Abstract
of the project for 2021-2025
Compressed Baryonic Matter Experiment (CBM)
(JINR participation)

P.G.Akishin, E.P.Akishina, E.I.Alexandrov, I.N.Alexandrov, S.P.Avdeev, M.Baznat, D.V.Belyakov, S.G.Belogurov, I.V.Boguslavsky, A.V.Bychkov, O.Yu.Derenovskaja, O.V.Fateev, I.A.Filozova, Yu.V.Gusakov, V.V.Ivanov, V.V.Ivanov (junior), G.D.Kekelidze, A.V. Kryanev, V.P.Ladygin, N.B.Ladygina, I.V.Lapshina, S.A.Lebedev, V.M.Lysan, A.I.Malakhov, Yu.A.Murin, S.S.Parzhitsky, V.V.Pavlov, A.M.Raportirenko, S.G.Reznikov, A.A.Savenkov, A.V.Shabunov, N.I.Veselova, A.I.Zinchenko, I.A.Zhukov, P.V.Zrelov, T.V.Andreeva, D.V.Dementiev, V.V.Elsha, A.A.Kolozhvari, V.G.Komarov, A.A.Rybakov, T.V.Semchukova, A.D.Sheremetiev, M.O.Shitenkov, E.A.Strelezkaya, A.L.Voronin, N.I.Zamiatin, N.V.Sukhov

Participating institutes:
Joint Institute for Nuclear Research, Dubna, Russia
GSI, Darmstadt, Germany
FAIR, Darmstadt, Germany
Frankfurt University, Frankfurt, Germany
Technical University of Darmstadt, Darmstadt, Germany
HZDR, Dresden-Rossendorf, Germany
J.Liebig University of Giessen, Giessen, Germany
Technical University of Munich, Munich, Germany
Nuclear Physics Institute, Academy of Sciences of Czech Republic, Rez, Czech Republic
Smoluchowski Institute of Physics, Jagiellonian University of Cracow, Cracow, Poland
Institut dIe Physique Nucléaire, CNRS/IN2P3 - Université Paris Sud, Orsay, Cedex, France
Institute for Nuclear Research, Russian Academy of Sciences, Moscow, Russia
Skobeltsyn Institute of Nuclear Physics of the Moscow State University, Moscow, Russia
National Research Nuclear University MEPhI, Moscow, Russia

Theme leaders: Ladygin V.P., Ivanov V.V.
Deputy: Derenovskaya O.Yu.

** The information on the CBM project can be obtained at http://www.gsi.de*

Abstract. The investigation of nuclear matter at extreme conditions, i.e. at high temperatures and/or at high baryon densities, is one of the most challenging fields of modern physics. Worldwide, major efforts are devoted to the exploration of the phase diagram of strongly interacting matter using high energy nucleus-nucleus collisions. While the experiments at the Relativistic Heavy Ion Collider (RHIC) at BNL and at the Large Hadron Collider (LHC) at CERN focus on the study of high temperatures, the Compressed Baryonic Matter (CBM) experiment at the future FAIR accelerator will concentrate on the investigation of highest baryon densities at still moderate temperatures. In particular, the CBM research program aims at the exploration of the structure of high density matter including the question of deconfinement and chiral phase transitions. The theoretical description of physics at high net baryon densities within the fundamental theory of strong interaction, Quantum Chromodynamics (QCD), is still strongly evolving and the scientific progress in "strong" nonperturbative QCD is driven by new experimental data. The CBM experiment will enter a new era with diagnostic probes never measured before in the FAIR energy range, and thus has a unique research potential.

Scientific goal. The goal of the research program on nucleus-nucleus collisions at the Facility for Antiproton and Ion Research (FAIR) is the investigation of highly compressed nuclear matter. Matter at very high densities exists in neutron stars and in the core of supernova explosions. In the laboratory, super-dense nuclear matter can be created in the reaction volume of relativistic heavy-ion collisions. The baryon density and the temperature of the fireball reached in such collisions depend on the beam energy. In other words, by varying the beam energy one may, within certain limits, produce different states and phases of strongly interacting matter.

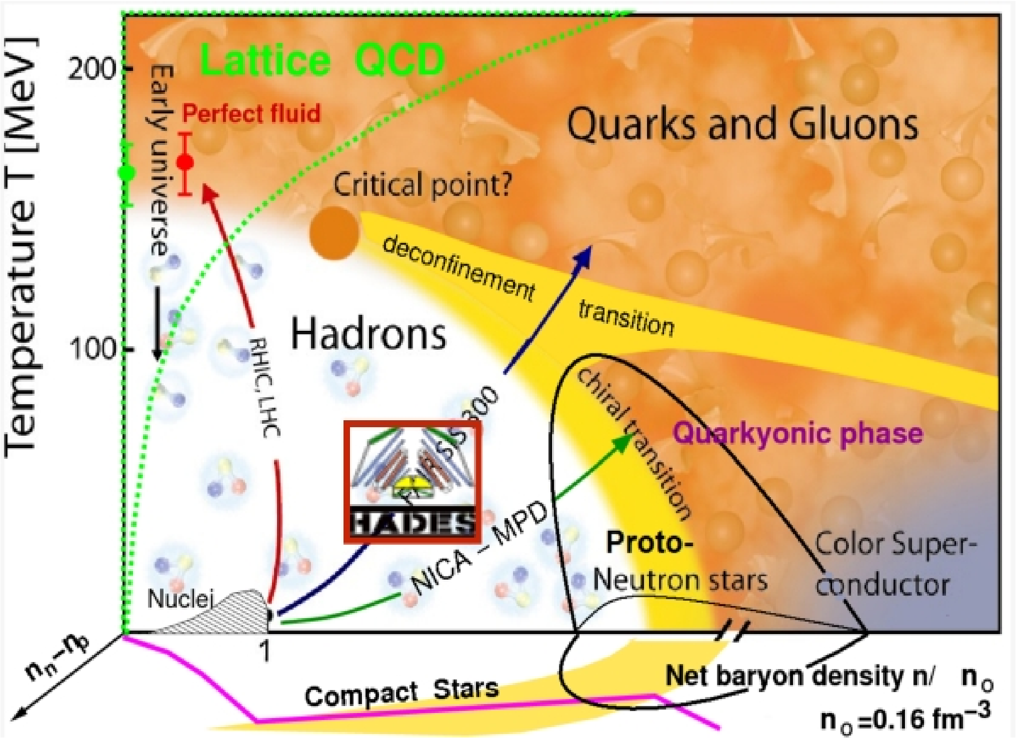

Figure 1: A schematic phase diagram of strongly interacting matter.

The phases of strongly interacting matter are shown schematically in figure 1. The "liquid" phase is realized in atomic nuclei at zero temperature and at saturation density (300 million tons/cm3). At low densities, the nucleons (i.e. protons and neutrons) behave like a gas. As the temperature and the density are raised, the nucleons are excited into "baryon resonances" which subsequently decay into pions and nucleons. This mixture of nucleons, baryonic resonances and mesons is called hadronic matter. This hadronic phase is represented by the white area in figure 1. At very high temperatures the hadrons melt and their constituents, the quarks and gluons, form a new phase of matter, the so called quark-gluon plasma. This "deconfinement" phase transition from hadronic matter to quark-gluon matter takes place at a temperature of about 170 MeV (at net baryon density zero) which is 130 thousand times hotter than the interior of the sun. Such conditions did exist in the early universe a few microseconds after the big bang and can be created in heavy ion collisions at ultra-relativistic energies as provided by the Relativistic Heavy Ion Collider (RHIC) in Brookhaven and by the Large Hadron Collider (LHC) at CERN. In highly compressed cold nuclear matter - as it may exist in the interior of neutron stars - the baryons also lose their identity and dissolve into quarks and gluons. The critical density at which this transition occurs, however, is not known. The same is true for the entire high-density area of the phase diagram. At very high densities and low temperatures, beyond the deconfinement transition, a new phase is expected: the quarks are correlated and form a color superconductor. At the "critical point" the deconfinement/chiral phase transition is predicted to change its character. Heavy-ion collisions at

FAIR energies permit the exploration of the "terra incognita" of the QCD phase diagram in the region of high baryon densities. This research program is complementary to the investigations performed at RHIC and LHC.

