STATUS OF THE COMPRESSED BARYONIC MATTER (CBM) EXPERIMENT AT FAIR

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- For the CBM Collaboration –

29th International Conference on Ultra-relativistic Nucleus-Nucleus Collisions (Quark Matter 2022)
Krakow, Poland, April 04 – 10, 2022
Facility for Anti-Proton and Ion Research (FAIR)

### SIS-100 Capabilities

<table>
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<tr>
<th>Beam</th>
<th>Z</th>
<th>A</th>
<th>$E_{\text{max}}$ [AGeV]</th>
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<tbody>
<tr>
<td>p</td>
<td>1</td>
<td>1</td>
<td>29</td>
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<tr>
<td>d</td>
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<td>Ca</td>
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<tr>
<td>Au</td>
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<td>197</td>
<td>11</td>
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<td>U</td>
<td>92</td>
<td>238</td>
<td>10.7</td>
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</table>

- **Intensity gain**: $x$ 100 – 1000 ($\sim 10^{13}/s$ for $p$; $\sim 10^{10}/s$ for $Au$)
- **10 x energy** (compared to SIS-18@GSI)
- **Antimatter**: antiproton beams
- **Precision**: System of storage and cooler rings


**Update on FAIR Construction (December 2021)**

- Interior work on SIS-100 tunnel ongoing
- CBM Building’s construction is on schedule and is ready for ‘heavy installation’ from 2022-23
- Consequence of the war in Ukraine and sanctions imposed on Russia are currently being evaluated
- Updates on construction available at: [GSI Webpage](#) | [YouTube](#) | ...

(SIS-100 TUNNEL)  
(CBM CAVE)
Most promising range to find the Critical End Point (CEP):

$(135, 450) \text{MeV} \lesssim (T, \mu_B)_{\text{CEP}} \lesssim (100, 650) \text{MeV}$
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Bayesian interference to show that constraints on Pure Neutron Matter (PNM) EoS obtained by heavy-ion collisions (HIC) are consistent with multi-messenger astrophysics at lower densities
The CBM research program aims to decipher dense QCD matter properties
Microscopic (CBM) + Macroscopic Collisions (Astro) = New Multi-Messenger Physics

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Symmetric Nuclear Matter:
- [FOPI], Nucl.Phys.A 945 (2016) 112-133

Symmetry Energy:
- [SnRIT], Phys.Rev.Lett. 126 (2021) 16, 162701
Comprehensive roster of physics goals and observables

QCD equation-of-state and symmetry energy
- collective flow of identified particles
- particle production at threshold energies

Phase transition
- excitation function of hyperons
- excitation function of LM lepton pairs

Critical point
- event-by-event fluctuations of conserved quantities

Chiral symmetry restoration at large $\mu_B$
- in-medium modifications of hadrons
- meson-baryon coupling
- dileptons at intermediate invariant masses

Strange matter
- (double-) lambda hyper-nuclei
- search for meta-stable objects (e.g., strange dibaryons)

Heavy flavor in cold and dense matter
- excitation function of charm production
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DOI: 10.1007/978-3-642-13293-3

DOI: 10.1140/epja/i2017-12248-y
CBM is designed to conduct its research program at up to 10 MHz beam-target interaction rates giving an unprecedent access to the ‘rare probes’.
Beam Monitoring (BMON) and $T_0$ System

Superconducting Dipole Magnet
Micro-Vertex Detector (MVD)
Silicon Tracking System (STS)

MUon CHamber (MUCH); or
Ring Image Cherenkov (RICH)

Transition Radiation Detector (TRD)

Projectile Spectator Detector (PSD)

