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CBM Experiment
Local and Global Implications

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***Abstract*—The research area of the compressed baryonic matter - CBM experiment (FAIR/GSI in Darmstadt) is sub-nuclear physics, thus hadron-baryon and quark-gluon, and the essence of phase transitions in the area of hot nuclear matter, and dense strongly interacting matter. Our interest in this paper are mainly considerations on the impact of such large infrastructural experiments and possibilities they give to local, smaller but very active, university based research groups and communities. Research and technical input from such groups is depicted on the background of the CBM detector infrastructure and electronic instrumentation just under design and test fabrication for this experiment. An essential input to this research originates from Poland via the agreed in-kind contribution. The areas of expertise of these groups are: superconductivity, structural large scale cabling, precision machined parts, RF and microwave technology, analog and advanced digital electronics, distributed measurement and control systems, etc.**

***Keywords*—CBM experiment, compressed baryonic matter, advanced electronic systems, measurement systems, DAQ systems, FAIR, GSI, European large research infrastructures**

I. Introduction

THE paper describes compressed baryonic matter - CBM experiment [fair-center.eu/for-users/experiments/cbm], [cbm-wiki.gsi.de], [1-2] which is one of experiments under preparation to be realized inside the newly build FAIR infrastructure [fair-center.eu] in GSI Darmstadt [gsi.de]. Its aim 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. The baryon and lepton numbers conservation rule was broken during the baryogenesis, when $T>10^{12}$K, which is a physics outside the SM and tried to be described by GUT. Chemical potential of baryons and fermions is associated with the number of particles and the temperature via the relevant statistics of Bose-Einstein and Fermi-Dirac. The CBM experiment research concerns such exotic matter and the conditions of baryogenesis, hadronization and strangeness. Appropriate experimental conditions are obtained during collisions of heavy ions like Au-Au. Heavy ions may also be probed by protons.

The experiment will use new fast-ramping, superconducting, heavy-ion synchrotron SIS100 (later after upgrade also SIS300) accelerator. There are a lot of sources describing FAIR infrastructure, and also its particular experiments like the CBM. There are, however, only a few papers touching special aspects of such discovery class infrastructures, like local social and correlated impact on the research communities, including young researchers.

FAIR experiences now some possible delay in the originally planned realization schedules which stems from financial issues and the recent change in the European safety regulations concerning nuclear infrastructures. FAIR – a purely scientific and leading edge research infrastructure, is by no means a nuclear power station, but such accidents, among others, like the Fukushima disaster, trigger a lot of afterthoughts. Despite the predicted now (2016) some delays, the devoted communities involved in the realization of FAIR, including Polish FAIR community, are strongly determined to continue, and even try hard to make up for possible delays. Facility operation should start in roughly a decade from beginning of the construction and continue for the next two decades. This is the time scale of the great and unique experiment of discovery class. The financial scale amounts to billion level of Euro, including approx. 10% of the cost of programming infrastructure, electronics and computer ICT. Some of these costs, amounting to tens of M€, shall be borne by our country as an in kind contribution. Creative contribution from Poland also includes the work of young scientists from universities.

Well organized Polish community participates in FAIR and in CBM via the Femtophysics Consortium and intergovernmental agreement concerning the in-kind contributions. Relevant cooperation agreements were signed internally in Poland with appropriate involved institutions, as well as internationally with the Hosts in Darmstadt. The participation of Poland in FAIR is of the in-kind type. Recently one of the first in-kind contributions was delivered. This was the first piece of cryogenic–bypass line, made at the Wrocław UT [cerncourier.com/cws/article/cern/63967]. The Active participation of Polish physics and advanced engineering communities in preparing research programs of FAIR, CBM and similar large European class and discovery scale infrastructures is of utmost importance not only globally but also locally. The local meaning is very special since Poland has no large research infrastructure in physics and engineering of the European class. Young Polish researchers who are interested in large experiments have to work somewhere. Due to mutual agreements they work in CERN, ESO, GSI and FAIR, PSI, INFN, DESY, European synchrotron light sources, etc. Increasingly frequently they do their Ph.D. degrees in cooperation between two institutions – large European laboratory and Polish university, to the benefit of young people and both involved institutions. Also to the huge benefit of the European Research Area -ERA.

Project is realized within the Femtophysics Consortium, via in-kind contribution to CBM FAIR, Darmstadt.

