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Contents

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1. STS components assembled for the CBM experiment at FAIR

This deliverable report of Work Package 2 Task 1 ("Integration, installation, and test of Silicon trackers for NICA and CBM") summarizes the status and achievements made with component assembly towards the construction of the Silicon Tracking System (STS), a central particle detector of the *Compressed Baryonic Matter* (CBM) experiment under realization at the FAIR accelerator facility, Darmstadt, Germany.

The STS detector's design and technology is one-of-a kind and specially matched with the scientific ambition of the CBM project, namely empowering the investigation of nuclear matter at neutron star core densities, produced in small amounts and for short times in collisions of nuclear beams with nuclear targets, which in its decay to ordinary ambient matter releases numerously produced particles which are being reconstructed by the CBM experiment's instrumentation including its STS detector. A derivative of the CBM-STS detection technology will also be applied in the *Baryonic Matter at Nuclotron* (BM@N) experiment at the NICA accelerator facility at JINR, Dubna, Russia, a scientific project complementary to the CBM physics and on the timeline of operation readiness scheduled slightly ahead of CBM, thus being of valuable interest to CBM also in terms of gaining knowledge towards preparing CBM-STS system operation. For the BM@N-STS, the status of component development and assembly has already been communicated in MS6 Report [1].
The components for the CBM-STS have been developed and are either already available in full amount to construct hundreds of higher-integrated detector components, or are under final prototype fabrication or prototype proving, or in the process of being series produced in industry. Prototype components have been used to establish assembly procedures, assembly tooling and related laboratory infrastructure, and to gather and train technical teams to achieve the basic functional STS unit, the *module*, and its higher integration into mountable detector *ladders* and mechanical detector *units*. Their operation also required developing the matching powering and grounding scheme, power regulating electronics, cooling of front-end and read-out electronics, and cooling for sensors requiring a fully thermally insulated detector enclosure. For the high-rate collision studies of CBM, a triggerless (free-streaming) read-out system with related hardware, firmware and software, and data transport to the acquisition and analysis computing nodes has been developed.

The validity of the detector concept has been demonstrated with the assembly, successful operation and data taking of the mSTS detector system in the CBM pre-cursor experiment mCBM at the GSI-SIS18 accelerator, which includes demonstrator versions of all CBM detector and service systems. Based on the achievements, towards the start of STS series component assembly, several Engineering Design Reviews and Production Readiness Reviews have been passed in the approval process at FAIR; the remaining ones are scheduled to take place in the course of 2022, to be followed by the start of series construction in 2023.

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2. Basic STS components

The basic operational unit of the STS detector is the *module,* being composed of a silicon microstrip sensor, custom-designed front-end electronics ASICs on dedicated boards for its read-out, and microcables that bridge a physical distance of up to 55 cm between the two, thus allowing to position the massive electronics boards and their cooling places outside of the physics aperture of the experiment.

Silicon sensors

The silicon microstrip sensors have been custom-designed by the CBM collaboration and series-produced with project funds from FAIR in-kind contributions from Germany, Russia and Poland. Production took place at Hamamatsu Photonics, Japan, from 2019 to 2020. A total of 1100 double-sided sensors were produced in four form-factors, shown in Figure 1, having all the same design, the same number of channels per front and back side, but differing in strip length. Ordering was handled through FAIR and the delivery in monthly batches of about 100 pieces was also at FAIR, where a thorough optical and electrical quality control was carried out going beyond the factory specifications and inspection possibilities. This allowed identifying defect channels and maximum operating voltage capability, thus optimized planning for their deployment according to the quality grade in the best possible location in the detector to achieve long lifetime in the CBM high-radiation environment. High quality sensors in sufficient numbers were confirmed.

The inspection was carried out in the clean room of the GSI detector laboratory, involving specialized equipment developed and built at EKUT - Univ. Tübingen [2], see Figure 2, installed and operated at GSI including GSI, EKUT and Univ. Frankfurt staff.

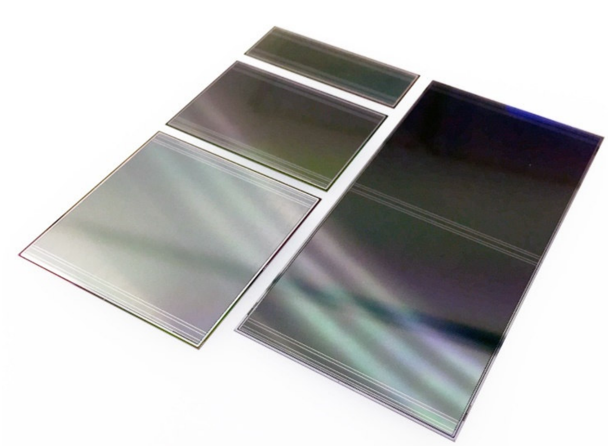

Figure 1 The four variants of the CBM-STS silicon microstrip sensors, accommodating on 6.2 cm width 1024 channels at 58 µm pitch, in 2, 4, 6 and 12 cm strip lengths.