Time-Of-Flight (TOF)
**Particle Identification With CBM**

**CBM Simulations, central Au-Au@10AGeV**

**ToF - Hadron Identification**

- Clear separation between charged protons, pions and kaons

**TRD + ToF - Electron, Light Nuclei, Heavy Fragments**

- Clear separation between pions and electrons, and light nuclei

**RICH - Electron ID**

**CBM Simulations, central Au-Au@10AGeV**

- **e^−, π^−, K^−, (e^+, μ^+), π^+**

- **p, D, He**
- Tools for the multi-differential physics analysis are prepared for strange hadrons and hypernuclei
- Reconstruction is based on the dedicated KFParticleFinder package
- Yield improvements demonstrated with $\Lambda$ by using Machine Learning techniques (XGBoost model)
- Further deployment on other (multi-)strange hyperons ($K^5_0$ and $\Xi^-$)
- Studies to reconstruct the properties of different EoS in THESEUS event generator (3-fluid hydro)
- ‘Temperature’ extraction within ~5% systematic error by using Blast-Wave and Boltzmann fitting
- Multi-differential study of $v_1$ for (multi-)strange hyperons: $\Lambda$, $K_0^s$, and $\Xi^-$
- Input model $v_1$ is recovered using data-driven methods
- First feasibility studies of performing multi-particle azimuthal correlations in flow analyses (symmetric cumulants)
- Challenging due to CBM’s fixed-target geometry at lower energies (non-uniform acceptance and low multiplicities), but possible
- Feasibility studies to conduct measurements of proton-proton and pion-pion correlations
- Further analysis with higher statistics and cuts ongoing for precise reconstruction of source properties
Clear peaks for the low mass vector mesons in both production channels, with negligible contribution from Drell-Yan
Access to thermal signal is feasible with good background description; Improvements ongoing
Prospects of charmonium measurements at sub-threshold energies (Au+Au) and to study cold nuclear matter effects (p+Au)
Mass resolution of ~35 MeV, with good mid-rapidity coverage
Recent (& Brief) Achievements in Detector Projects

Beam Monitoring (BMON) Detector
- Halo/tail detector
- CBM target

Superconducting Dipole Magnet
- T0 detector

Micro-Vertex Detector (MVD)
- Technical Design Report for the CBM

Silicon Tracking System (STS)
- Full-size mechanical demonstrator on assembly stand

Muon Chambers (MUCH)
- MUCH GEM at GIF++ (Nov.21)

Ring Imaging Cherenkov (RICH) Detector
- RICH/MUCH Mechanics

Transition Radiation Detector (TRD)
- Technical Design Report for the CBM

Time-of-Flight (ToF) Wall
- TOF mainframe

Projectile Spectator Detector (PSD)

More info in poster sessions 3 T15_1, 3 T15_2 and backup slides
Conceptual verification of the triggerless-streaming read-out and data transport of CBM
Detailed high-rate tests for validation of components’ radiation tolerance
Benchmark runs targeting Λ reconstruction in Au+Au collisions at 1.24 AGeV and Ni+Ni collisions at 1.93 AGeV in 2022
HADES-RICH: Already 1/2 (430 MAPMTs + FEE) of CBM-RICH

STAR-eTOF: 10% (108 MRPCs) of CBM-TOF

CBM Online Reconstruction Software for STAR-BES

Double-ring pad pattern

Overlapping double-ring pad pattern

STAR Preliminary $\text{Au+Au } \sqrt{s_{NN}} = 3$ GeV

Guannan Xie, Strangeness in Quark Matter (2021)
CBM@SIS-100 has significant discovery potential
- excitation function of hyperon production
- excitation function of di lepton production
- study of light hyper-nuclei

Pushing the high-rate capability frontier
- to achieve high precision of multi differential observables
- to enable rare processes as sensitive probes

CBM Phase 0 activities (HADES, STAR, mCBM)
- understanding of major components
- production of physics results with CBM devices

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CBM@SIS-100 (2 – 11 AGeV Au-Au) provides unique conditions in lab to probe QCD matter properties at neutron star core densities, including the high-density EOS, and the search for new phases at higher densities