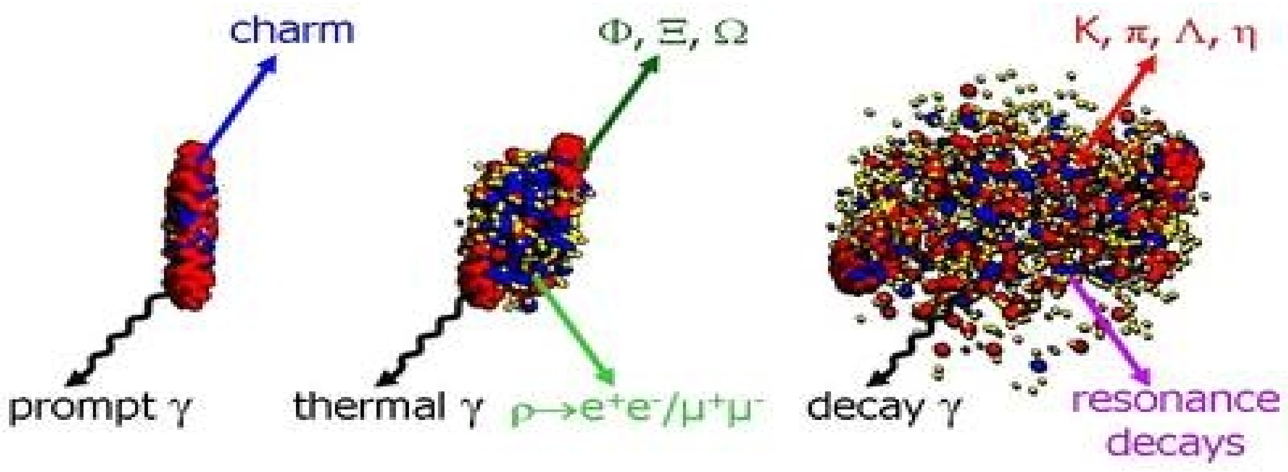

Figure 2: Sketch of the expansion phase of a U+U collision at 23 GeV/nucleon beam energy at different time steps: initial stage where the two Lorentz-contracted nuclei overlap (left), high density phase (middle), and final stage ("freeze-out") when all hadrons have been formed (right). Projectile and target nucleons are illustrated in red, exited baryons in blue, mesons in yellow. Different particles are created in different stages of the collisions or escape from the interaction region at different times. Almost 1000 charged particles are created in such a collision, most of them are pions.

By exploring the phase diagram, one probes the strong interaction andits underlying theory, Quantum Chromo Dynamics (QCD). In particular, fundamental properties of QCD such as confinement and the broken chiral symmetry, which is related to the origin of hadron masses, can be explored in heavy-ion collisions. A quantitative understanding of these two phenomena is still lacking and hence poses a challenge for future research. An experimental approach to these problems is to search for modifications of hadron properties in a dense and hot nuclear mediumand for deconfined matter consisting of quarks and gluons.

In the region of highest baryon densities and moderate temperatures the QCD phase diagram is only little explored. Baryon densities of up to about 3 times that of nuclei can be produced and have been investigated in heavy-ion collisions at the present SIS18 accelerator of GSI. The highest net baryon densities are expected for nuclear collisions in the beam energy range between 10 and 40 GeV/u. The energy range up to 15 GeV/u was pioneered at the AGS in Brookhaven. In a second generation experiment the energy range from 10 to 40 GeV/u should be scanned searching for:

-in-medium modifications of hadrons in dense matter;

-indications of the deconfinement phase transition at high baryon densities;

-the critical point providing direct evidence for a phase boundary;

-exotic states of matter such as condensates of strange particles.

The approach of the CBM experiment towards these goals is to measure simultaneously observables which are sensitive to high density effects and phase transitions (see figure 2 for an illustration). In particular, the research program is focused on the investigation of:

-short-lived light vector mesons (e.g. the ρ-meson) which decay into electron-positron pairs. These penetrating probes carry undistorted information from the dense fireball;

-strange particles, in particular baryons (anti-baryons) containing more than one strange (anti-strange) quark, so called multistrange hyperons (Λ, Ξ, Ω);

-mesons containing charm or anti-charm quarks (D, J/Ψ);

-collective flow of all observed particles. event-by-event fluctuations.

In the CBM experiment, particle multiplicities and phase-space distributions, the collision centrality and the reaction plane will be determined. For example, the study of collective flow of charmonium and multi-strange hyperons will shed light on the production and propagation of these rare probes in dense baryonic matter. The simultaneous measurement of various particles permits the study of cross correlations. This synergy effect opens a new perspective for the experimental investigation of nuclear matter under extreme conditions.

The CBM detector. The goal of the experiment is to measure multiplicities, phase-space distributions and flow of protons, pions, kaons, hyperons, hadronic resonances, light vector mesons, charmonium and open charm including their correlations and event-by-event fluctuations in heavy-ion collisions.

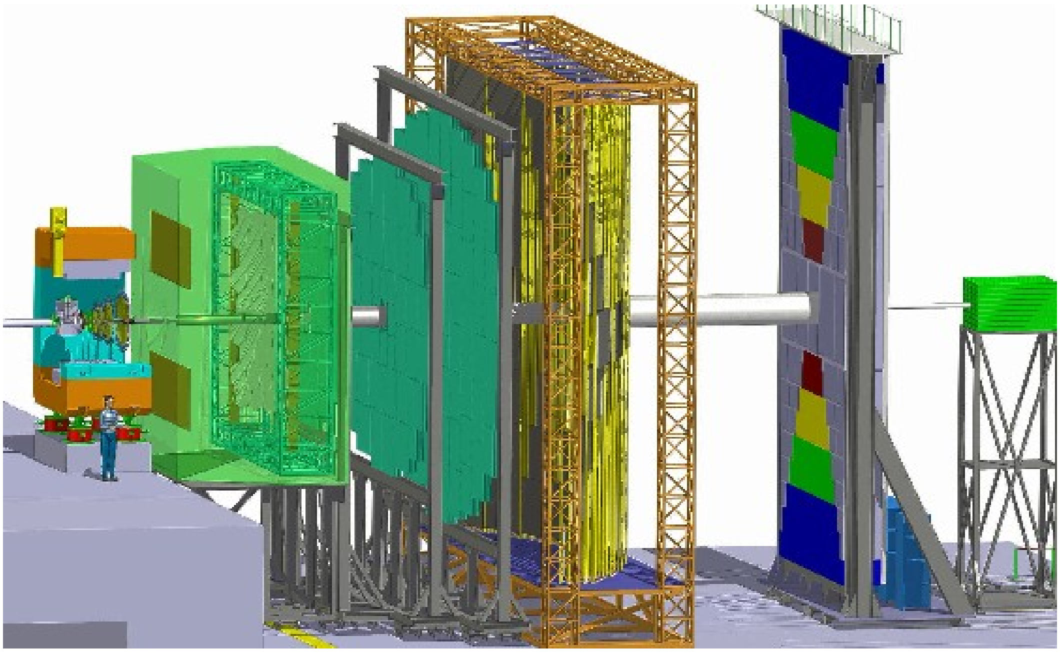

Figure 3: CBM setup for electron detection option. It includes superconducting dipole magnet, Vertex Detector, Silicon Tracker System, Ring Imaging Cherenkov detector, Transition Radiation Detector, Time of Flight System based on Resistive Plate Chambers, Electromagnetic Calorimeter, Projectile Spectator Detector.