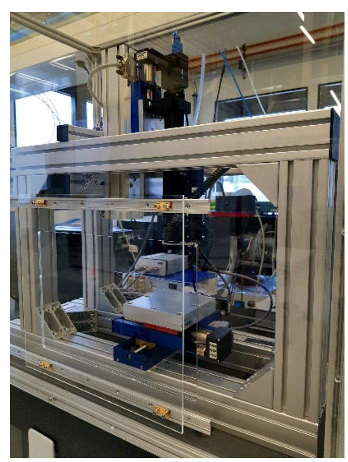

Figure 2 Optical inspection station from EKUT located in a clean room of the GSI Detector Laboratory.

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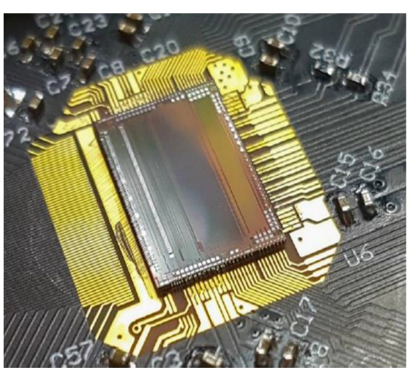
Front-end electronics

The silicon sensors are being read out with the custom-developed ASIC STS-XYTER, designed in cooperation of GSI at AGH University, Krakow, Poland, for the CBM Collaboration [3,4]. Its design addresses high count-rate scenarios and provides self-triggering on signals from the silicon strip sensors, compatible with high-resolution time and energy measurements, despite of large capacitive and resistive load from the sensor and interconnect to the electronics. The final ASIC, approved for series production in 2021 in its design variant 2.2, features 128 channels with a slow branch for energy measurement in 5-bit resolution, and a fast branch for 14-bit time stamp measurement at 5 ns effective resolution. The signal range is up to 15 fC, thus per channel charged particles up to several MIP equivalents can be resolved. The ASIC is radiation tolerant and produced in a 180 nm CMOS process at UMC. The pilot production carried out in 2020 yielded several thousand ASICs which have been used for detailed characterization (see Figure 3) and prototype component assembly. The series production of several 10 thousand ASICs has been ordered but is currently facing significant delay due to the disruptions of supply and delivery chains in worldwide industry caused by the COVID pandemic. The delay with the ASIC reception will finally define the start of STS module and ladder series assembly. Preparation for production readiness can be achieved with the available material, though.

The read-out ASICs are finally arranged on Front-end electronics boards. Eight ASICs are powered and their incoming control lines and LVDS data uplinks are routed to a high-density connector for a cable-based link to a read-out board hosting the CERN-developed GBT chip set for data-combining and optical data transferring. The front-end board is required in two variants for a lower (FEB8-2, see Figure 4) and a higher bandwidth (FEB8-5). The pilot production of the final FEB8-2 is currently ongoing through GSI, the one of FEB8-5 has been launched through JU, Poland. Both board productions are also being delayed by the current industrial bottlenecks with material and work force due to the pandemic and will impact the date of the production readiness review for the start of component series assembly.

With the pilot-produced ASICS, and close-to-final prototypes of the FEBs, module assembly has been exercised in sizable numbers, though, leading to functional detector components which were successfully subjected to laboratory and in-beam tests.



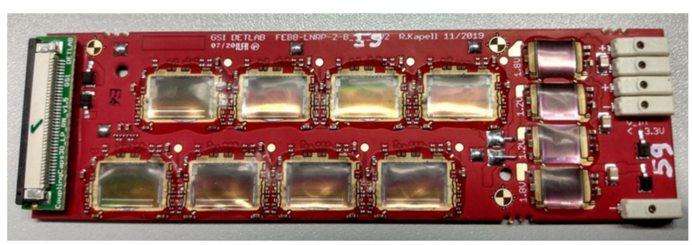


Figure 4 Eight STS-XYTER ASICs on a prototype Front-end electronics board FEB8-2 prepared for functionality tests. It comprises also four power regulating LDO ASICs custom-developed for CBM.

Figure 3 STS-XYTERv2.2 ASIC on a test board.

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Microcables

Microcables link the silicon sensors with the front-end electronics and bridge gaps between few centimeters and up to half a meter for modules with sensors in the center of the STS tracking stations. Only this way, a low material budget per detector ladder (0.3% - 0.8% radiation length) can be accommodated in the physics aperture of the experiment while allowing for electronics capable of high data rates keeping up with the intended high collision rates for high-density baryonic matter studies. This is a key STS performance parameter resulting in a momentum resolution of the detector system of around 1.8% $\Delta p/p$.
A custom solution was found employing ultra-thin aluminum-polyimide microcables, with a line pitch matching that of the silicon microstrip sensors. The cables are produced at LTU Ltd, Kharkov, Ukraine, as a unique supplier, partly with production equipment and other support, e.g. high-resolution photo masks, provided through GSI.