MOVING TOWARDS A NEW MULTI-MESSENGER PHYSICS ERA
Physics Working Groups

#466. CBM performance for anisotropic flow of charged hadrons and (multi)-strange hyperons in heavy-ion collisions, O. Lubynets, 06.04.22, Poster Session 1 T14_2
#506. Application of the Three-fluid Hydrodynamics-based Generator THESEUS in CBM at FAIR, E. Volkova, 06.04.22, Poster Session 1 T14_2
#573. Prospects of dilepton and charmonium measurements with CBM experiment, S. Chatterjee, 06.04.22, Poster Session 2 T13
#706. Performance studies of femtoscopy at CBM, D. Wielanek, 06.04.22, Poster Session 2 T07_1
#461. CBM performance for (multi)-strange hadron measurements using Machine Learning techniques, S. Khan, 08.04.22, Poster Session 3 T11_2
#503. Feasibility study of multiparticle correlations in flow analyses in CBM at FAIR, A. Bilandzic, 08.04.22, Poster Session 3 T15_1
#471. Perspectives on (multi-strange) hypernuclei physics with the CBM experiment at FAIR, I. Vassiliev, 08.04.22, Poster Session 3 T16
#966. Feasibility Studies of Di-Electron Spectroscopy with CBM at FAIR, C. Feier-Riesen, 08.04.22, Poster Session 3 T15/T16

Detector Working Groups and mCBM

#828. The powering scheme of the CBM Silicon Tracking System: concept and first implementations, A. Lymanets, 08.04.22, Poster Session 3 T15_2
#811. Performance of the mSTS detector in O+Ni collisions at 2 AGeV with the mCBM setup at SIS18, D. Ramirez, 08.04.22, Poster Session 3 T15_2
#454. Study of the material budget and data rates for the STS detector system of the CBM experiment, M. Shiroya, 08.04.22, Poster Session 3 T15_1
#451. Test and characterization of the final readout ASIC for the CBM Silicon Tracking System experiment, O. Maragoto Rodriguez, 08.04.22, Poster Session 3 T15_1
#691. Optimization of the calibration parameters for the front-end electronics of the Silicon Tracking System of the CBM experiment, A. Rodriguez Rodriguez, 08.04.22, Poster Session 3 T15_2
#689. Recent developments in the Silicon Tracking System of the CBM experiment towards starting system assembly, A. Rodriguez Rodriguez, 08.04.22, Poster Session 3 T15_2
#650. Solutions for humidity and temperature monitoring in the Silicon Tracking System of the CBM experiment: Sensors, Testing and DCS integration, M. Bajdel, 08.04.22, Poster Session 3 T15_2
#622. Performance study of CBM Muon Chamber detectors at the mCBM setup of SIS18 with Pb+Au collisions at 1.06 AGeV, E. Nandy, 08.04.22, Poster Session 3 T15_2
#900. The mCBM experiment at SIS18 of GSI/FAIR - a CBM precursor and demonstrator, A. Weber, 08.04.22, Poster Session 3 T15/T16
THANK YOU
**Physics Case 1: Equation of State and Neutron Star Properties**

Heavy-Ion Collisions

Equation of State

Mass-radius

Core composition

Exterior space-time
ANISOTRIPCIC FLOW

Nucelar EoS \( \propto (\text{In})\text{Compressibility} \) of the nuclei \( \propto \) ‘Flow’
direction of participants and spectators

\[
\frac{dN}{d\phi} \propto 1 + (2 \cdot v_1 \cdot \cos \phi) + (2 \cdot v_2 \cdot \cos 2\phi) + \ldots
\]

SUB-THRESHOLD STRANGENESS PRODUCTION

Nucelar EoS \( \propto (\text{In})\text{Compressibility} \) of the nuclei \( \propto \) Density \( \propto \) Strangeness Yield

\[
\text{dN} \propto 1 + 2 \cdot v_1 \cdot \cos \phi + 2 \cdot v_2 \cdot \cos 2\phi + \ldots
\]
CBM, with its capability with observables like particle flow and sub-threshold particle production, is in pole position to push our understanding of SNM and PNM at higher densities, thereby enhancing HIC’s compatibility with astrophysical observations.