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There has recently been published a series of articles describing large-scale, electronic instrumentation equipment of world-class experiments in high energy physics of elementary particles, nuclear physics, high temperature plasma, accelerator and laser technologies of extreme intensities and energies, and particle astrophysics, with active participation of young researchers from universities. These experiments have a common denominator: they are of ultimate infrastructural scale, unfortunately they are not located in Poland, they are infrastructures of cutting edge discovery class, in all of them take part young researchers from Poland, and especially from Warsaw University of Technology -WUT, but also AGH Kraków, Wrocław UT, Łódź UT. Previous articles described research infrastructures and experiments in lasers, accelerators, tokamaks [3-6], like LCLS, FLASH, EXFEL, TESLA, LHC, CMS, TOTEM, JET, ITER and CBM [7]. But first of all, the participation and intellectual input of young researchers from the Institute of Electronic Systems of WUT in all these experiments was emphasized. This article is a continuation of this series of publications, trying to show the impact of large experiments on small, university based, young research teams.

Construction of instruments for such large experiments is a real challenge, not only for young scientists. The work is done in teams and tightly scheduled. The components of the work are not only research or technical and include: an international team, very specific and well established habits of teamwork, specific sometimes hermetic team language relevant to particular experiment, used advanced tools, equipment and software, complex variety of laboratory equipment, conditions and methods of work, management of the research team, schedules, system implementations and commissioning, frequent seminars, joint decisions to continue particular work directions, very accurate weighing of the cost and labour involvement, feasibility studies, weighting risk-taking and research responsibility for team work and for individual members, total dedication to common endeavours. These factors together shape in a unique way the personality of the young scholar. If he/she is able to follow up all these, is a winner.

II. The Roots of CBM Experiment and Questions to be Answered

The first experiments with heavy ions collisions were carried out in a number of research infrastructures as in Bevelac/Berkeley, AGS in Brookhaven, SPS synchrotron in CERN - experiments NA49, NA60, CERES Collaboration, NA61/SHINE, STAR experiment at RHIC, HADES/SIS18 and planned HADES/SIS100, JINR/Nuclotron, and planned JINR/NICA with multipurpose MPD detector. Most of these experiments, excluding the planned and future ones, are limited by low-frequency of interactions (tens of Hz), non-optimal energy beams, low luminosity, measurements done too late - during a post-phase of strongly interacting matter – when it is already hadronized. These experiments have no possibility to do accurate measurements of rare phenomena and the studies are limited to observations of integrated volume effects. The CBM experiment has been planned so as not to restrict in this way the possibility of measurement. CBM will not be limited to the volume measurement or observation but will measure, with a considerable accuracy, rare individual effects in the optimal range of energy, extending to lower energies where the results were already obtained in the SPS and RHIC. The fundamental requirements of the CBM were: sufficiently long availability of beam time, large beam intensity, large impact frequency of 10 MHz, fast detector relevant to the rate of bunch impacts. FAIR infrastructure has two synchrotrons - SIS100 with ion beam energy in the range of 2 - 14 A GeV; then planned SIS300 with ion beam energy of 11 - 45 A GeV, Q = 0.5 A. At these energies of the colliding beams and bunches the participating nuclides and nucleons are completely dissociated.

In the CBM experiment, the constituent particles of atomic matter undergo such a strong compression of nucleons (baryons) so as to make partons, which are their components, "melt" into a quark gluon plasma QGP - strongly interacting matter, described by the theory of quantum chromodynamics QCD. The aim is to understand the possible phase transitions in such matter, to determine phase boundaries, critical points, etc. It is essential that the life of the plasma, and its size were large enough to enable observations of the properties of this state of matter. Observations of phase transitions, properties and phenomena occurring in high temperature, high density plasma, require very sophisticated instrumentation, algorithms and measurement systems.

The matter present immediately around us has a low temperature and low density. Only in close proximity, surrounded by this sort of matter, the life possible. However, 90% of the visible matter in the universe is in the form of plasma, sometimes called the fourth kind of matter. There are still more states of baryonic matter. There are still more completely different forms of matter and energy. Only 4% of the matter in the Universe is visible baryonic matter, the rest being dark matter and dark energy. The state of baryonic matter may be presented on a diagram in the coordinates where the temperature is ordinate and the baryonic chemical potential is abscissa. In these coordinates, changing widely temperature and pressure, one can expect the existence of at least a few other states of baryonic matter. From our point of view, these are extreme conditions, and from the point of view of the amount of matter in the universe, not so much. The matter in low temperature and low density (on a cosmic scale, not ours) is in the hadronic phase. Outside the hadronic area of matter existence, there are substantial areas of strongly interacting matter, quark matter or quark - gluon plasma. Distinct sub-areas can be distinguished there, with expected different properties of matter residing in these conditions. There are two well defined poles and intermediate space between them. These poles are: areas of high temperatures and small baryon chemical potential of the matter, and areas of lower temperatures but great baryonic potential. The remaining are the areas in between.