A set to equip one detector module comprises 32 microcables of 64 lines at 116 µm pitch, closely matched in design for a given module variant and its p- and n-side read-out as well as geometrical orientation of the front-end electronics board in the detector system (see Figure 5 and Figure 6). Also further passive spacer layers of the cable stackup achieve low mass, together with low dielectric constant, to minimize capacitive load on the front-end electronics. Shielding layers and shielding strips equalize electronics performance. The sensor bias is carried through special lines on microcables to the microstrip sensor chips. No defect is tolerated and thus required from the producer. Quality checks have been done at GSI for a subset of cables upon reception. More than 60% of the full production has been carried through and the material is available in storage racks at the GSI STS assembly center. Altogether, cable sets with several 10 thousands of individual components will be produced and handled by the assembly logistics.

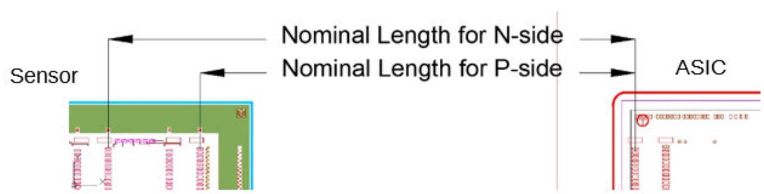

Figure 5 Principle of microcable line routing between contact pads on the silicon sensor and the ASIC, for p- and n-side connections and separated on two sub-cables connecting to two staggered contact rows with even- and odd numbered channel numbers. The cable lengths are between 160 and 495 mm.

Figure 6 A microcable of 64 lines and a meshed Kapton spacer on top, with its „technological zone" for testing, to be cut away before bonding to the sensor (left), and bond area to the ASIC (right).

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3. Module assembly

The work procedure called module assembly realizes the mechanical integration and electrical interconnect of the three basic components introduced in the previous section, yielding the basic operational object of the STS. In an 18-step workflow, carried out including the utilization of semi-automatic wire bonder equipment in a clean room of the GSI Detector Laboratory, shown in the photo of Figure 7, the different components are mechanically aligned, interconnected, and reinforced/protected with glue where needed. This is partly illustrated in Figure 8 to Figure 11. Intermediate functionality tests, e.g. ASIC operation with a pogo-pin miniature prober allows checking for possible weak bonds which can be re-tabbed once more in-situ. This is essential because the completed modules cannot be reworked any further. The last steps of module assembly are to attach two shield cables to either sides of the stackup, and to glue the two front-end boards to an L-shaped cooling fin which is brought into contact with a cooling plate for removal of the power dissipated by the front-end electronics.

Figure 7 Module assembly section in the clean room of the GSI Detector Laboratory.

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Completed modules (Figure 12) are then installed into a test stand with a light-tight and electromagnetically shielding box (Figure 13), equipped with such cooling plate and related connectors for powering and configuration/read-out of the electronics. A comprehensive quality control program is carried through to prove the targeted module performance with respect to the parameter optimization in the electronics, fraction of functional channels, and noise level. Also a window foil is integrated into the test box to enable using a radioactive source as charge generator.

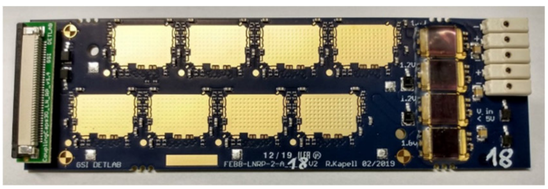

Figure 8 Front-end board equipped with passive components and connectors, ready for being used during module assembly.

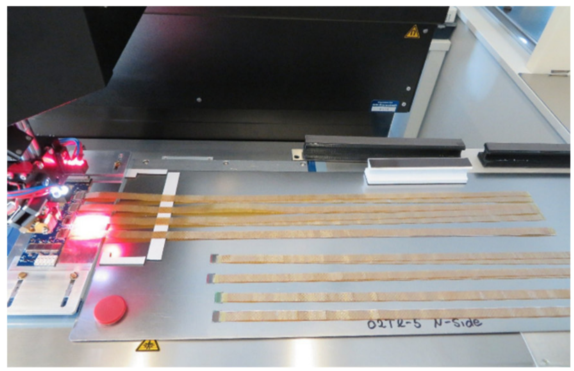

Figure 9 Initial Module assembly step: Attachment of STS-XYTER ASICs via TAB bonding to microcables, yielding “chip cables”.