**HIC PRESENT (@SIS-18)**
- HIC constraints the EoS only where its sensitivity is highest (~1.5\(n_{\text{sat}}\)), where it favours stiffer EoS
- Constraints are consistent between HIC and astro

**HIC FUTURE (@SIS-18, SIS-100, …)**
- Higher density constraints are currently driven by Astro (which are limited in statistics)
- HIC has the potential to limit the constraints at higher densities
**Physics Case 2: Caloric Curve and Deconfinement**

Non-monotonous behaviour of the caloric curve potentially signals phase transition

![Diagram](http://www.splung.com/content/sid/6/page/latentheat)

**DI-LEPTONS**

Dileptons, being electromagnetic probes, act as a thermometer of the strong-interacting fireball medium

\[
\frac{dN}{dM} \sim M^{3/2} \cdot \exp \left( -\frac{M}{T_s} \right)
\]


![Graph](image.png)

**CBM**

Terra Incognita

CBM will be the first experiment to use di-leptons for systematic measurements in both production channels \((e^+e^-\text{ and } \mu^+\mu^-)\) in the same coverage.

Nucl. Phys. A 1005 (2021) 121755

\(\sqrt{s_{NN}} < 6\text{GeV} - \) Eur. Phys. J. A 52 (2016) 131
Based on the recent fRG and L-QCD results, there are no signs of criticality for $\mu_B/T \lesssim 4$

Most promising range for finding the Critical End Point (CEP): $(135, 450)\text{MeV} \lesssim (T_{\text{CEP}}, \mu_{B_{\text{CEP}}}) \lesssim (100, 650)\text{MeV}$
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CBM can systematically study the higher-order cumulants and ratios to contribute significantly to the search of QCD-CEP

Higher-order cumulants and ratios of conserved quantities (B, Q, S) are sensitive to QCD CEP

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- CBM

EVENT-BY-EVENT FLUCTUATIONS

- Higher-order cumulants and ratios of conserved quantities (B, Q, S) are sensitive to QCD CEP

M.A. Stephanov, Phys. Rev. Lett. 102 032301 (2011)
**RECENT ACHIEVEMENTS IN DETECTOR PROJECTS — [I]**

**BMON (GSI, TU Darmstadt)**
- BMON detector concept for CBM Day 1: two stations for HALO and T0 measurement
- Start detector concept for Day-1 based on pcCVD high purity diamond sensors
- R&D on novel sensor technologies → LGAD in HADES, MedAustron, S-DALINAC

**Magnet (GSI, BINP Novosibirsk*, JINR Dubna*)**
- Yoke produced and assembled
- Yoke support production ongoing
- Production of Power Supply and Energy Extract. Syst. in progress
- Finalization of coil and cryo system FDR ongoing
- Evaluation of the impact of sanctions imposed on Russia on the project ongoing

**MVD (U Frankfurt, GSI, IKF Frankfurt, IPHC Strasbourg, Pusan Nat’l Univ.)**
- TDR accepted by ECE in 10/2021 ([link](#))
- Extensive MIMOSIS-1 test campaign; analysis ongoing
- MIMOSIS-2 submission (PRR in January 2022)

*Collaboration suspended*
**RECENT ACHIEVEMENTS IN DETECTOR PROJECTS — [II]**

**STS** (GSI Darmstadt, JINR Dubna*, KIT Karlsruhe, JU Cracow, AGH Cracow, KINR Kiev, Univ. Tübingen, Warsaw UT)
- Preparation of pre-series production and PRR
- STS Mechanics EDR successfully concluded
- STS-XYTER v2.2 series production, order placed through AGH
- FEB pilot production for module/ladder pre-production

