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# THE SILICON TRACKING SYSTEM OF THE CBM EXPERIMENT AT FAIR

*The Compressed Baryonic Matter (CBM) experiment at FAIR (Darmstadt, Germany) is designed to study the dense nuclear matter in a fixed target configuration with heavy ion beams up to kinetic energies of 11 AGeV for $Au + Au$ collision. The charged particle tracking with below 2% momentum resolution will be performed by the Silicon Tracking System (STS) located in the aperture of a dipole magnet. The detector will be able to reconstruct secondary decay vertices of rare probes, e.g., multistrange hyperons, with 50 μm spatial resolution in the heavy-ion collision environment with up to 1000 charged particle per inelastic interaction at the 10 MHz collision rate. This task requires a highly granular fast detector with radiation tolerance enough to withstand a particle fluence of up to $10^{14}$ $n_{\rm eq}/cm^2$ 1-MeV equivalent accumulated over several years of operation. The system comprises 8 tracking stations based on double-sided silicon microstrip sensors with 58 μm pitch and strips oriented at 7.5° stereo angle. The analog signals are read out via stacked microcables (up to 50 cm long) by the front-end electronics based on the STS-XYTER ASIC with self-triggering architecture. Detector modules with this structure will have a material budget between 0.3% and 1.5% radiation length increasing towards the periphery. First detector modules and ladders built from pre-final components have been operated in the demonstrator experiment mCBM at GSI-SIS18 (FAIR Phase-0) providing a test stand for the performance evaluation and system integration. The results of mSTS detector commissioning and the performance in the beam will be presented.*

*Keywords*: low-mass tracking system, double-sided silicon microstrip sensors, self-triggering readout.

## 1. Introduction

A number of research centers worldwide carry out or prepare research programs to shed light on the fundamental questions of the QCD physics, e.g., the origin of the mass of hadrons, structure of neutron stars, or evolution of the early Universe. They can be addressed in high-energy collisions of heavy nuclei in which a fireball of hot and dense nuclear matter is formed prior to the hadronization. The measurement of heavy-ion collision products thus gives an experimental access to the deconfined system of quarks and gluons in a wide range of temperatures and baryon densities. The Compressed Baryonic Matter (CBM) experiment [1] at the Facility for Antiproton and Ion Research (FAIR) is a fixed target spectrometer being designed to measure multiple observables, including rare probes, with statistics high enough to build multidifferential cross-sections.

The measurement of particle yields, momentum spectra, angular distributions, as well as fluctuations and correlations of hadrons, requires a set of detectors for the vertex reconstruction and tracking, particle identification, and calorimetry. Thus, two detectors located in the aperture of a superconducting dipole magnet, a Micro-Vertex Detector (MVD) operating in the vacuum closest to the target and a Silicon Tracking System will provide the precise vertex reconstruction and the momentum determination, respectively. The detector composition further downstream implements two configurations driven by the detection of charmed or strange particles and low-mass vector mesons decaying into di-leptons. In elctron-hadron configuration, a Ring Imaging Cherenkov counter (RICH) and Transition Radiation Detector (TRD) provide the electron identification and the electron-pion separation. A time-of-flight system consisting of resistive plate chambers (RPC) and a diamond start counter will identify fast hadrons. Elect-

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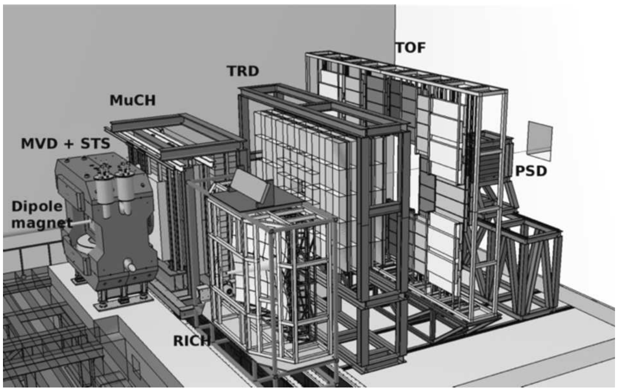