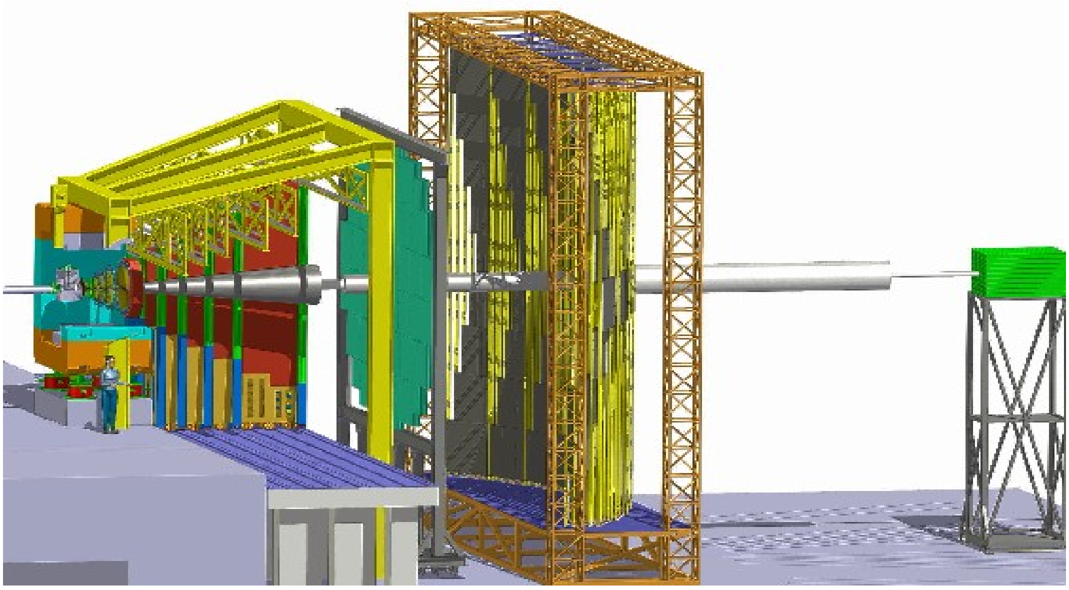

Figure 4: CBM setup for muon detection option. It includes superconducting dipole magnet, MicroVertex Detector, Silicon Tracker System, Muon Chambers detector based on GEM and Straw tubes, 1 station of Transition Radiation Detector, Time of Flight System based on Resistive Plate Chambers, Projectile Spectator Detector.

The technical challenge of the CBM experiment is to identify both, hadrons and leptons, and to filter out rare probes at reaction rates of up to 10 MHz with charged particle multiplicities of up to 1000 per event. Measurements at these high rates cannot be performed with slow detectors like Time-Projection Chambers (TPC), but rather require extremely fast and radiation hard detector (and electronic) components. Moreover, the experiment has to provide lepton identi_cation, high-resolution secondary vertex determination and a high speed trigger and data acquisition system. The CBM detector system will have the capability to measure both electrons and muons. This approach combines the advantages of both methods, and guarantees reliable results as in the end both data sets should agree to each other in spite of the very different background sources. The layout of the CBM experimental setup is sketched in Figs. 3 and 4. The heart of the experiment will be a silicon tracking and vertex detection system installed in a large acceptance dipole magnet. The Silicon Tracking System (STS) consists of low-mass silicon micro-strip detectors possibly complemented by one or two hybrid-pixel detector layers providing unambiguous space point measurements. The STS allows for track reconstruction in a wide momentum range from about 100 MeV up to more than 10 GeV with a momentum resolution of about 1 %. The Micro-Vertex Detector (MVD) is needed to determine secondary vertices with high precision for ***D*** meson identification. The MVD consists of two layers of ultra-thin and highly-granulated Monolithic Active silicon Pixel Sensors (MAPS) which are located close to the target. The measurement of electrons will be performed with a Ring Imaging Cherenkov (RICH) detector (for momenta below 8-10 GeV/c) together with Transition Radiation Detectors (TRD) for electrons with momenta above 1.5 GeV/c. Muons will be measured with an active hadron absorber system consisting of iron layers and muon tracking chambers (MuCh). For muon measurements the MuCh will be moved to the position of the RICH. Charged hadron identification will be performed by a time-of-flight (TOF) measurement with a wall of RPCs located at a distance of 10 m behind the target. The setup is complemented by an Electromagnetic Calorimeter (ECAL) in selected regions of phase space providing information on photons and neutral particles, and by a Projectile Spectator Detector (PSD) needed for the determination of the collision centrality and the orientation of the reaction plane. A key feature of the CBM experiment is online event selection which requires free streaming read-out electronics and fast algorithms running on computer farms based on future many-core architectures.

JINR contribution to CBM.

-The physicists from JINR are responsible for the expertise of the design, of the CBM Superconducting Dipole Magnet. The JINR physicists performed the magnetic and stress calculation for the several options of the magnet. They played a leading role in the preparation of the CBM Technical Design Report (TDR) for the Superconducting Dipole Magnet. The TDR was accepted by FAIR Council in 2014. The results obtained in 2016-2020 are published in refs [1-23]. JINR within international experts group participates in the expertise to be ensure that the required parameters of the CBM Dipole Superconducting Magnet and its reliable functionality are satisfied by the design proposal from BINP. JINR already participated in the Conceptual Design Review (CDR), in the Preliminary Design Review (PDR) and will participate in the Final Design Review (FDR) of the CBM Dipole Superconducting Magnet. JINR performs the magnetic field analysis with TOSCA, structural analysis with ANSYS, The design of a new option of the shielding box providing the blocking of the penetration of the magnetic field in the working chamber for a new version of the RICH photodetectors is on the track. The JINR experts provide of the three-dimensional maps of the magnetic field distribution for the needs of computer simulation of physical processes in the CBM experiment for electron and muon options of the detector. JINR develops the data base for the magnet. The JINR experts will participate in the follow up of the production and in the Factory Acceptance Test (FAT) and Site Acceptance Test (SAT).

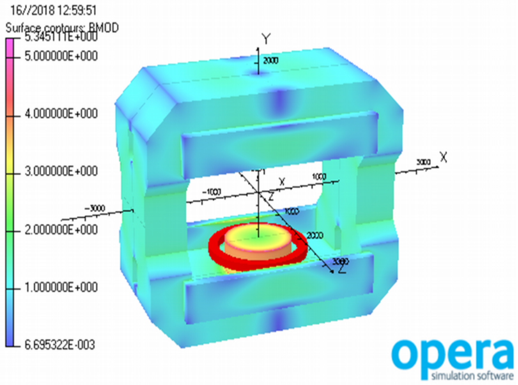

Figure 5: The CBM magnet saturation picture in OPERA model.