The CBM is expected to be a factory of “fireballs”, generated with large frequency. The fireball, resulting from the dissociative collision of dense ultra-relativistic heavy ions, evolves from the initial transient strong compression phase to the dense matter phase and then proceeds to the hadronization phase which stabilizes chemically the matter at a temperature of 155 - 165 MeV. It seems that this temperature defines the critical value of a smooth transition between parton matter and hadron matter. Till now, the range of baryon chemical potential for which the phase transitions occur for baryon high-density is unknown experimentally. Theoretical calculations predict the existence of quark matter in the form of a Fermi gas of free quarks, with a permanent confinement of thermal excitation and Fermi plane.

In the laboratory, such conditions for some areas of quark matter existence (quark - gluon plasma) can be obtained for a very short time and in a very small volume via collisions of energetic hadron (or heavy ion) bunches. Hadron collisions give high temperature and low baryon chemical potential. Heavy ions collisions give lower temperature but greater chemical baryon potential. The fireball produced during the collisions of hadrons and/or heavy ions spreads and cools characteristically, revealing transformations occurring inside of matter phases. The lifetime of the fireball is small. Different transformation phases of hot matter have various parameters like time of duration, temperatures, homogeneity of fireball expansion, jets emanating transversely and in other directions from the fireball, jet quenching, etc. Despite the short lifetime of the fireball, the period of coexistence of parton and hadron phases takes a relatively long time. This is long enough to allow to observe the phase transition. Accelerator experiments are carried out using intensive energetic pulses – bunches of particles, of hadrons or heavy ions, colliding with very high frequency or repetition rate of the order of MHz. The well-focused, thus dense, individual bunches contain multiple billions of particles and collide very often. Integrated lifetime of the fireball increases significantly due to the large frequency of bunch crossing in identical conditions and allows for "filming" of its transformation in time. The observations of various phases of changes in the fireball require extremely precise time synchronization of labelled collision to the main clock of the experiment. The LHC experiments, where the p-p bunch collisions (also p-Pb, and Pb-Pb) occur every 50 or 25 ns produce matter of great energy density, low baryonic density, and equal amount of particles and anti-particles, which means a low value of the chemical baryon potential. It is expected that the phase transition between hadron and parton matter, hadronization conditions of matter, a critical point, and the new phases, such as quark matter, is in the area of larger baryonic density and lower temperatures. The study of phase transitions is of fundamental importance for understanding the properties of strongly interacting matter, the structure of neutron stars, the origin of hadron mass, recovery of chiral symmetry, etc.

The assumption is that the CBM experiment, which is just being built, will allow during the Au-Au bunch collisions to create the matter of parameters similar to the centre of neutron stars – in terms of the ultra-high baryon density. The core of a neutron star is expected to be a mixture of hadron and quark phases for the density equal from 5 to 8 times the saturation density ρ_o , and pure quark matter above this boundary. Due to high repetition frequency of the bunch collisions, observation time of matter in this mixed phase state is incomparably longer than in previous analogous experiments. A significant observation time allows to gather and calculate reliable statistics and thus gain considerable measurement accuracy. Large interaction frequency will allow for the disclosure of rare and very rare interactions. Such rare interactions are diagnostic samples of the parameters observed during the dense phase of the nuclear fireball pointing to the existence of strangeness and transformations of multiple-strange hyperons, electromagnetic radiation in the form of pairs of leptons (dileptons), charm and its propagation in the fireball, particles containing charm quarks and antiquarks (not existing in normal matter), particles multiplicity, phase-spatial distribution of interaction products, collective flow and correlations and fluctuations in the flow, hyper nuclei and hyper-matter, and others. FAIR and CBM will be the first global research facilities where there are possible such observations in this energy range, measurements of multi-differential observers, in a long period of time, with unprecedented accuracy, with considerable frequency of collisions, and with a significant reduction factor of the background noise of large statistical meaning. During the initial stage of the experiment, the source of ion beams will be a ring accelerator synchrotron SIS100 and next SIS300 with greater intensity and energy of ion beams, so as to close the gap energy with the previous experiments with heavy ion collisions on the SPS and RHIC.