*Fig. 1.* CBM detector in the muon and electron-hadron configurations

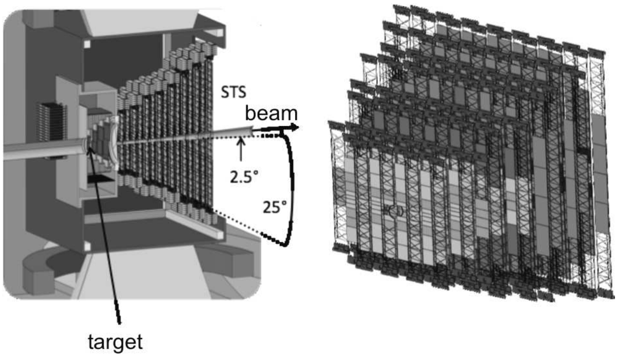


*Fig. 2.* Conceptual design of the STS consisting of eight tracking stations

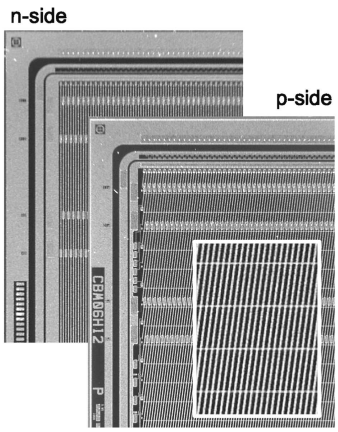


*Fig. 3.* Close-up of corners of a prototype sensor produced by Hamamatsu. Shown are strips on the p-side, oriented under a stereo angle with respect to the n-side strips. The horizontal lines are second-metal routing lines between short corner strips, allowing to read out the full sensor area from the staggered read-out pads at the top edge

rons and photons will be detected by the Electromagnetic Calorimeter (ECAL). The collision plane and centrality will be determined by the Projectile Spectator Detector (PSD). In the muon configuration, the RICH detector will be replaced by an instrumented absorber with muon tracking capability.

## 2. Silicon Tracking System

The STS consists of eight tracking stations located in the aperture of a dipole magnet with 1 T field, 30–100 cm downstream of the target. Its main mission is the momentum measurement for charged particles with a resolution of $\delta p/p < 2\%$ [2]. Therefore, a detector module must have the minimum amount of a material in the physical acceptance (polar angle 2.5–25°) with front-end electronics operating at the periphery of the stations. The system is required to have the track reconstruction efficiency >95% for tracks with momentum above 1 GeV. For this, the detector modules based on double-sided silicon microstrip sensors need to have hit the reconstruction efficiency close to 100% and the low-noise performance ensuring the operation with signal-to-noise ratio well above 10 during the whole detector lifetime.

The goal of the STS is to reconstruct up to 1000 charged particles created in the collision of gold ions with gold target at beam energies up to 11 AGeV at SIS-100 and up to 45 AGeV at a future SIS-300 synchrotron. Depending on the physics case, the interaction rate will range between 0.1 MHz and 10 MHz. In the latter case, a significant challenge is posed to the detector design and data acquisition system due to high radiation load and data rates generated by the collision products, as well as $\delta$-electrons. The tracking stations will have to withstand radiation damage up to $10^{14}\, n_{\rm eq}/{\rm cm}^2$ within its planned operation.

In total, the STS stations will consist of 896 double-sided silicon sensors installed onto 106 carbon fibre ladders with the total area of 4 m$^2$ (see Fig. 2). The pre-final module components, their integration into detector modules and ladders as basic functional and structural units of the tracking stations are presented in the following sections.

## 3. Module Components

### *3.1. Sensors*

Final protptypes of double-sided silicon microstrip sensors 320 $\mu$m in thickness have been produced in cooperation with Hamamatsu (Japan) [3]. The sensors