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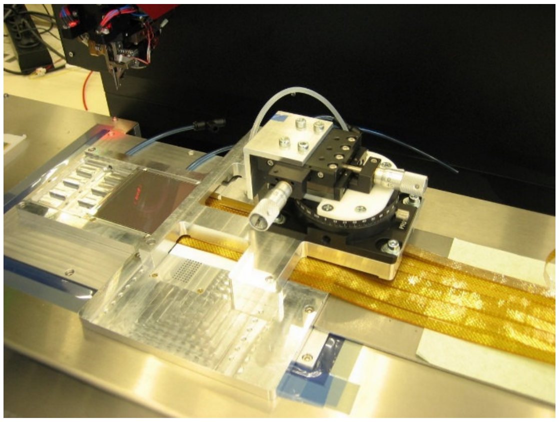

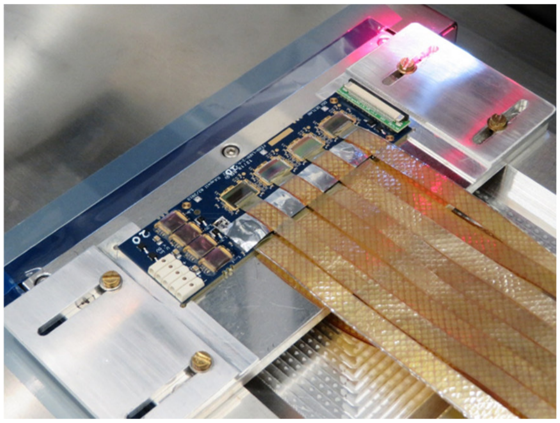

Figure 10 Chip cables aligned on a support structure for sub-sequent attachment to the silicon microstrip sensor, also via TAB bonding. This procedure is done in two steps of 8 chip cables each to complete one sensor side; then the assembly has to be turned over for attachment of the chip cables to the back side of the sensor (top).
Finally, the ASICs are installed into two Front-end boards, one board per module side (bottom).

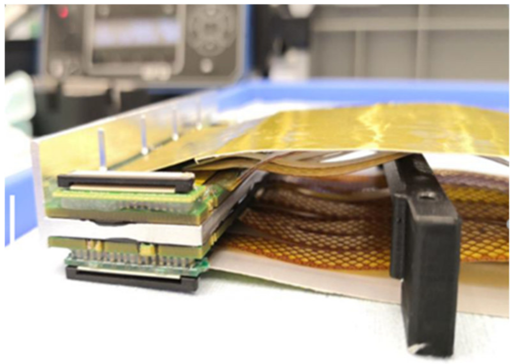

Figure 11 Assembled module (top). As the last step, the two front-end boards are attached to either sides of an L-shaped cooling fin (bottom). Finally, a shielding layer is attached on the outside faces of the module's microcable stacks.

Figure 12 Completed module, prior to shield layer attach-ment, in a temporary storage box.

Figure 13 Test box as part of the module final acceptance procedure.

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4. Ladder assembly

After functionality tests passed, a set of up to ten modules can be assembled into the basic mechanical structure, a detector ladder. This is carried out in the GSI clean room of the GSI Detector Laboratory. The modules, having different matching lengths of microcables, are arranged onto a carbon fiber support structure (Figure 14), one on top of the other, in such way that the sensors cover the full length of the ladder, having the cable stacks in-between the silicon and the carbon fiber structure (Figure 15). The electronics is aggregated at the left and rightmost end of the ladder where the cooling fins are integrated into an electronics box that will be attached to cooling plates later on the detector frame. A full ladder is then optically surveyed on a camera-based setup to determine the geometrical position of the sensors with high accuracy of below 10 µm. The technique applies pattern recognition to define the lateral sensor orientation, and proximity-focus method to determine the vertical dimension. The survey system is shown in Figure 16 and a height profile along a ladder is depicted in Figure 17. Completed ladders are then operated and quality controlled in a dedicated test stand, built around a test box as shown in Figure 18.

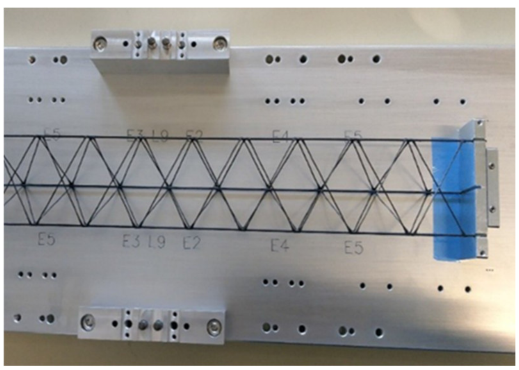

Figure 14 Carbon fiber ladder structure produced from fiber roving and fiber rods, installed on an assembly fixture.