Some of the main questions to be solved by the FAIR infrastructure and CBM experiment are as follows [1-2]:

- What is the equation of state of nuclear matter at densities in the core of a neutron star? What are the degrees of freedom of matter at these densities? Is there a phase transition between hadron and quark-gluon matter of? Do the phases coexist? Is there a quark matter?

- To what extent the properties of hadrons are modified in dense baryonic matter? Is it possible to find signs of deconfinement and chiral symmetry restoration?

- How far the area of the existence of nuclei can be extend into the third strange (s) dimension through the production of single and double hyper-nuclei? Does the strange matter exists in the form of heavy multi-strange objects?

- What is the mechanism of charm quarks (c) for the threshold beam energy? How open and hidden charm propagates in a cold and hot nuclear matter?

III. CBM Detector Characteristics

CBM detector The CBM detector is a universal, multi-tasking device capable of measuring hadrons, electrons and muons generated during heavy ion collisions at full energy beam range from SIS100/S300 accelerators. Extraction of the most interesting dilepton signals requires accurate determination of the physical background for lepton pairs. Simultaneous measurement of electrons and muons significantly reduces the systematic error because background sources for both particles are completely different. Multi-differential measurements of high accuracy require a significant activity of the experiment at appreciable frequency (100 kHz-10 MHz) for most of the year, i.e. several months. A complex topology of particles decay such as omega hyperons and D mesons prevents the use of simple triggers. Events must be reconstructed and selected online by very fast algorithms operating on computer farms. Readout chain bases on the front end electronics working in the non-synchronous streaming mode, providing time marked signals from each detector channel without correlation of the events. Reconstruction algorithms operate in the hardware architecture of multi-core CPUs. The detector comprises a steady target. It accepts polar emission angles between $2{,}5^o$ – 25^o, covering the intermediate values of rapidity for symmetric collision, for the beam energy between 2-40 A GeV. The detector consists of a superconducting dipole magnet with large-aperture and the elements listed below, and described briefly in the following paragraphs. These are sub-detectors - silicon, Cherenkov, muon, time, calorimeter. Additionally, there is DAQ electronics and ICT infrastructure. Superconducting magnet of H type builds the central part of the detector and ensures the curving strength of the CBM equal to 1 Tm over a distance of 1 m from the target, at the energy storage 5 MJ. Magnet aperture 250x140cm has inbuilt target, micro-vertex detector and silicon tracker.

Micro-vertex detector Working in vacuum, micro-vertex detector CBM-MVD uses a monolithic active pixel sensor MAPS (CPS), which is made in 180 nm CMOS and 20-30 μm period technology, and has the nonionizing radiation resistance of 10^{13} n_{eq}/cm^2. Mimosa-26 AHR is a prototype integrated circuit of pixel detector made inside the project PRESTO with the aim to test bilateral integration technology. Mimosa-28 prototype of this detector, made in larger 350 nm technology, is tested in the STAR-HFT experiment. Development and optimization work is done on the detector resistance to ionizing radiation and work speed, which parameters are currently unsatisfactory for such experiments as ALICE and CBM. Parameters improvement is obtained by application of: highly-resistive epitaxial layer with 6 kΩcm characteristic resistance, smaller characteristic size of electronics, larger pixel size, more advanced readout logic in a pixel, and lower power consumption. There was built a prototype (FSBB-M0) of MIMOSA-34 detector with the following parameters: 416x416 pixels, 14x10mm dimensions, 40 μs readout time, the level of statistical and systematic noise and the offset signal of dark pixel less than 1 mV. To be effective, the sensor should provide a low material budget, ability to work in vacuum (use compatible no evaporative adhesives and cooling), the ability to integrate mechanically with several adjacent modules to obtain a suitable detection surface, resolving power of spatial measurement better than 5 μm in both directions, resolution of the secondary vertices 70 μm, pixel period 20 μm, detection efficiency greater than 99.5% for minimum ionizing particles, noise occupancy $<10^{-5}$. Local wiring and connecting front end electronics FEE for CBM-MVD is made in the form of a flexible printed circuit – FPC, which meets the requirements of ultra-low material budget for the acceptance area of the CBM detector. MVD readout electronics is the interface between MAPS and TRB3 DAQ FPGA-based board developed by HADES experiment. Configuration tested with the TRB3 allows to connect in parallel 16 Mimosa-26 sensors. MVD readout electronics provides sensors powering, converting various digital standards, ADC, sensor parameters monitoring, diagnostics, etc.