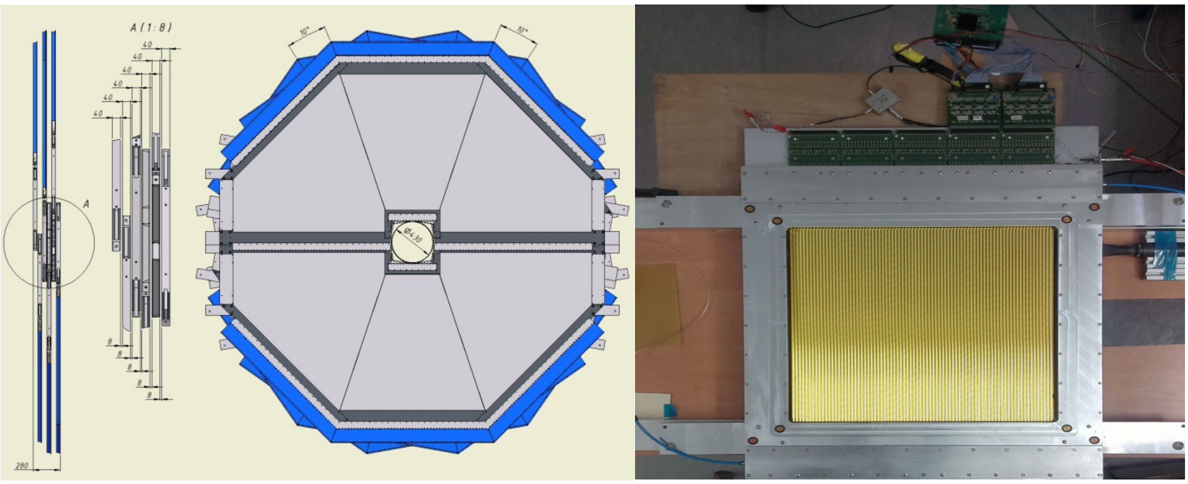

Figure 6: Schematic view of the muon detectors based on straw tube technology.

-The physicists from JINR are responsible for the R&D of straw detectors as two last (3-rd and 4-th) tracking stations for the MuCH detector. These tracking detectors will be based on the straw tube technology. The JINR physicists produced and tested several straw tubes prototypes, they produced full size prototype of the straw detector and straw tube prototype for mCBM shown in left and right panels of figure 6, respectively. New FEE readout board is developed using new ASIC. The results obtained in 2016-2020 are published in refs [24-30]. These developments will be applied also at NICA (for instance, for tracker and test zone detectors at SPD).

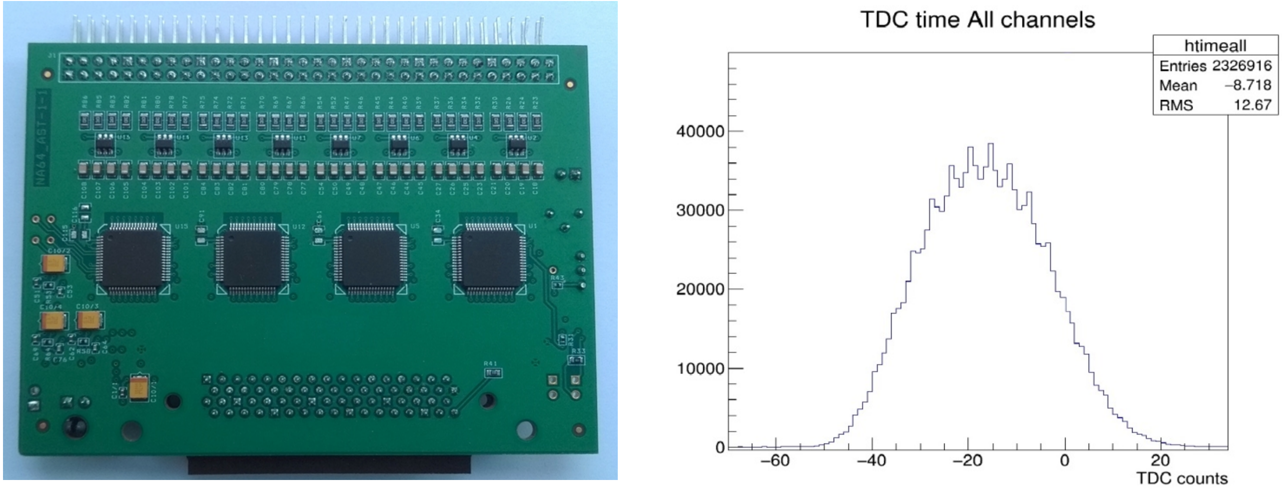

Figure 7: Front-end electronics PCB for straws (left) and drift time for 32 straws (right).

-JINR physicists play a key role in the development of the algorithms and software for track and ring reconstruction in MuCH, TRD, MVD and RICH detectors as well as for the global track reconstruction. Ring reconstruction is based on the Hough Transform method. The track reconstruction methods are based on the track following and Kalman filter procedures. The JINR team participates in the FLES software development using different manycore CPUs and GPUs platforms. They develop so-called 4D- event reconstruction procedure based on the use of the time slice information, as well as the CBM detectors data bases. The following studies have been carried out with a significant role of JINR:

Time-based cluster finder for the STS detector in the CBM experiment was developed and integrated into the CbmRoot. STS hit finder was updated for work with time slices.

L1 CA track finder in the CBM experiment was improved for work with MVD detector. MVD and STS hits now are used together without any difference between them for the algorithm. It improves the tracks quality and allows to find short-lived particles, which decay at the beginning of the STS detector.

Time based hit finder/clusterizer for the Time of Flight (ToF) detecting system has been developed.

A software library for standalone track reconstruction (Binned Tracker algorithm) in MUCH in the time based mode (without preliminary data subdivision to events) has been created. The software has optimized for SIS300 setup and SIS100 and included into the CbmRoot.

A simple and effective trigger option for detecting rare J/ψ →μ+μ- events and background suppression has been proposed. For its implementation, only information recorded by the coordinate detectors of the MUCH station is required.

Standalone track reconstruction based on Binned Tracker algorithm in TRD detector has been done. The method for selection of the J/ψ→e+e - decays based on the fast Binned Tracker algorithm for track reconstruction of charged particles has been developed. New criteria for the selection of the useful events with TRD have been developed: limit on the track deviation in the TRD and the distances between the tracks forming the J/ψ-candidates. These criteria make it possible to further suppress the combinatorial background with minimal loss of signal events. The comparison of different methods for particle identification with the transition radiation detector TRD was carried out. As a result the ω(k,n) goodness-of-fit criterion was chosen according to the efficiency-speed-reliability ratio.

The possibility of heavy fragments identification using energy loss method in the STS detector was studied. The ω(k,n) criterion was successfully adapted for the separation of the doubly charged particles from singly charged and included into the CBMROOT. The combination of the energy loss method with the ω(k,n) criterion has shown high level of the background suppression without substantiation signal loss. The combination of the information from the TOF and STS detectors allowed to separate 3He and 4He from the deuteron background.

Cellular Automaton (CA) track finding algorithm was investigated in application to the TPC data in the STAR experiment within the FAIR Phase 0 as a part of preparation to the Beam Energy Scan II (BES II) program. A method for searching of very low momentum tracks in the TPC detector has been developed to improve tracking in the eTOF (CBM) detector as a part of FiXed Target (FXT) program within BES-II.