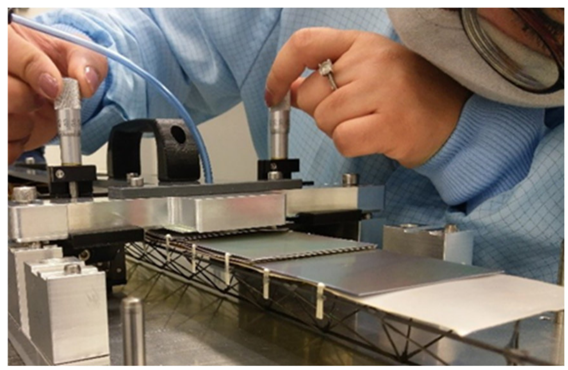

Figure 15 Specialized tooling allows installing one-by-one the modules onto the carbon fiber frame, thus yielding a detector ladder.

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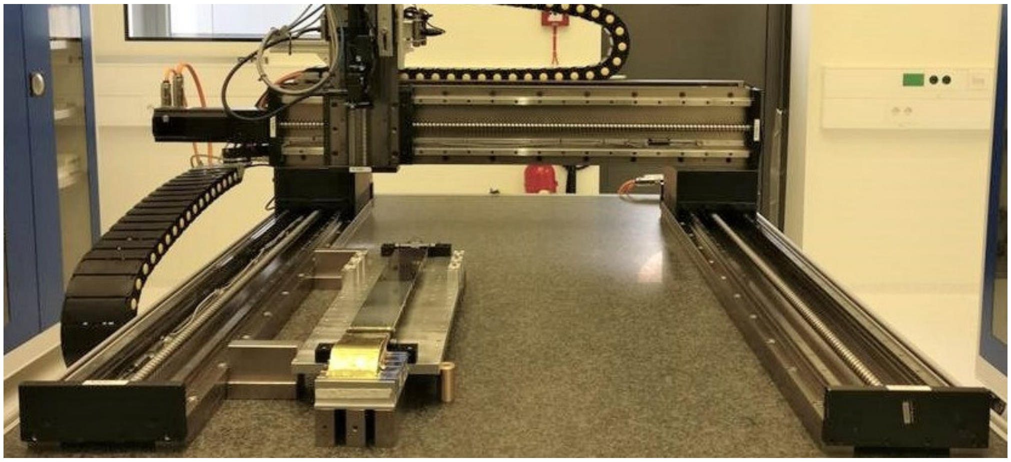

Figure 16 Station for ladder geometrical survey by optical means, with a ladder installed.

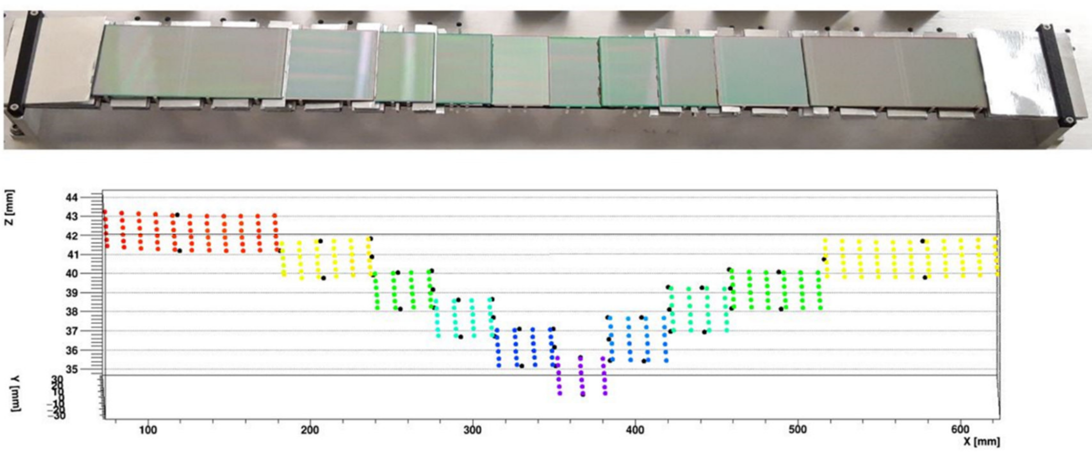

Figure 17 Survey results showing the height profile of the modules' silicon sensors mounted on the carbon fiber support.