Silicon tracker Placed in a dipole magnet, silicon tracker – STS is used to reconstruct the tracks and define momenta of charged particles generated during the interaction of the beam with the target. Internal regions of the tracker are exposed to significant irradiation. For the construction of the STS tracker (silicon tracking station) there were used prototype silicon microstrip detectors of dimension 62x62 mm (long version 62x124 mm). The total number of sensors is 1300, and the total area of is approximately. 4 m^2, with more than 2 million readout channels. There are tested solutions with a single and a double metallization of lines, i.e. single-sided and double-sided placed on light carbon fibre substrate. Optimized design allows for the detection and reconstruction of multiple hits from the same sensor, however, at the expense of resolution. The sensors are automatically tested for electrical, mechanical, and thermal parameters. The ability of charge collection on sensor surface is measured. Charge splitting between the adjacent detector strips are measured, when excited with a stream of alpha particles and with the laser beam. There are studied effects of detection efficiency degradation of charge cluster in conditions of strong irradiation of the micro-strip detector. Further studies predict irradiation with beta beam of the sensor connected to the microelectronic integrated readout Alibava chip. Distribution of the charge from one event between adjacent micro-strips leads to the detection of physically correlated signals. A significant number of particle trajectories are reconstructed from the events spanning over two and even three micro-strips. Analog layer of the readout improves the positional resolution of the detected signal. The readout channels carry also signals which are not physically correlated like substrate crosstalk, aerial crosstalk, fluctuations of common modes. The STS prototype was tested, in terms of the distribution of charge between the strips, in the COSY Julich synchrotron using proton beam of 2.4 GeV/c, with the aid of such tools as the distribution of cluster sizes of charge, different angles of incidence of the beam. STS Sensors are tested also for resistance to neutron radiation. Required radiation survival is over 10^{14} n_{eq}/cm^2. To interrogate the sensors, there was constructed a dedicated 130-channel ASIC STS-XYTER [10.1109/NSSMIC.2013.6829538], now under design in the second version STS-XYTERv2. Each channel includes a 5-bit ADC and 8-bit fifo circuit. The readout system will be protected against pile-ups and overfilling with wrong data. The prototype application STS module consists of a sensor, ASIC, micro-cable, and software. XYTERv2 circuits are placed on the front end electronics boards PCB FEB equipped with GBTX, SCA CERN links. Works on XYTERv2 are conducted at AGH.

Ring imaging Cerenkov detector The CBM-RICH detector is designed to identify the electrons and pions suppression in the momenta energy region below 10 GeV/c. RICH is a gas detector, where CO_2 gas is the Cherenkov radiator, with a precise set of focusing mirrors and PMT photodetector. The mirror consists of 36 reflecting plates of 6 mm thickness and 40x40 cm of surface. The adjacent tiles should not be subjected to deformation when heated. In the Cerenkov detector the total number of photons is proportional to 1/λ, and the carbon dioxide wave cut-off is 185 nm, thus for proper detection the most important is the short-wavelength part of the spectrum, poorly transmitted through the PMT window. It is necessary to use techniques of wavelength shifting - WLS and multi-anode photomultipliers - MAPMT. RICH is located directly after the magnet and in front of other sub-detectors. The geometry of the RICH detector is just subject to optimization. The RICH readout electronics is based on a 16-channel PADIVA module based on FPGA chip. The main component of the readout is TRB3-TDC board connected to the input stage of Padiva through LVDS transmission channels. The TRB3 PCBs operate synchronously with a clock frequency of 200 MHz, allowing for TDC channel synchronization on other boards.

Muon chamber detector Muon detector MUCH is a layered set of absorbers sandwiched by tracker chambers. Dimensions and absorber materials are chosen to optimize the efficiency of the detector to identify muon pairs derived from the decay of different mesons (rho, omega, fi) produced by the collisions of heavy ions. Muons momenta of SIS100 energy are low. For Au ion beams with energies of 2-4 A GeV, the MUCH consists of three layers of absorbers: carbon plate having a thickness of 60 cm, a lead screen around the beam pipe, and two steel plates of thickness of 20 cm each, and three detector stations located between the absorbers. For beam energy in the range of 6-10 A GeV, the MUCH consists of four layers of absorbers and four detector stations. Hadrons passing through MUCH are detected by the time-of - ToF detectors. Detector stations between the absorbers are of GEM type – gas electron multipliers. In some cases they are supplemented with straw and TRD detectors. Full dimensional And full functional prototype of MUCH detector has already been constructed. A prototype of GEM detector was tested at COSY.

