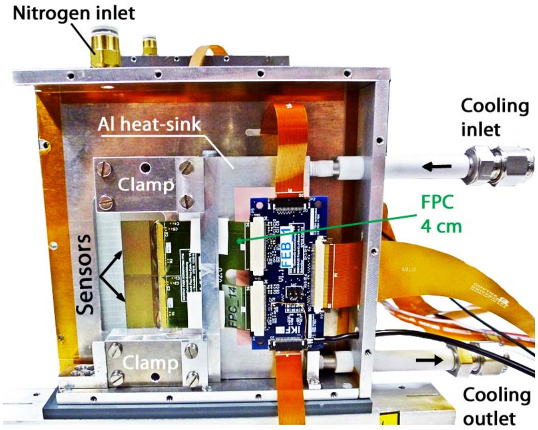

Figure 6: Photo of the MVD prototype as tested as the SPS pion beam.

26AHR sensors were integrated on different supports. They were inspected visually prior to the integration but tested electrically only after bonding. According to the electrical tests, 16 sensors were found operational, one sensor showed 25% broken pixels and one sensor failed fully. Those losses are compatible with the known production yield of the sensors and the integration procedure is considered as reliable.

After assembly, the prototype module was connected with a liquid cooled heat sink (see Figure 6). The performance of the cooling system was tested (so far in air, which increases the heat load) by means of an infrared camera and fixed temperature sensors. We observed a temperature gradient of < 1 °C on the diamond support, which matches our needs. The heat transfer between the diamond support and the cooling fluid was not yet optimized and a temperature gradient of 9 ± 1 °C was observed once the sensors were turned on.

The read-out of the sensors was done by means of a free running DAQ system based on the TRBv2 [12] standard. The compressed data, which is pushed out of the sensors, was received and checked for errors. Idle bits were removed and the data trains were encoded according to the TRB standard and sent to a standard PC. The implemented bandwidth (100 MB/s) of the parallel read-out topology can be scaled up by adding hardware.

The prototype was complemented with a beam telescope made from four reference stations based on the same technology. It was tested in the CERN-SPS. The system operated stably and reliably even once the sensors were exposed to the highest particle flux (~ 350 kHz/cm^2) compatible with the radiation safety protocols of the beam line. After an intentionally overload was forced by reducing the threshold of some sensors, the DAQ introduced controlled dead times by rejecting all data from certain time periods and the remaining data of all sensors could be used for tracking. According to our preliminary data analysis, a spatial resolution of 3.5 µm and detection efficiency of $> 99\%$ at a dark rate below 10^{-5} was observed. This matches the requirements of CBM and is considered as compatible with earlier performance measurements [7, 11] of the sensors.

4. The Silicon Tracking System

The STS of CBM is formed from eight equi-distant detector stations, which are made from double sided silicon strip detectors and located $30-100$ cm from the target in the ~ 1 T field of the CBM dipole magnet. The layers should combine a spatial resolution of ~ 25 µm, a close to 100% single hit efficiency and a low noise rate. As described in more detail in the related Technical Design Report [13], the STS is to provide an tracking efficiency of $> 95\%$ for charged particles with $p > 1$ GeV/c and measure their momenta with a precision of $\delta p/p \approx 1\%$. The momentum resolution is dominated by multiple scattering, which calls for minimizing the material budget of the individual stations to $\sim 1\%$ X_0 in the active area. To match this goal, most infrastructure including the front-end read-out electronics are moved out of this area and the strips are connected to the read-out chips by means of ultra thin cables.

At the full collision rate of 10 MHz Au+Au collisions, we expect charged particle rates of ~ 10 MHz/cm^2 in the innermost regions of the STS. They fall off by two orders of magnitude in the outer regions of the detector. In order to avoid pile-up, fast self-triggering front-end electronics with a shaping time of the order of 20 ns will be used.

Depending on the precise running scenario and the beam energy, the STS will accumulate between 10^{12} n_{eq}/cm^2 and 10^{14} n_{eq}/cm^2 per year in its innermost regions. As for the MVD, the most exposed elements may be replaced once their radiation tolerance limit is reached. Over all, the STS breaks down into 8 tracking stations, 106 detector ladders, 896 modules, 1272 sensors in three strip lengths, about 1.9 million read-out channels, almost 15 thousand read-out chips. The active area is about 4 m^2, the STS volume about 2 m^3. The power dissipation of the read-out electronics is expected to be up to 40 kW.

The development effort of the STS addresses technical solutions for the sensors, the read-out electronics, the construction of modules and ladders as building blocks of the tracking stations, and the system integration into the gap of the CBM dipole magnet.