**MUCH** (Aligarh Muslim Univ., Bose Inst. Kolkata, Panjab Univ., Univ. of Jammu, Univ. of Kashmir, Univ. of Calcutta, B.H. Univ. Varanasi, VECC Kolkata, IOP Bhubaneswar, NISER Bhubaneswar, IIT Kharagpur, IIT Indore, Guwahati Univ., PNPI Gatchina*)
- Built and tested the first GEM chamber for the 2nd station of MuCh
- Assembled and tested the real size RPC for the 3rd station of MuCh
- First HV supply crate assembled at VECC and tested with GEM
- CDR completed: MuCh gas system, GEM chambers, chamber mechanics

**RICH** (Univ. Giessen, Univ. Wuppertal, PNPI Gatchina*, GSI Darmstadt)
- Mechanical design close to final
- Readout electronics – first of series available
- DIRICH frontend module tested up to 300 kHz/pixel (CBM full rate), no performance issues
- RICH photon camera design finalized, Mirror PRR in April ’22

*Collaboration suspended

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RECENT ACHIEVEMENTS IN DETECTOR PROJECTS – [III]

**TRD** (NIPNE Bucharest, Univ. Frankfurt, Univ. Heidelberg, Univ. Münster, IRI Frankfurt)
- Addendum to TRD TDR for TRD2D submitted to ECE
- Successful CRI-based data taking with SPADIC and FASP based readout
- Tests of SPADIC 2.3a/b continue, toward final submission of SPADIC 2.4

**TOF** (THU Beijing, NIPNE Bucharest, GSI Darmstadt, TU Darmstadt, USTC Hefei, Univ. Heidelberg, ITEP Moscow*, HZDR Rossendorf, CCNU Wuhan)
- Mitigation for observed aging ongoing, several sealed counter constructed for mCBM high rate running 2022
- FEE PRR in April ‘22
- Main frame CDR passed
- Gas system under development

**PSD** (INR Moscow*, TU Darmstadt, CTU Prague, NPI Rez)
- All modules produced; upper support structure arrived at FAIR in 09.2020
- Commissioning of the FHCal at the BM@N during SRC run at the BM@N – Feb. 2022.
- Start of ordering and purchase of the PSD FEE and readout electronics, PRR concluded in Dec. 2022

*Collaboration suspended*
**CBM-DAQ & mCBM@SIS-18**

- DAQ nowadays utilizes common readout interface (CRI)
  - Dedicated FPGA board that connects the custom front end electronics to the commercial servers of the entry node
  - Each detectors uses several CRI boards for its DAQ
  - Entry nodes already connect to GreenCube
    - Timeslice building on FLES processing nodes
  - mCBM readout chain is already small scale of future CBM readout

New mCBM DAQ with CRIs (prototype for CBM) in an entry node
FIRST RESULT WITH mCBM@SIS-18

• Aim of benchmark runs in 2022: Reconstruct Lambdas without magnetic field
• Reconstruction based on topology cuts
• Ni+Ni @ 1.93 AGeV is benchmark measurement with FOPI data as reference
  - Full lambda reconstruction without tracking and magnetic fields

• Data yields in 10 ms intervals for all detectors taking part to the July 2021 mCBM campaign.
• Volumes of data for each system is in sync with the beam on/off structure
• Data correlation between ToF and all other systems.
FIRST RESULT WITH mCBM@SIS-18

- Establishing of full readout chain with STS, TRD, TOF and RICH
- Handling of data from data stream
  - Full unpacking of data (digis: unpacked data)
    - Assigning of timestamp to each data point
  - Complete event building with unpacked data
  - Event selection
  - Archiving of events
- Demonstration of the full online data processing chain
- Extraction of time correlation between sub-detectors and seed time of an event from data stream

Histograms created from streamed data in online histogram server

1st results from March 10, 2022, 3:36 am