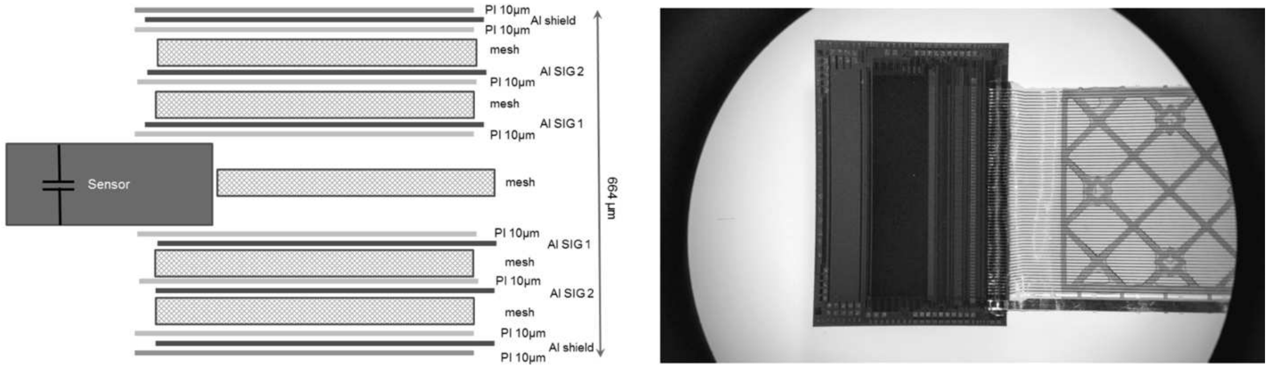


***Fig. 4.*** Multilayer structure of microcables with two signal layers per side, shielding layers, and meshed spacers shown in the attachment to both sides of a microstrip sensor (left); photo of a single microcable layer attached to a readout chip (right)

feature four discrete sizes (62 mm width and 22, 42, 62 and 124 mm height). The wafer material is of the $n$-type. One prototype is shown in Fig. 3. The sensor layout has been optimized for the attachment of microcables by *TAB* bonding for read-out and bias connections, minimum trace resistance, and inter-strip capacitance. The sensors are segmented into 1024 strips per side at a strip pitch of 58 $\mu$m. The strips are read out through integrated $AC$ coupling. The $p$-strips are arranged under a stereo angle of 7.5° with respect to the $n$-strips. The short corner strips are interconnected using a second metal layer in order to enable the full readout of the $p$-side from one sensor edge only, like with the simpler topology of the $n$ side. The sensors are oriented with the strips vertically in the dipole magnetic field to be sensitive to the track curvature. They have been tested under the anticipated thermal operation conditions, –5 °C, and were shown to be radiation-tolerant up to twice the nominal lifetime in the experiment, $2 \times 10^{14}$ 1-MeV $n_{\rm eq}$ cm$^{-2}$.

### *3.2. Microcables*

In the STS module concept, the microcables are the important component to yield a low material budget. They are also central to the noise performance, because they allow one to have the readout electronics outside of the detector acceptance. A microcable is implemented as a stack of two signal layers per side with aluminum traces on a polyimide substrate with spacers inbetween and additional shielding layers on the outside (see Fig. 4). One stack is designed to read out 128 channels. Thus, 16 microcable stacks are required for the full readout of a sensor. The microcable structure aims at balancing the trace capacitance and series resistance based on the ENC contribution to the total noise seen by the preamplifier. A signal layer comprises 64 *Al* lines at 116 $\mu$m pitch, twice the strip pitch on the sensor. Two signal layers are stacked to match the read-out pitch. The thickness of aluminium and polyimide is 14 $\mu$m and 10 $\mu$m, respectively. Such a structure of a cable stack corresponds to 0.23% $X_0$ equivalent to 213 $\mu$m of silicon. The cables are produced in lengths up to 55 cm. The current pre-series production of microcables aims at maximizing the yields [4].

### *3.3. Front-end electronics*

The readout chip STS-XYTER has been developed specifically for the STS. It is a mixed signal ASIC with data driven architecture [5]. Each channel has a fast branch for the time stamp generation with less than 5 ns resolution and a slow one for the amplitude measurement (see Fig. 5). The chip provides 128 independent channels with switchable signal polarity and two gain settings that makes it suitable for use with the STS and a further CBM sub-system, the muon detector with its GEM chambers. For the silicon detector read-out, the dynamic range of the integrated 5-bit ADC is 12 fC, which can be switched to 100 fC for the gas detectors. The design goal with STS-XYTER is to achieve a noise performance of 1000 e$^-$ with a power consumption that is estimated to be <10 mW/channel. This will ensure the matching with the STS detector module structure, where significant noise contributions are expected from the capacitance and the series resistance of the microca-