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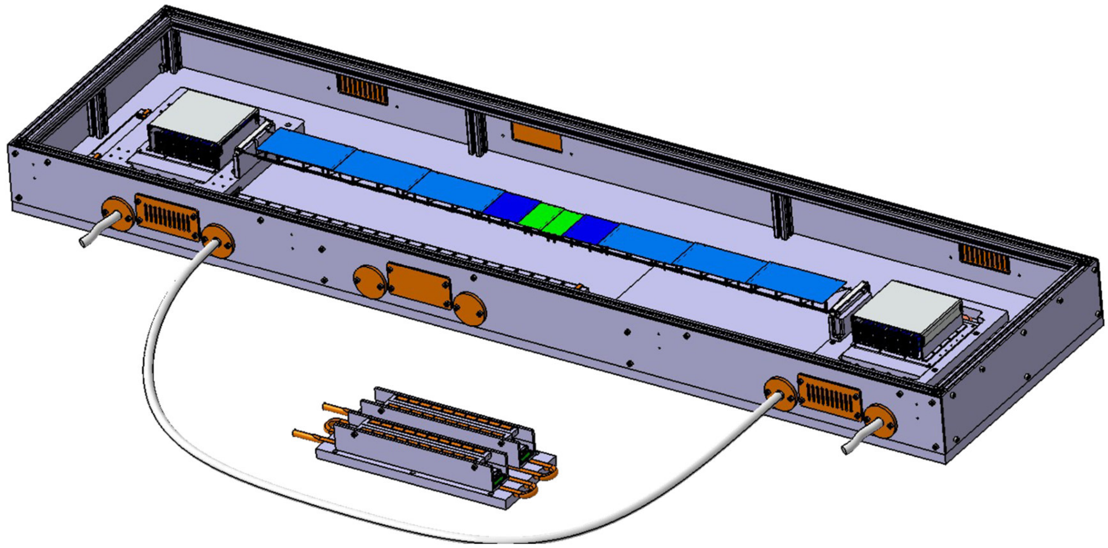

Figure 18 Depiction of a ladder test box, allowing to operate the modules on the ladder with its front-end electronics boards installed in the two boxes to its left and right ends, which are attached to cooling plates to remove dissipated power. The required power supplies and read-out electronics is operated outside of the box and is interfaced through connectors in the walls of the box.

5. Assembly and operation of the mSTS demonstrator system

The validity of the detector concept has been shown in the *mini*STS demonstrator system, which is a test detector demonstrating certain constructional and functional features of the full STS detector for the CBM experiment. It is part of the CBM Collaboration's precursor and demonstrator experiment *mini*CBM, conceived to operate in heavy-ion beam extracted from GSI's SIS18 accelerator and to detect particles originating from beam-target interactions under rate and particle density conditions similar to those in the forthcoming CBM experiment at FAIR-SIS100. The STS demonstrator system is shown in Figure 19 among the other CBM demonstrator detectors installed in the mCBM cave at an SIS18 extraction beam line.

The mSTS comprises 11 modules arranged on 5 ladders which form two tracking stations, with their physics aperture overlapping with that of the other detector systems. The two tracking stations are realized by integrating the ladders onto mechanical structures, called C-frames, which are part of a mainframe with light-tight and electromagnetically insulating walls, including low-mass "windows" if the same properties in the angular acceptance. A closer look on mSTS is given in the photos of Figure 20. Main effort with the conception and realization of the mSTS system was the realization of the complex scheme of floating powering of sensors and front-end electronics, grounding, and shielding against external electromagnetic noise sources. This gave very important feedback into the main STS construction for CBM.

Set-up of mCBM started in 2018; the most recent data taking took place in Summer 2021 and achieved numerous results of the overall system performance and data transport capabilities towards high-rate collision studies. mSTS operated successfully. First results from the analysis are shown in the histograms of Figure 21, illustrating particle hits in the detector stations, spatial correlations of hits among the stations, tracklet formation with hits from the two STS stations pointing to the target, and timing resolution of the self-triggered channel information with respect to the TOF detector.

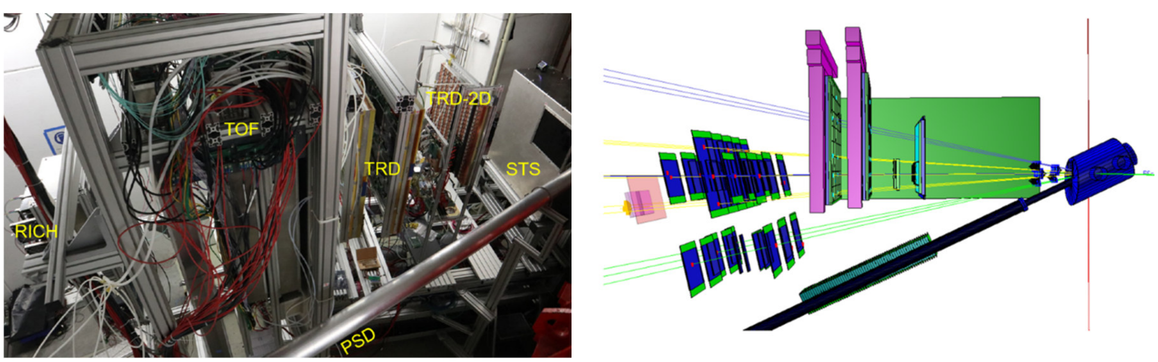

Figure 19 mCBM demonstrator experiment: Photo in the cave (left); detector geometry (right). The mSTS detector is installed downstream of the target and receives secondary particles produced at the target and sprayed out under CBM aperture angles between 2.5 and 25 degrees with respect to the non-interacting beam particle.