The missing mass method for reconstruction of decays with neutral daughter has been developed. With TOF PID the missing mass method reconstructs particles with high efficiency and S/B ratio. Further the mathematics of the missing mass method for reconstruction of the strange particle is improved: reconstruction of the whole decay is done in one go. Two-step search of the DCA point between mother and daughter tracks now takes into account inhomogeneous magnetic field. Two-step extrapolation and correct estimation of the vertex position has been done to improve the fit quality. New method for reduction of background from interaction with the STS stations material has been proposed. As a result of improvements the efficiency of reconstruction of strange particles has approximately doubled, significance by 25-30%.

The “CATIA-GDML geometry builder” package has been optimized and extended with a number of new tools.

Multiple versions of parameterized Monte-Carlo geometry of the CBM RICH detector have been build using the “CATIA-GDML geometry builder” and included into the CbmRoot framework following the development of the engineering design. A few versions of the magnetic shield for the photosensitive camera have been developed and included into the CbmRoot simulation framework.

The analysis of the impact on the basic characteristics of the magnetic field caused by expansion of the dipole magnet aperture to 144cm has been conducted. Three-dimensional models of the magnetic system for two options of the CBM experiment (MUCH and RICH) were built. We got a picture of the magnetic field distribution in the area of the RICH photodetectors protected by a screen. The magnetic field maps for both options of the magnetic system with an extended aperture have been prepared.

Detailed study of the CBM RICH readout and data acquisition system (DAQ) prototype has been performed. The method of time corrections determination from beam data has been developed allowing dynamic calibration without additional measurements. The procedure allows to determine time resolution of the PMT readout chain. This method has been implemented in software and applied to estimate the time resolution of CBM RICH readout chain.

The three-dimensional CBM experiment magnetic system simulation for MUON option was carried out. The maps of the magnetic field distribution were prepared with the aim at enabling simulations of physical processes.

The Geometry Database (Geometry DB) was developed. The purpose of this database is to provide convenient tools for managing the geometry modules of the detectors, assembling various versions of the CBM setup as a combination of geometry modules and additional files. The CBM users of the Geometry DB may use both GUI (Graphical User Interface) and API (Application Programming Interface) tools for working with it. The privilages system supports different types of users for working with this database.

A workable prototype of the Geometry DB for the BM@N experiment was developed on the basis of the experience of the Geometry DB design for the CBM experiment. The developed information system includes a database, intuitive and compact GUI tools and API tools as a set of ROOT macros. The Geometry DB is being prepared for production.

The main results of this activity in 2016-2020 yy are published and reported [31-69]. The developed approaches can be adopted also for NICA experiments: MPD, BM@N and SPD. This activity will be continued in 2021-2025 yy.

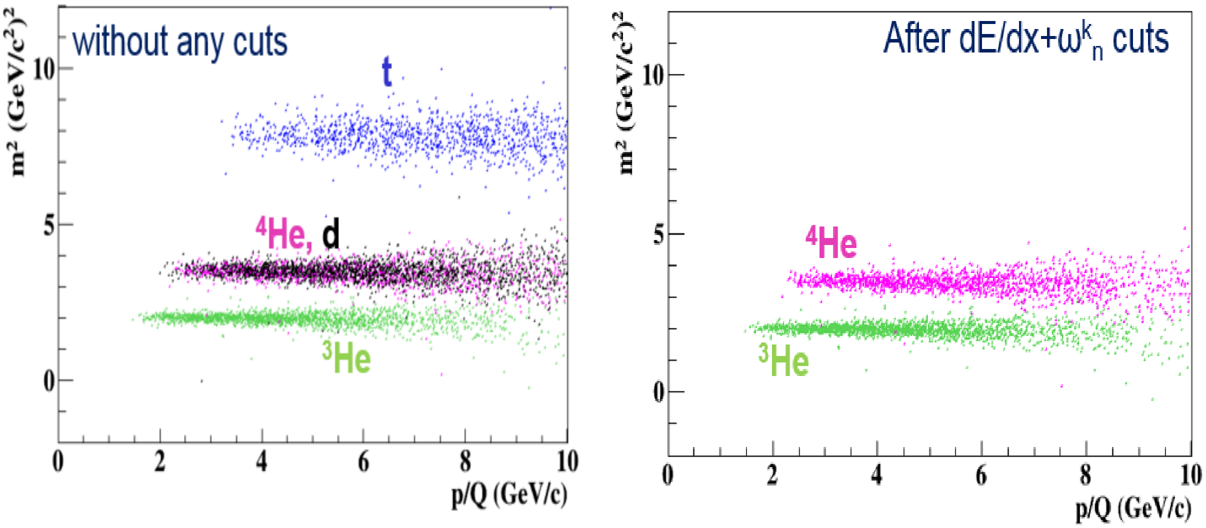

Figure 8: Selection of the nuclear fragments in Au+Au collisions: without cuts (left) and with the application of the dE/dx information in STS and $\omega^k{}_n$ criterion (right).

-JINR physicists participate in the simulation of the observables of the heavy ion collisions within the CBMRoot framework. The goal of the multi-particles dynamics studies is to perform the simulation and feasibility studies for different observables with hadrons and nuclear fragments sensitive to the details of the nuclear matter modification in heavy ion collisions at CBM at SIS100 and SIS300 energies. The program of the investigations includes the simulation of the multi-hadrons correlations in the central and non-central heavy ion collisions at CBM at SIS100/SIS300 energies as a function of the transverse momentum and rapidity, as well as the simulation for the light nuclear fragments and hyper-nuclei production in the central Au+Au collisions at SIS100 energies. Development of the algorithms of the physics processes selection for different subdetectors of CBM are also performed. Development of the algorithms of the physics processes selection for different subdetectors of CBM is under permanent work. The simulation of the C_2 azimuthal correlations, sensitive to the mini-jet production, for the central Au+Au collisions at SIS100 energies for different event generators is performed. “Vector-finding” approach to reconstruct the tracks of muons in MUCH CBM based on the building of the track segments (vectors) for each MUCH station and further merging of them with each other (and finally with STS tracks) through the absorbers is optimized for the geometry of the CBM muon option. The advantage of this approach is that the vector finder can be run for all stations in parallel, the procedure is based on the straight line fit of a few measurements, what provides the possibility to be used in FLES. “Vector-finding” approach to reconstruct the tracks of muons developed for MUCH CBM adopted for the reconstruction of ω– meson via measurements of di-muons is under development to select J/ψ→μ+μ- decay. These approaches can be adopted for muon detector at SPD at NICA. The results obtained in 2016-2020 are published and reported in refs [70-82]. Such investigation will be continued in 2021-2025 yy.

-JINR physicists participate in further detectors R&D, especially, for SIS300 version, and testbeams at different accelerators. In particular, they works together with physicists from NPI (Rez, Czech republic) and INR (Moscow) on the studies of the radiation hardness of different SiPMs and APDs for calorimetry at CBM and BM@N as well as for the luminosity and polarization monitoring at SPD [83-85]. Development of the additional high granularity detector placed in front of PSD will help to detect nuclear fragments and to improve the centrality and reaction plane determination.

Plans for 2021-2025 years. According to the FAIR plans the minimal start version (MSV) of CBM experiment should be prepared and installed in CBM/HADES hall to be ready for the commissioning with SIS1000 beam. Therefore, 2021-2025 is the Construction Phase of the CBM detector. JINR as a part of CBM Collaboration has to sign the Construction MoU and fulfill its obligations.