Transition radiation detector The TRD detectors for the CBM are based on multi-wire proportional chambers - MWPC in two options, with or without the drift region and the carbon-frame (instead of Al). The TRDs were tested at CERN's PS. The construction of MWPC of thin and symmetrical geometry ensures fast signal gathering and separation of particles e/π. The TRD readout circuits are based on a dedicated ASIC and SPADIC PCB. An alternative solution under tests is to use a hybrid FASP ASIC, also dedicated to the CBM-TRD, and comprising an analog processor. TRD DAQ operates asynchronously, triggerless, or freely with a significant acquisition rate. FASP and Spartan6 chips support 64 TRD readout channels with sampling rate of 2Msps of 12b ADC MAX resolution.

Time of flight detector CBM-ToF detector will be built of multi-gap resistive plate chambers - MRPC. CBM-ToF prototype solutions were tested in the HADES/GSI experiment. Data acquisition for the CBM-ToF is designed on a unified TRB3 platform and the input ToF-FEE boards. There was tested a set of 30 FPGA TDC, each with 32 time channels. TDC detector digitizes arrival time of both slopes - rising and falling of the incoming signal via the LVDS link. The signal is created in an ASIC PADI preamplifier-discriminator, which in turn is directly connected to the readout electrodes of MRPC. The width of LVDS signals corresponds to the time over the discrimination threshold of analog ToT detector. The inner areas of CBM-ToF require significant granularity. For this purpose, a prototype MGMSRPC is tested. The prototype is based on glass plates with a low resistivity of 10^{10} Ωcm, in order to realize substantial count rate foreseen for this wall region of CBM-ToF. Determination of the initial ToF measurement time, uses a counter of beam fragmentation BFTC (beam fragmentation time counter). This detector is located in the most central part of the ToF wall.

Calorimeters ECAL calorimeter is located a few meters behind the target. It consists of two halves. It contains more than 1000 units and more than 4000 readout channels. ECAL detector allows for precise measurements, together with RICH, of J/psi decay to a pair of e^{+}+e^{-}. The full set of CBM detectors for SIS100source consists of STS chain, magnet, RICH, ToF, calorimeter, PSD, and several TRD planes.

Scintillation calorimeter PSD (projectile spectator detector) – a detector observing the reactions between participants, is used to record nucleons observers in the forward direction and fragments emitted during the nucleus-nucleus collision for very small values of polar angles. It is used to determine the centrality of the collision and the orientation of reaction plane. The scintillating signals are read by the neutron radiation resistant avalanche photodiodes coupled to optical fibres which shift the wavelength.

IV. Data Acquisition and Online Event Selection

The CBM experiment does not have a classic synchronous multi-level trigger, as for example FLT, HLT, and TRIDAQ in many HEP experiments, like CMS and ATLAS at the LHC. In a sense, the CBM-DAQ system may be regarded as trigger-less. Such systems have different features than the classic multilevel TRIDAQs, because the work "freely", not rigorously synchronized to the experiment clock. The DAQ system must have mechanisms of discrimination and/or selection of events, the best working online, i.e. in the real-time. This role is fulfilled in CBM-DAQ by the CBM-FLES (first level event selector). In addition, the DAQ system, of such class as for the CBM, must also have many other functionalities such as: safeguards against “flood” of bad data, and therefore the permanent registers overfilling leading to the loss of valuable event data. Invalid data are caused by temporary loss of control over the ion/hadron beam, or other disorders.

Each one of the above detectors needs to cooperate with a relevant measurement system, data pre-processing and concentration, then the full processing and data acquisition which is often combined with diagnostics, control, selection and/or online reconstruction of events. Standardized data processing boards DPB represent the possibility of a broader design unification of the electronics for the entire experiment. This may lead to costs and labour savings, shortening of design time. Such boards are developed in cooperation between GSI, FAIR, PW and AGH [6]. A universal DPB solution is tested for the construction of the CBM detectors readout and control system. The DPB performs data pre-processing and concentration before being sent to the FLES (first level event selector). DPBs provide fast and slow control for the front end FEE electronics, distribute the reference clock signal, and time-critical information to synchronize messages, as well as timing and data flow control –TFC. Designing of optimal system runs continuously, and freezing particular chosen solutions will probably be done just before the final implementation of the first operational version, so only a few years from now. During this period, the electronics will for sure change a lot. Continuous development has a great sense to keep with the pace of the technology development.