4.1 Silicon microstrip sensors

Double-sided silicon microstrip sensors have been chosen as an adequate solution for the tracking stations of the STS. In standard p-in-n material of about 300 µm thickness, space point reconstruction can be achieved with the required material budget, including the signal-routing cables to the read-out electronics. The layout of the sensors has been developed in several prototypes produced with CiS, Erfurt, Germany, and Hamamatsu Photonics, Japan. A read-out strip pitch of 58 μm has been chosen matching the requirement on spatial resolution. The strips on either sides are oriented forming a stereo angle of 7.5°, which results from balancing the spatial resolution in the bending direction in the dipole field, and the combinatorial points due to the projective geometry. Different strip lengths (2, 4 and 6 cm) were chosen for different regions of the STS to keep maximum strip occupancies at the level of a few percent. The sensors are 6.2 cm wide and carry 1024 strips per side which are read out through coupling capacitors integrated in the sensors. The large sensors can be daisy-chained to form 12 cm long strips that will be deployed in the outer regions of the stations where hit occupancies are lowest. The sensors are to be read out from one edge, a requirement from the module design that keeps the electronics outside the physics aperture, see Fig. 7. This design made the integration of double-metal interconnections of the corner strips

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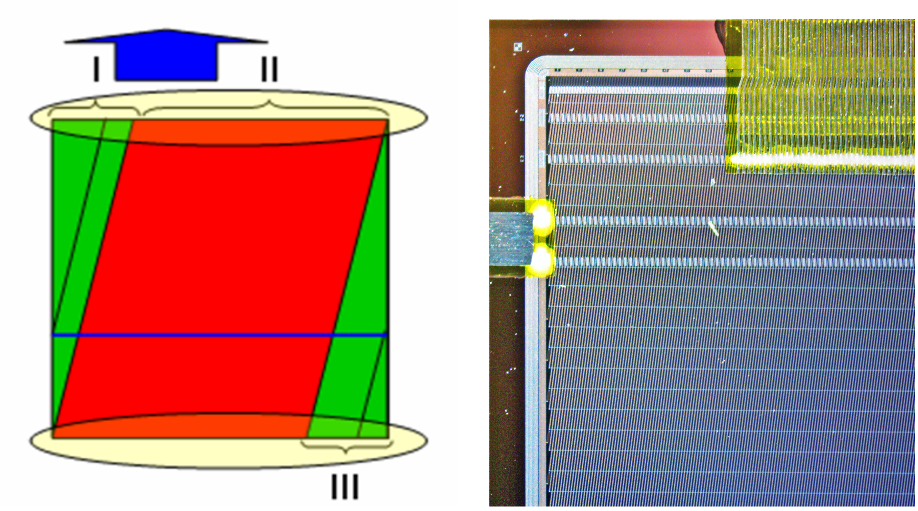

Figure 7: Concept of the CBM microstrip sensors, suitable for read-out of a single or two daisy-chained sensors from one edge towards the periphery of the STS. The photograph shows a recent prototype with read-out lines tab-bonded to it.

on the stereo side necessary (denoted as I and III in the figure). As an alternative, the deployment of a separate thin cable bonded across the sensor is under test. The sensors will be operated up to neutron equivalent fluences of 10^{14} n_{eq}/cm^2, at bias voltages of up to several hundred volts and a temperature of around -5° C to limit leakage currents induced by radiation damage.

4.2 Read-out electronics

The silicon sensors will be read out with custom designed front-end electronics. Its capabilities include a self-triggering data transport, i.e. the auto-detection of charge above signal per channel and forwarding of the digitized information with a time stamp to data aggregation and event building outside of the detector. This enables the STS, and the entire CBM experiment, to operate with the non-bunched high-intensity beam from the FAIR synchrotrons SIS100/SIS300. Early prototyping of several CBM sub-systems has been done with the n-XYTER chip [14]. The development for the STS read-out, called STS-XYTER [15], picks up on its concept but takes into account the specific needs of the STS, including faster shaping time, robustness against noise at high capacitive and resistive load per channel, increased radiation hardness, and reduced power consumption. The first prototype has been available since early 2013. The chip provides 128 channels. The input from the detector is processed by a charge-sensitive amplifier. The signal path is then split into a fast and a slow. The fast path includes a fast shaper with a typical shaping time of 30 ns, a discriminator and a timestamp latch. It is optimized to provide good timing resolution (< 10 ns). The slow path consists of a slow shaper with a typical shaping time of 80 ns, a 5-bit flash ADC and a digital peak-detecting logic. It is optimized for energy measurement and noise performance. For a particle hit, each channel provides the timestamp and the ADC value corresponding to the deposited charge. Data from the channels are read out using a token-ring structure, controlled by a read-out controller. The gathered data are sent out via up to four 500 Mbit/s LVDS serial data links. The essential new feature compared to the n-XYTER architecture is an effective two-level discriminator scheme. It adds a veto to the transmission of data in case the flash ADC has generated “zero”. The intended power dissipation of less than 10 mW per channel was confirmed