The JINR participation in CBM:

- the expertise of the design and particpation in the maintenance and commissioning of the CBM Superconducting Dipole Magnet.
- the development of the algorithms and software for track and ring reconstruction in different CBM subdetectors as well as for the global track reconstruction.
- preparation of the physics program for multi-particles dynamics at SIS100 energies.
- the R&D of the straw detectors prototype as an the option for two last (3-rd and 4-th) tracking stations for the MuCH detector, R&D of the detectors with SiPM readout.
- Participation in the data taking at mCBM, participation in the analysis of the data obtained within FAIR PHASE0 program.
- Participation in the commissioning of the CBM detector.

Time schedule.

In 2021 development of technical documentation and preparation of production of detectors, participation in the magnet expertise, creation of databases, simulation of the detectors and setup, development of a physics program for the CBM project; participation in FAIR Phase 0 experiments at SIS18.

In 2022-2023 manufacture of detectors, participation in the magnet expertise, development of the reconstruction of events, the elaboration of the physics program of studies on the CBM project; participation in development of the detector prototypes and event reconstruction algorithms; participation in FAIR Phase 0 experiments at SIS18 and Nuclotron.

In 2024-2025 installation of the magnet and detectors in the CBM/HADES experimental hall, participation in the commissioning of different detector systems and CBM detector as a whole, development of the reconstruction of events, the elaboration of the physics program of studies on the CBM project; preparation of the CBM detector to the data taking.

Expected results in 2025. Upon completion of the 5-years term is expected to finish the establishment of the CBM subsystems, mediated by JINR. In particular, it is planned to produce a part detectors for the front stations of the silicon tracking system based on silicon strip detectors and incorporate them into CBM detector. Program of the researches on pions with large transverse momenta, nuclear fragments, correlation measurements in nucleus-nucleus processes will be prepared. A number of computer programs for the reconstruction of events of different types in CBM. The experimental data within FAIR Phase 0 program will be obtained.

Collaborations and synergies between NICA-MPD and FAIR-CBM.

MPD at NICA and CBM at FAIR are two new generation detector systems designed to perform high-precision measurements in order to explore the QCD phase diagram at neutron star core densities. The research programs of both facilities exhibit a large scientific overlap, but are complementary with respect to the beam energy range.

The collaboration between the teams from JINR and GSI lasts for more than 15 years. Two projects were funded within the JINR-BMBF agreement: In 2004 the project “CBM” was launched, covering the development of a large-aperture superconducting dipole magnet, the development of fast gas detectors and global tracking algorithms, and the study of multi-particle dynamics in heavy-ion collisions. The software packages developed for feasibility studies and event reconstruction were used both for CBM and MPD.

The second common project related to the joint development of Silicon micro-strip detectors started in 2009. In addition to this activity, a joint project on the development of a Silicon tracking detector for the BM@N experiment and MPD/NICA was launched in 2012 and financed by the BMBF by 2.1 M€. According German-Russian Federation Road Map about 14 M€ will be delivered for join activity at NICA.

The experience obtained by JINR physicists in these developments can be used for the MPD, SPD and BM@N at NICA.

Requested resources.

The requested resources for 2021-2025 are 871k$ including 371k$ from JINR budget and JINR-BMBF grant (90k€ /year). The additional resources can be obtained from BMBF, RFBR, JINR PP grants as well as from FAIR-JINR contracts.

References.

[1] Yu.V.Gusakov, A.V.Bychkov, P.K.Kurilkin, V.P.Ladygin, A.I.Malakhov, A.V.Shabunov, Feed box for CBM superconducting dipole magnet , CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p.4.

[2] Yu.V.Gusakov, A.V.Bychkov, P.K.Kurilkin, V.P.Ladygin, A.I.Malakhov, G.Moritz, P.Senger, A.V.Shabunov, CBM superconducting dipole magnet, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p.5.

[3] P.Kurilkin, A.Bychkov, Yu.Gusakov, V.Ladygin, A.Malakhov, A.Shabunov, The quench protection scheme based on the heating of the CBM magnet coil, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p.6.

[4] P.Kurilkin, P.Szwangruber, E.Floch, F.Toral, V.Ladygin, A.Malakhov, 3D calculations for the quench protection scheme based on the heating of the CBM magnet coil, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p.7.

[5] P.K.Kurilkin et al., Quench calculations for the superconducting dipole magnet of CBM experiment at FAIR , in Proceedings of the 4-th International Workshop for young scientists with research interests focused on physics at FAIR (FAIRNESS 2016), 14-19 February 2016, Garmisch-Partenkirchen, Germany, J.Phys.Conf.Ser. 742 (2016) 012017.

[7] Yu.V.Gusakov et al., Summary and Outlook Magnet, talk at the 27th CBM Collaboration Meeting, 11-15 April 2016, GSI, Darmstadt, Germany.

[8] P.K.Kurilkin et al., Superconducting dipole magnet for the CBM experiment at FAIR, Proceedings of the XXIII-rd International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics", 19-24 September 2016, Dubna, Russian Federation, EPJ Web.Conf. 138 (2017) 12001.

[9] P.G.Akishin et al., 3D calculation for enlarged CBM superconducting dipole magnet, CBM Progress Report 2016, ISBN 978-3-9815227-4-7, GSI, Darmstadt, 2017, p.6.

[10] Yu.V.Gusakov, A.V.Bychkov, P.K.Kurilkin, V.P.Ladygin, A.I.Malakhov, A.V.Shabunov, CBM superconducting dipole magnet with the enlarged aperture, CBM Progress Report 2016, ISBN 978-3-9815227-4-7, GSI, Darmstadt, 2017, p.7.

[11] P.K.Kurilkin et al., 3D calculation for the CBM magnet quench protection system, CBM Progress Report 2016, ISBN 978-3-9815227-4-7, GSI, Darmstadt, 2017, pp.8-9.

[12] V.Ladygin et al., Status of enlarged CBM superconducting dipole magnet, talk at the 29th CBM Collaboration Meeting, 20-24 March 2017, GSI, Darmstadt, Germany.

[13] P.G. Akishin et al., ANSYS and TOSCA calculations for new design of the CBM superconducting dipole magnet, CBM Progress Report 2017, ISBN 978-3-9815227-5-4, GSI, Darmstadt, 2018, pp.7-8.

[14] P.G. Akishin, A.A. Sapozhnikov, V.P. Ladygin, Magnetic field calculations with the volume integral equation method for CBM dipole magnet, CBM Progress Report 2018, ISBN 978-3-9815227-6-1, GSI, Darmstadt, 2019, pp.123-124.

[15] P.G. Akishin, Yu.V. Gusakov, A.V. Bychkov, V.P. Ladygin, 3D- simulation for new design of the CBM

superconducting dipole magnet, CBM Progress Report 2018, ISBN 978-3-9815227-6-1, GSI, Darmstadt, 2019, pp.127-128.

[16] P.G. Akishin, V.P. Ladygin, Magnetic field calculations for RICH detector, CBM Progress Report 2018, ISBN 978-3-9815227-6-1, GSI, Darmstadt, 2019, pp.125-126.

[17] P. Akishin, Yu. Gusakov, ANSYS and OPERA calculation for new design of the CBM magnet, talk at the 31st CBM Collaboration Meeting, 19-23 March 2018, GSI, Darmstadt, Germany.

[18] P. Akishin, 3D modelling of the CBM dipole magnet, talk at the 32nd CBM Collaboration Meeting, 1-5 October 2018, GSI, Darmstadt, Germany.