In order to enable continuous system testing of different possible implementations and required, or predicted and future oriented functionalities, but also maintain reasonable choice ability, there has been designed, developed and fabricated a quite universal platform based on the Open Hardware methodology. The platform is based on recognized and widely used standards like AMC, FMC, Kintex Carrier (AFCK). The AFCK board can work in the MTCA crate, or in stand-alone versions. Resources of the board depend on the specific implementation. The board may contain one or two FPGA chips (now contains relatively big Kintex 7 325T FFG900 FPGA chip), multiple GTX transceivers, several FMC slots, RTM connectors, backplane ports, flexible clock system for working with multi-gigabit links of different baud rates, repeater for the received signal - removing jitter and noise, multi-gigabit SDRAM for data storage and debugging. There were developed simple tests of different transceivers mounted on the FMC boards, without modifying the motherboard. The algorithms for data pre-processing and concentration are carried out in the vicinity of the detectors. The DPB was realized in several prototypes and tested in laboratory conditions. There are under development now several functional protocols for different detectors and for cooperating dedicated ASICs, e.g. like for the STS-XYTERv2.

In many electronics solutions for the CBM, there are used custom integrated ASICs circuits developed and practically used by other large experiments or organizations. CERN research teams have developed several extremely useful ASICs dedicated to the transmission, aggregation, data processing, for example the gigabit optical link - GOL and the like. The data aggregation system from MUCH-FEE detector uses a popular and perfectly performing GBTs ASIC developed in CERN. It is used as a bridge to the CBM-DAQ. The GBTx transmits data from the STS-XYTER (MUCH-XYTER) via e-links and fibre optic links, using the GBT protocol to communicate with the FPGA DBP layer. GBT-FPGA core can also be used to implement the functionality of the GBTx ASIC from the FPGA.

A special dedicated, fast, autonomous, stand-alone, programming block (driver environment) is built for the TDR detector. The driver – feature extraction framework – FEF, checks the incoming signal for characteristic features. These operations on the signal like finding maxima, curves characteristics, centre of gravity of areas, time above threshold, detection of clusters of charge, and others, are implemented in FPGA chips as algorithmic process cores in the event reconstruction network. The FEF is configurable in a wide range via a GUI.

The CBM FLES is a central system of selection of events. It is implemented in hardware, and in software as a specialized computer farm - high performance computing cluster HPCC. In practice the FLES is implemented as a scalable supercomputer with dedicated, high-speed, programmable FPGA-VHDL technology with interface input boards and ultrafast FLES-NET network. Its purpose is to build/reconstruct the events. In fact, FLES is a fundamental part of the specialized software for computers, networks, and FPGA circuits, that implements the functionality of selection, reconstruction, communication, synchronization, etc. The main task of the FLES is the selection of data to be retained, based on the online analysis, including the complete reconstruction of particular event. FLES is a multi-channel data concentrator for the data being transported by many various links from many different sources, but origination from the same time intervals. FLES combines simultaneous data and distributes them to separate computing nodes using high-quality multi-gigabit dedicated FLES-NET network.

A parallel goal of FLES is to analyse data online and complete reconstruction of events from the available data. FLES calculations are conducted at rates exceeding 1 TB/s. FLES tests, for the construction of time slices, and software functionalities, are conducted in the GSI with specially developed, scalable, highly dedicated Micro-FLESx model. Time Slice - TS is a fundamental structure of the data which manages the access to the raw data from all detectors in a specific period of time. TS is performed by a dedicated software, which is currently under development using such tools as InfiniBandVerbs, MPI and others. Data streams from the detectors are partitioned into micro-slices DDMS (detector data micro-slice) before they are combined into a TS. Micro-slices are specialized containers including a fixed time-frame, of real-time equal for all subsystems. TS is a portrait of time while in detectors, abstracting from data and subsystems. Partitioning is performed by the above-described DPB board, as the last stage of the readout tree, which contains the components specific for subsystems.