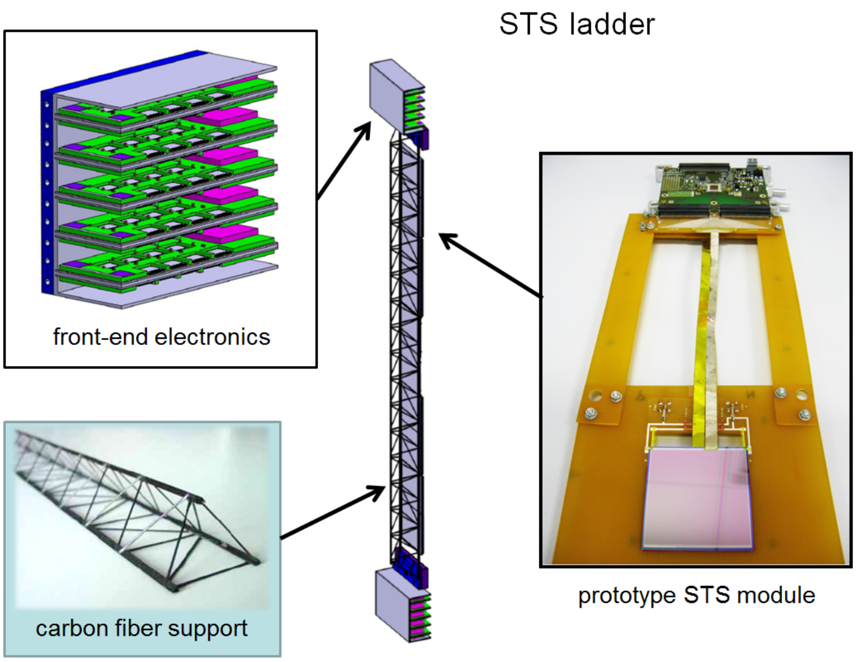

Figure 8: Concept of the STS ladder with a carbon fiber structure supporting two times 5 modules, the functional units of microstrip sensors, read-out cables and front-end electronics.

with the first prototype specimen. The layout of the STS-XYTER chip is specifically matched to be integrated onto a high-density front-end board, carrying 8 of them for the read-out of the STS sensors.

4.3 Modules and ladders

The composition of the STS stations from more basic units is shown in Fig. 8. Sensors and read-out electronics are combined into modules. The 1024 channels per sensor side are connected to one read-out board by means of two staggered layers of fine-pitch 14 µm thin aluminum lines on a polyimide carrier. Suitable spacers and shield layers are included. The cables are up to ca. 50 cm long, depending on the location of the sensor in the station and the necessary bridge towards the electronics at the station's perimeter. The interconnection of the cable to both sensor and read-out chips is realized through tab-bonding. First prototype modules, with a sub-set of the channels connected due to the n-XYTER based read-out boards used, have been assembled and operated in the laboratory and in a high-energy proton beam. It was shown that the signal transmission from the sensors to the read-out electronics matched the expectation of attenuation and noise. In December 2013, also first prototype modules with daisy-chained sensors were successfully operated in beam. The modules are mounted onto a carbon fiber support to form ladders as mechanical units of the stations. Two times five modules build up a ladder which can be used to construct tracking stations. The current engineering focus is directed towards establishing the handling procedures for module assembly, and to assess the yield issues with the cable and module production[4].

[4]This work is carried out in cooperation with LTU (formerly with SE SRTIIE), Kharkov, Ukraine.

4.4 System integration

The effort on the integration of the STS detector system and its installation into the magnet focusses on finding solutions for suitable mechanical and thermal stability, connectivity of services, and maintenance. The large aperture of the CBM superconducting dipole magnet allows placing connectors also at the lateral walls of the thermal enclosure. The volume is shared with space for the MVD, and is intersected by the vacuum beam pipe. For the removal of the power dissipated by the STS front-end electronics, totaling to about 40 kW, a cooling system based on bi-phase carbon dioxide is being explored.

5. Summary and conclusion

The CBM experiment aims to measure rare probes, which are produced in heavy ion collisions. To do so, the silicon detectors of CBM have to provide simultaneously a high sensitivity and rate capability: The Micro Vertex Detector (MVD) will provide a secondary vertex resolution of $\sim$ 50 μm along the beam axis and operate at rates of up to 10^5 Au+Au collisions/s. It is based on CMOS Monolithic Active Pixel Sensors, which are operating in vacuum. Their heat and data is evacuated by means of a highly heat conductive, carbon based support and flex print cables respectively. The Silicon Tracking System will do track reconstruction at collision rates of up to 10^7 Au+Au collisions/s and measure particle momenta with a resolution of $\delta p/p \approx 1\%$. The signal of its double-sided silicon strip detectors are moved to a front-end electronics located outside the CBM acceptance by means of ultra-thin cables. Prototypes of both detector systems have been built and the feasibility of the technological concepts were demonstrated by means of in-beam measurements.

Acknowledgements

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