[19] P.G.Akishin, The CBM magnet system field update for the MUCH option, talk at the 33rd CBM Collaboration Meeting, 1-5 April 2019, GSI, Darmstadt, Germany.

[20] Yu.V.Gusakov, Stress calculation of CBM dipole magnet, talk at the 33rd CBM Collaboration Meeting, 1-5 April 2019, GSI, Darmstadt, Germany.

[21] P. G. Akishin and V.P.Ladygin, 3D- magnetic field calculations for the muon setup of the CBM experiment, CBM Progress Report 2019, ISBN 978-3-9815227-8-5, GSI, Darmstadt, pp.148-149.

[22] Yu.V. Gusakov, A.V. Bychkov, V.P. Ladygin, Stress calculations for the CBM superconducting dipole magnet coils, CBM Progress Report 2019, ISBN 978-3-9815227-8-5, GSI, Darmstadt, p.150.

[23] P.G.Akishin, The CBM RICH magnetic shielding box modelling, talk at the 36th CBM Collaboration Meeting (virtual), 19-23 October 2020, GSI, Darmstadt, Germany.

[24] A.Zinchenko, V.Myalkovskiy, D.Peshekhonov, V.Peshekhonov, Further development of the “vector finding” method for track reconstruction in the CBM-MUCH, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p.114.

[25] G.D.Kekelidze et al., Straw tube prototype for the CBM muon detector, CBM Progress Report 2016, ISBN 978-3-9815227-4-7, GSI, Darmstadt, 2017, p.85.

[26] G.D. Kekelidze, V.A. Kramarenko, V.P. Ladygin, V.M. Lysan, Rectangular straw tube detector prototype for CBM, CBM Progress Report 2018, ISBN 978-3-9815227-6-1, GSI, Darmstadt, 2019, p.60.

[27] G.D. Kekelidze, V.A. Kramarenko, V.P. Ladygin, V.M. Lysan, A.A. Solin, A.V. Solin, Front-end electronics for the straw tube detector, CBM Progress Report 2018, ISBN 978-3-9815227-6-1, GSI, Darmstadt, 2019, pp.61-62.

[28] S.Roy et al., Aging studies of Straw tube detector, CBM Progress Report 2018, ISBN 978-3-9815227-6-1, GSI, Darmstadt, 2019, p.68.

[29] S.Roy et al., R&D of Straw Tube detector for High Energy Physics experiments, Proceedings of the 64-th DAE BRNS Symposium on nuclear physics, DAE Symp.Nucl.Phys. 64 (2020) pp.990-991.

[30] S.Roy et al., Stability study and time resolution measurement of Straw Tube detectors, E-print: arXiv: 2007.12457 [physics.ins-det].

[31] V. Akishina, I. Kisel , Parallel 4-Dimensional Cellular Automaton Track Finder for the CBM Experiment, J.Phys.Conf.Ser.762 (2016) no.1,012047, DOI:10.1088/1742-6596/762/1/012047.

[32] G. Kozlov and I. Kisel, Time-based cluster finder for the CBM-STS detector, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016. p. 118

[33] T.O. Ablyazimov and V. V. Ivanov:, Online Selection of $J/\psi \rightarrow e^+e^-$ Decays in the CBM Experiment, EPJ Web of Conferences, 108, 02001 (2016) DOI: 10.1051/epjconf/201610802001

[34] E. Ovcharenko, S. Lebedev, T. Mahmoud, C. Pauly, Yu. Ryabov, C. Hoehne, V. Schetinin, Update of the MC-geometry of the RICH detector, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p.47.

[35] E. Ovcharenko, P. Akishin, C. Pauly, T. Mahmoud, Yu. Ryabov, C. Hoehne, V. Schetinin, Development of the magnetic shielding box for the CBM RICH camera, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p.53.

[36] E. Ovcharenko, S. Belogurov, C . Pauly, Study of p-terphenyl WLS effect on timing in the CBM RICH prototype, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p.60.

[37] S. Lebedev, C. Hoehne, and E. Ovcharenko, Implementation of the new RICH geometry in CBMROOT, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p.119.

[38] J. Adamczewski-Musch, ..., E. Ovcharenko, et al., RICH summary, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p.44.

[39] S. Lebedev and C. Höhne, First simulation results with the new RICH geometry, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p. 48.

[40] S. Lebedev and C. Höhne, Electron identification performance with the new RICH detector, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p. 49.

[41] G. Kozlov and I. Kisel, Time-based cluster finder for the CBM-STS detector, CBM Progress Report

2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p. 118.

[42] T. O. Ablyazimov and V. V. Ivanov, Visualization of track reconstruction in the MUCH detector, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p. 122.

[43] E. P. Akishina et al., Development of databases for the CBM experiment, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p. 123

[44] I. Kisel, P. Kisel, P. Senger, I. Vassiliev, M. Zyzak, Σ+ and Σ- reconstruction by the missing mass method, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0, GSI, Darmstadt, 2016, p. 130

[45] J. Adamczewski-Musch, ..., E. Ovcharenko, et al., The CBM RICH detector, JINST 11 (2016) no.05, C05016

[46] J. Adamczewski-Musch, ..., E. Ovcharenko, et al., The CBM RICH project, NIM A, doi: 10.1016/j.nima.2016.05.102

[47] J. Adamczewski-Musch, ..., E. Ovcharenko, et al., Development of the CBM RICH readout electronics and DAQ, NIM A 876 (2017) 76–79

[48] O. Yu. Derenovskaya, V. V. Ivanov and D.S. Ogorodnikova, J/ψ→e+e− decay selection criteria for Au-Au collisions at 10 AGeV, CBM Progress Report 2016, GSI Darmstadt, 2017, p. 173.

[49] O. Yu. Derenovskaya, T. O. Ablyazimov V. V. Ivanov, Towards to the J/ψ→e+e− decays triggering with TRD in the CBM experiment, EPJ Web of Conferences 173, 04004 (2018)

[50] O. Yu. Derenovskaya, V. V. Ivanov, J/ψ→e+e− decay selection criteria in the CBM experiment, J. Phys.: Conf. Ser. 937 012010 (2018).

[51] E. P. Akishina , E. I. Alexandrov , I. N. Alexandrov , I. A. Filozova , V. Friese , and V. V. Ivanov, Geometry database development for the CBM experiment, GSI Scientific Report 2016, GSI Darmstadt, 2017.

[52] E.P. Akishina, E.I. Alexandrov, I.N. Alexandrov, I.A. Filozova V. Friese, V.V. Ivanov, Development of the geometry database for the CBM experiment, Physics of Particles and Nuclei Letters, 2018, Vol. 15, No. 1, pp. 97–106.

[53] T.Ablyazimov, V.Ivanov, Fast reconstruction of muon trajectories in the MUCH detector of the CBM experiment, 2017, Physics of Particles and Nuclei Letters, 2017, Vol. 14, No. 3, pp. 504–511

[54] T.Ablyazimov, V.Friese, V.Ivanov, Finding the needle in the haystack: a charmonium trigger for the CBM experiment, Journal of Physics: Conf. Series 898 (2017) 032043

[55] I. Kisel, P. Kisel, P. Senger, I. Vassiliev, M. Zyzak. Σ+ and Σ- reconstruction by the missing mass method, CBM Progress Report 2016, ISBN 978-3-9815227-4-7, GSI, Darmstadt, 2017, p. 176.