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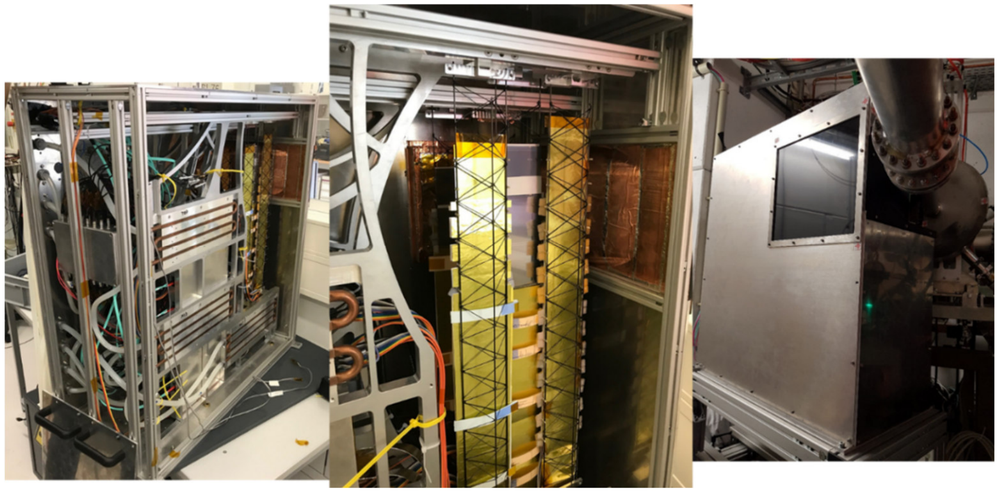

Figure 20 Views of the mSTS detector system after completed assembly. Detector ladders of the downstream stations (middle), C-frames with water-circulating cooling plates for the read-out boards visible installed in the detector mainframe (left), and closed detector box with the downstream particle window at the final installation point in the mCBM cave near the target and downstream beam pipe for the non-interacting beam.

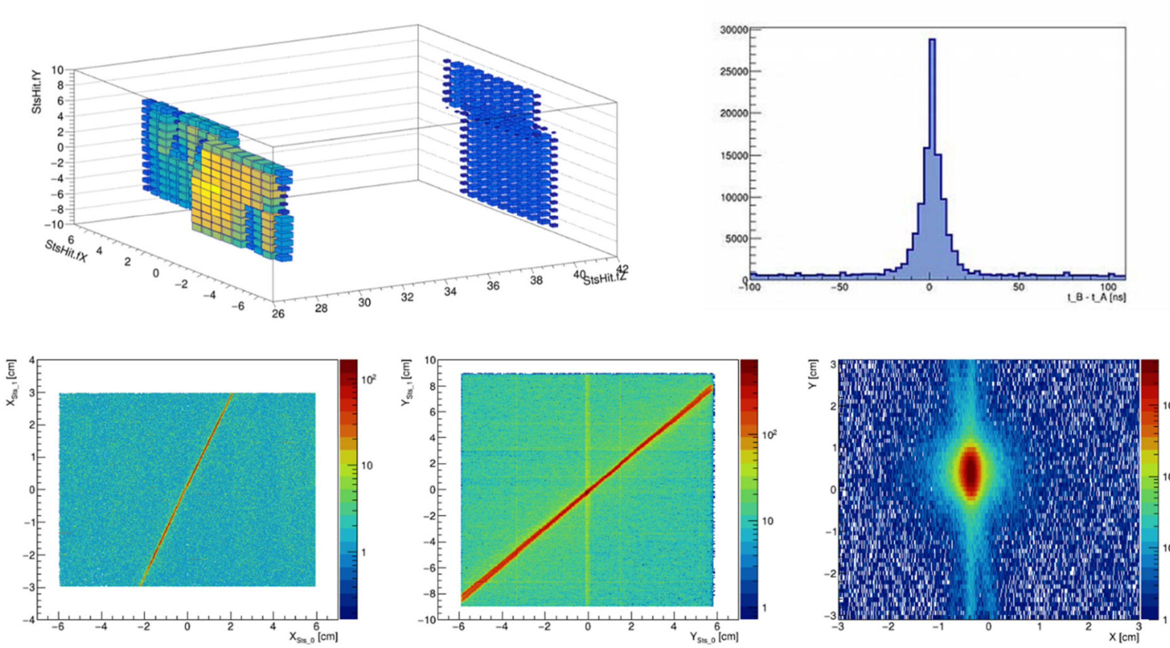

Figure 21 Results emerging from mSTS data reconstruction (*preliminary*): Space distribution of reconstructed hits (top left), time distribution with respect to Time-of-Flight detector hits (top right), X,Y correlation of STS hits in Stations 1 and 2 (bottom left), and extrapolation of the vertex in the target plane (bottom right).