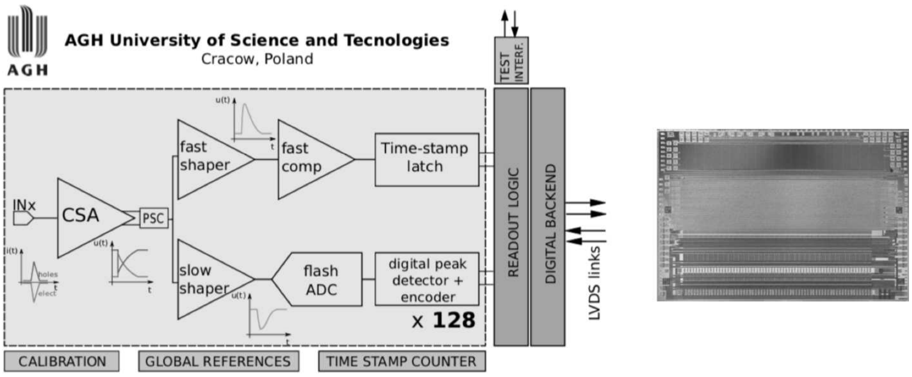


***Fig. 5.*** Block diagram of the STS-XYTER architecture

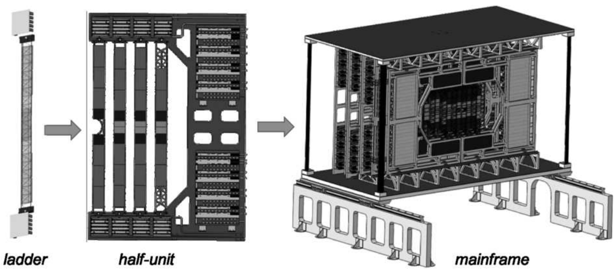


***Fig. 6.*** System integration concept: from ladders to half-units mounted in the mainframe

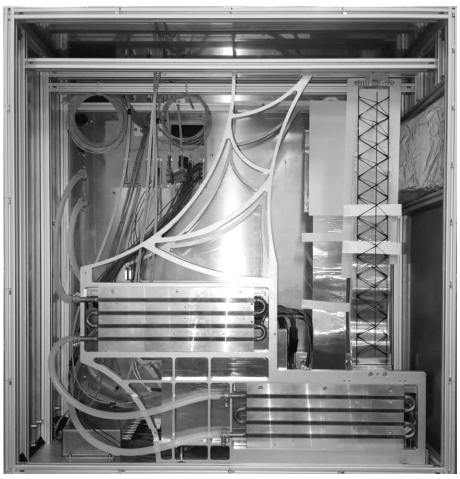

***Fig. 7.*** mSTS detector modules mounted on the *C*-frames. Microcables running along the ladders and integrated cooling plates are visible

ble signal traces and sensor strips. The noise performance is addressed in the chip architecture using the double-threshold technique, where triggers generated by the fast branch are vetoed if no coinciding signal peak was detected. The chip is currently under production in its second iteration, compatible with the CERN GBT read-out protocol, using a 180 nm CMOS process.

## 4. System Integration

The current activities on the system integration focus on devising a detailed engineering solution for the assembly of a system from individual mechanical units and its installation in the magnet aperture taking the intersection of the active volume by the beam pipe and MVD vacuum vessel into account. A thermal enclosure will have to provide numerous interfaces for services, e.g., cooling, powering, and data cables in its side walls. The integration concept foresees a hierarchical mechanical structure of the STS (see Fig. 6), where modules are mounted onto the carbon fiber ladders. The so-called half-units will carry the ladders and the necessary infrastructure so that every half of a tracking station will be formed by two such units. The stations are thus separated into two halves for the maintainability and will be movable in order to allow for the replacement of broken modules. A system [6] cooling the plates with channels for circulating the cooling liquid integrated into the *C*-frames of half-units is devised to remove the power dissipated by the STS front-end electronics, amounting to about 42 kW.

## 5. mSTS at mCBM

As a part of the FAIR Phase-0 program, a long-term beam test campaign of CBM pre-final detector systems has been started at GSI in 2018 at SIS18 synchrotron (mini-CBM or mCBM) [7] with high-rate heavy-ion collisions and followed up by a beam campaign in March 2019. The goal was to operate the full system with complex hardware and software components and to optimize their performance before the final series production. The subsystems had common free-streaming readout with the data transport to the prototype online event selection system.