[56] E.P.Akishina et al.: Geometry database development for the CBM experiment, CBM Progress report 2016, ISBN 978-3-9815227-4-7, GSI Darmstadt, 2017, p.162

[57] T. Ablyazimov, V. Friese and V. Ivanov: Time-based selection of J/ψ→μ-μ+ decays with the CBM-MUCH, CBM Progress report 2016, ISBN 978-3-9815227-4-7, GSI Darmstadt, 2017, p.170.

[58] O. Yu. Derenovskaya, V. V. Ivanov and D.S. Ogorodnikova: J/ψ→e-e+ decay selection criteria for Au-Au collisions at 10 AGeV, CBM Progress report 2016, ISBN 978-3-9815227-4-7, GSI Darmstadt, 2017, p.173 .

[59] E.P. Akishina et al.: Geometry database for the CBM experiment, CBM Progress Report 2017, ISBN 978-3-9815227-5-4, GSI Darmstadt, 2018, p. 142.

[60] T. Ablyazimov, V. Friese and V.V. Ivanov: Using the binned track finder in mCBM, CBM Progress Report 2017, ISBN 978-3-9815227-5-4, GSI Darmstadt, 2018, p. 189.

[61] T Ablyazimov, V Friese and V Ivanov, Time Based Global Track Reconstruction in CBM, EPJ Web of Conferences 173, 04001 (2018)

[62] E.P. Akishina, E.I. Alexandrov, I.N. Alexandrov, I.A. Filozova, V. Friese, K.V.Gegtsenberger, V.V. Ivanov, O.V. Rogachevsky, CEUR Workshop Proceedings, Vol.2267, 2018, pp. 504 – 508.

[63] O.Yu. Derenovskaya, V.V. Ivanov, I.O. Vassiliev, Yu.V. Russov, Heavy Fragments Identification Using Energy Loss Method in the STS Detector of the CBM Experiment, EPJ Web of Conferences 226, 03005 (2020).

[64] V. Friese, O. Yu. Derenovskaya, T.O. Ablyazimov, V. V. Ivanov and Yu. V. Russov: Selection of event data based on the J/ψ →$\mu^+\mu^-$ triggering, CBM Progress Report 2018, ISBN 978-3-9815227-6-1, GSI Darmstadt, 2019, p. 154.

[65] O. Yu. Derenovskaya, T. O. Ablyazimov, V. V. Ivanov, and Yu. V. Russov: Detecting Rare J/ψ → μ+μ− Events in the CBM Experiment, Physics of Particles and Nuclei Letters, 2020, Vol. 17, No. 2, pp. 246–249.

[66] O.Yu. Derenovskaya, V.V. Ivanov, I.O. Vassiliev, CBM Computing Note, CBM-CN-20001, 2020, 4 pp.

[67] E.P. Akishina, E.I. Alexandrov, I.N. Alexandrov, I.A. Filozova, V. Friese, V.V.Ivanov, Geometry Database for the CBM Experiment, CEUR Workshop Proc. 2019. V. 2507. P. 306 – 310. http://ceur-

ws.org/Vol-2507/306-310-paper-55.pdf

[68] E.P. Akishina, E.I. Alexandrov, I.N. Alexandrov, I.A. Filozova, V. Friese, and V.V.Ivanov, Evolution of the geometry database, CBM Progress Report 2018, ISBN 978-3-9815227-6-1, GSI, Darmstadt, 2019, p.167.

[69] Akishina E., Alexandrov E., Alexandrov I., Filozova I., Gertsenberger K., Ivanov V., Priakhina D., Shestakova G., Development of the Geometry Database for the BM@N Experiment of the NICA Project, Eur. Phys. J. Web Conf. MMCP 2019 selected papers. 2020. V. 226. 03003. 4 pp.

[70] V.P.Ladygin, M.I.Baznat, K.K.Gudima, N.B.Ladygina, Deuteron coalescence for central Au + Au collisions at 4 A·GeV, CBM Progress Report 2015, ISBN: 978-3-9815227-3-0 , GSI, Darmstadt, 2016, p.127.

[71] A.I.Zinchenko et al., Some results on CBM-MUCH simulation at SIS100, talk at the 27-th CBM Collaboration Meeting, 11-15 April 2016, GSI, Darmstadt, Germany.

[72] A.I.Zinchenko, Status of the vector finder for MUCH, talk at the 28-th CBM Collaboration Meeting, 26-30 September 2016, Eberhard Karls Universität Tübingen, Tübingen, Germany.

[73] O.Yu.Derenovskaya et al., Study of compressed baryonic matter at FAIR: JINR participation, Proceedings of the International session-conference of the NP section of RAS "Physics of fundamental interactions", 12-15 April 2016, Dubna, Russian Federation, Phys.Part.Nucl.48 (2017) 935.

[74] V.P.Ladygin et al., Investigations of compressed baryonic matter at the GSI accelerator complex, Proceedings of the XXIII-rd International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics", 19-24 September 2016, Dubna, Russian Federation, EPJ Web.Conf. 138 (2017) 01020.

[75] T. Ablyazimov et al., Challenges in QCD matter physics - The Compressed Baryonic Matter experiment at FAIR, Eur.Phys.J. A53 (2017) 60.

[76] A.I.Zinchenko and V.P.Ladygin, Improvements to the vector finding-based track reconstruction method in the CBM MUCH , CBM Progress Report 2016, ISBN 978-3-9815227-4-7, GSI, Darmstadt, 2017, p.169.

[77] S.P.Avdeyev et al., Study of the source velocity with the light relativistic ions at CBM, CBM Progress Report 2016, ISBN 978-3-9815227-4-7, GSI, Darmstadt, 2017, p.187.

[39] A.Zinchenko, Status of the vector track finder, talk at the 30th CBM Collaboration Meeting, 24-28 September 2017, CCNU, Wuhan, China.

[78] A.Zinchenko and V.Ladygin, Application of the vector finding-based track reconstruction method for the CBM muon setup, CBM Progress Report 2017, ISBN 978-3-9815227-5-4, GSI, Darmstadt, 2018, p.146.

[79] S.Avdeyev et al., Time scale of the thermal multifragmentation in ^{4}He + Au at FAIR energies, CBM Progress Report 2017, ISBN 978-3-9815227-5-4, GSI, Darmstadt, 2018, p.162.

[80] A.Zinchenko and V.Ladygin, Current status of the vector finding-based track reconstruction method at the CBM muon setup, CBM Progress Report 2018, ISBN 978-3-9815227-6-1, GSI, Darmstadt, 2019, p.153.

[81] A.Zinchenko and V.Ladygin,Status of the vector track finder, talk at the 31st CBM Collaboration Meeting, 19-23 March 2018, GSI, Darmstadt, Germany.

[82] A.Zinchenko and V.Ladygin, Status of the track reconstruction for the muon setup, talk at the 32nd CBM Collaboration Meeting, 1-5 October 2018, GSI, Darmstadt, Germany.

[83] V.Kushpil, V.Mikhaylov, A. Kugler, S.Kushpil, V.Ladygin, S.Reznikov, O.Svoboda, P.Tlustý, Neutron irradiation study of silicon photomultipliers from different vendors, Nucl.Instrum.Meth. In Phys.Res. A845 (2017) 114-117.

[84] V.Kushpil, V.Ladygin, S.Kushpil, Study of electric field in SiPM active volume by the volt-farad characteristics analysis, EPJ Web Conf. 204 (2019) 07008.

[85] A.Tishevsky et al., Development of the scintillation detector prototypes with SiPM readout for SPD at NICA, talk at 5th ICPPA-2020, 5-9 October, Moscow, submitted to J.Phys.:Conf.Ser.