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6. Outlook on STS series assembly and system integration

As an important deliverable on the way to the construction of the Silicon Tracking System for the CBM experiment, we have demonstrated the successful assembly of STS components, and their integration into a demonstrator detector system. The mSTS demonstrator was operated under real experimental conditions as part of the mCBM full-system test setup at SIS18.

Since the start of the CREMLINplus project, several CBM project milestones were achieved and certified through reviews [5]:

- CBM-STS Module and Ladder Engineering Design Review, 16 December 2020
- Production Readiness Review of CBM-STS Microcables, 30 March 2021
- Production Readiness Review of the STS-XYTER v2.2 ASIC, 31 March 2021
- Engineering Design Review of the STS powering scheme and power supplies, 9 June 2021
- Engineering Design Review of CBM-STS Mechanics, 5 November 2021

Moving beyond, the following further checkpoints are to be carried out before the series assembly of modules and ladders and their integration into the CBM-STS detector system will be started:

- Production Readiness Review of STS modules and ladders (planned for Fall 2022)
- Production Readiness Reviews of mechanical components (planned for second half of 2022)

The respective preparation for those milestones are ongoing and include:

- the outfitting of the STS assembly laboratory with test stands for module “burn-in” under thermal cycling representing later operation modes in the detector system, as well as test stands for ladder and unit quality control after assembly;
- the finalization of the detector CAD design to the point that all components are fully described and match together also with other connecting parts as the beam pipe and the target chamber, thus can be released for manufacturing or procurement.

In Figure 22 a technical view of a C-frame is provided, populated with detector ladders and further components as cooling plates and shelves with read-out and powering boards. Those mechanical units are to be integrated into the main detector frame, and cabled up. The integration laboratory at the GSI Detector Laboratory is being prepared and includes, as shown in the photograph of Figure 23, the STS assembly stand and various supply systems, like the powering and cooling systems located in an outside container and interconnected through piping or via cable bridges to patch panels near the detector assembly position in the laboratory. Detector assembly is planned to commence in 2023, when all components for series assembly will be available. The detector may be completed by the end of 2024.

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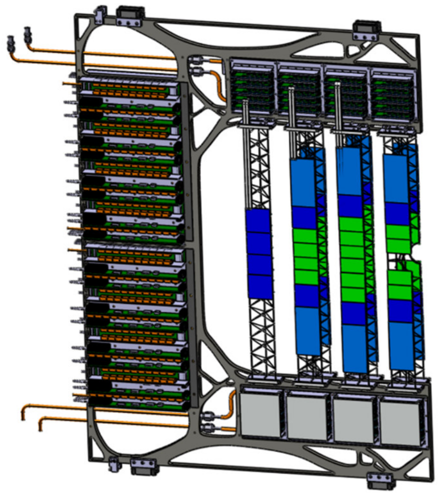

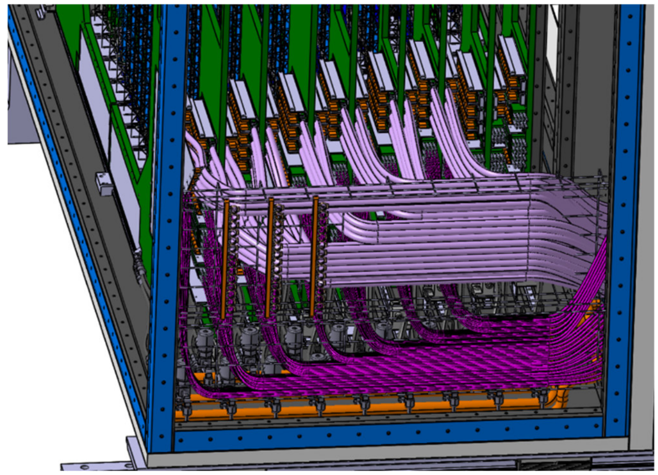

Figure 22 System integration of the STS detector. The detector ladders will be mounted on the mechanical C-frames, hosting also the cooling plates for the module's front-end electronics and the read-out boards (left panel). Altogether 18 C-frames, called detector units after full double-sided population with all components, will be installed into the detector mainframe and cabled up to the power supplying, read-out and cooling services through connectors located at the upstream wall of the detector box (right panel).

Figure 23 View into the emerging STS integration laboratory at GSI with a mechanical demonstrator of the STS mainframe on the assembly stand and some test ladder components mounted on C-frames.

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Acknowledgements

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- GSI-FAIR (Germany) *
- EKUT Eberhard Karls Universität Tübingen (Germany) *
- GU Goethe Universität (Germany)
- KIT (Germany)
- JINR (Russia) **
- AGH (Poland)
- JU (Poland)
- WUT (Poland)
- KINR (Ukraine)
- KEK (Japan) - associate CBM member

* WP2.1 participant on the CBM-STS assembly
** WP2.1 participant on the related BM@N-STS assembly

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