At the time of the beam test, the mSTS detector shown in Fig. 7 consisted of two $C$-frames equipped with four detector modules mounted on carbon fiber ladders using $L$-legs. All modules provided the full double-sided readout of sensors with $62 \times 62$ mm$^2$ dimensions using about 45 cm long stacked microcable. Each sensor side is read out by a front-end board (FEB) with 8 STS-XYTER ASICS. The FEBs are mounted on the cooling plates integrated into the $C$-frames [8]. The plates are cooled by the chilled water circulating inside them. Apart from front-end electronics, the $C$-frames carry the common readout boards ($C$-ROBs) based on CERN GBT and Versatile Link components [9]. The functions of the $C$-ROB are the data aggregation from the front-end boards and the further data transport via the optical interface, control of the front-end ASICs, clock distribution, and synchronization.

In future runs, the mSTS will concentrate on optimizing the system performance towards particle tracking in combination with other detectors and increasing the number of detector modules to 13. The mCBM operation is planned till 2022.

## 6. Summary and Outlook

The CBM experiment will measure rare probes in the heavy-ion collision environment. This will require a tracking system with hit position resolution better than 20 $\mu$m, fast detectors compatible with operation at an interaction rate up to 10 MHz, and radiation tolerance up to $10^{14}$ $n_{\rm eq}$cm$^{-2}$. The Silicon Tracking System based on double-sided silicon microstrip detector modules compatible with these requirements will provide the charged particle tracking and measure particle momenta with a resolution of $\delta p/p < 2\%$. For this, it requires a particularly low-mass design of the system. The signals from the double-sided sensors are read out via ultra-thin analog microcables by the front-end electronics located outside of the detector acceptance. Currently, the production readiness of the system components has been achieved, and the production phase has started. The feasibility of the detector concept has been demonstrated in the mCBM beam campaign.

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КРЕМНІЄВА ТРЕКІНГОВА
СИСТЕМА ЕКСПЕРИМЕНТУ CBM
НА КОМПЛЕКСІ ПРИСКОРЮВАЧІВ FAIR

Р е з ю м е

Експеримент CBM на прискорювальному комплексі FAIR (Дармштадт, Німеччина) розробляється для вивчення ядерної речовини з високою густиною в експериментальній установці на фіксованій мішені із струменем важких іонів з енергіями до 11 ГеВ/нуклон у системі Au + Au. Трекінг заряджених частинок із роздільною здатністю по імпульсу краще, ніж 2%, буде проводитись Кремнієвою Трекінговою Системою (КТС), розташованою у апертурі дипольно-

го магніту. Детектор зможе реконструювати вторинні вершини розпадів рідкісних частинок, наприклад, гіперонів із кількома дивними кварками з точністю 50 мкм в оточенні продуктів зіткнення важких іонів, що породжує до 1000 заряджених частинок на кожне непружне зіткнення з частотою взаємодії до 10 МГц. Ця задача вимагає швидкого детектора із високою гранулярністю і радіаційною стійкістю, достатньою для роботи при еквівалентному флюенсі до $10^{14} n_{\rm eq}/{\rm см}^2$, накопиченому за кілька років роботи. Система складається із 8 трекінгових станцій на основі двосторонніх кремнієвих мікростріпових детекторів із кроком 58 мкм і орієнтацією стріпів під стереокутом 7,5°. Аналогові сигнали із сенсорів зчитуються через багатошарові мікрокабелі довжиною до 50 см найсучаснішою електронікою на основі STS-XYTER ASIC із самозапускною архітектурою. Детекторні модулі із цією структурою матимуть кількість матеріалу від 0,3% до 1,5% радіаційної довжини, із збільшенням товщини в напрямку до периферії. Перші детекторні модулі та утворені з них "драбини" на основі компонентів, готових до серійного виробництва, тестувалися в ході демонстраційного експерименту міні-CBM на синхротроні SIS18 у GSI (Дармштадт, Німеччина) в рамках програми FAIR Phase-0. Експеримент являв собою тестовий стенд для оцінки роботи установки та системної інтеграції. Представлено результати запуску детектора та його робочі характеристики.