The current model of the FLES input interface is implemented on a dedicated PCIe FPGA board with substantial computational resources and memory – FLIB, which is for FLES Interface Board. FLIB has an optical interface to the DPB board, from where it receives micro-slices, and to the FLES input nodes. FLIB algorithm works as follows: obtaining micro-slices, pre-processing of micro-slices to build the TS, and dedicated autonomous DMA engine. DMA engine, without involving the CPU, transfers the micro-slices and metadata to the PC memory. The CPU periodically confirms the processing of data segments in order to allow the reuse of buffer space. The constructed software model of FLES-FLIB-FLESNET has been tested in the CERN PS infrastructure. The model will cooperate with DPB in creation of the micro-slices, and data sources from Syscore3 and TRB3.

Continuous development of different framework systems for the CBM-DAQ entails the necessary modifications to its individual components. There are carried out now development and adaptation works among others, on the following system components: readout firmware controller for ASIC circuits - n-XYTER and GET4, modernization of CBMNet-v3, board firmware for SysCore-v3, etc.

The CBM-CSB system board (control system board) with real time operating system RTEM is designed as an I/O controller in the EPICS environment. RTEM-BSP (board support package) is developed for the TMS570 microcontroller. The microcontroller is specialized for safety-critical applications. Hardware Development Kit – HDK for the TMS570 microcontroller is used for the development of the CSB board. EPICS - experimental physics and industrial control system (frequently present in HEP systems) is used here, operating in the client – server configuration with OPI client (operator interface) and IOC server (I/O controller). The IOC controls devices via all major measurement buses.

An important issue of building the CBM-DAQ system is the radiation resistance of these parts of the chain of functional electronics, which are exposed to ionizing radiation. Readout board ROB for the CBM-ToF is a link in the ToF functional chain between the front end electronics FEE, the DAQ, and data processing. ROB, unlike other parts of the DAQ chain is situated near the FEE and is exposed to elevated levels of ionizing radiation. The ROB contains FPGA circuit for data pre-filtering and compression with the ability to prevent such effects as radiation errors in the configuration memory of CPU, and generally preventing the SEU (single event upsets) and SBU-MBU (single-multiple bit upsets), etc. Mitigation consists of storing the master copy of local Flash memory and using appropriate FPGA driver in the SysCore-v3. Flash memories have much lower limits for total ionizing dose TID parameter than FPGA/SRAM. Tests are carried out with the resistant ferroelectric FRAM memory. There is considered ROB option without a local memory and a controller exposed to ionizing radiation. Research is done on SEU-MEU prevention using a SEM driver (soft error mitigation), which is a part of the Xilinx IP Core. SEM controller detects and corrects autonomously the SBU and reports the MBU. Distorted MBU frame is reported to configuration management unit of CME (configuration management entity) located at a different level of the DAQ chain. The damaged frame can be overridden by CME via JTAG, without having to reset the FPGA. Reset is needed only if there are more than two errors in the same frame, due to the limited ability to locate more errors by the current version of the SEM. GBTx circuit, which is predicted for the final version of ROB, is immunized against radiation, has remote JTAG and GPIO connections realized by GBT-SCA and therefore there is no need for a local driver. DAQ chain for CBM-ToF with ROB has been tested in COSY/Julich.

TRB Collaboration has developed another version of the FPGA based system board TRB3, mainly for the HADES detector at GSI. It is a comprehensive, modular and flexible DAQ and TRIDAQ platform. It has all the basic functionality of the motherboard such as central triggering and readouts, multi-channel data acquisition, data concentration, bridging between networks, dedicated TrbNet network, with the possibility of significant further expansion of communications and data acquisition on 5 functional daughter-boards. Universal TRB3 board is also used effectively by the prototype detectors CBM-MVD (reading of MAPS) and CBM-RICH. Efficient use of all the functionalities of the board, requires an additional bridge, which is constructed between the CBMNet and TRB3. The TRB3 has 5 low-cost FPGA circuits of average resources, optimized for fast I/O communication but not for considerable computing power. That computing power is not required in the early stages of the DAQ chain, where the TRB3 is located. One central FPGA circuit supports mostly the system management level and network maintenance tasks. Other FPGAs on the TRB3 board and on the daughter-boards form four independent sub-systems. Possible applications of such a system include: FPGA-TDC with 264 channels on board with an accuracy of a few ps RMS; ADC measurements, readings of fast digital signals. Autonomous operation of TRB3 requires an external power supply and GbE cable link. Larger sets of boards and big systems, for the use of full functional capabilities, require support by the internal TrbNet network protocol, developed originally for Hades. Because the networks are semantically different, the applied CBMNet-TrbNet bridge, allows to synchronize and use directly of all applications created for the TRB. The network bridge was tested in combination with the CBM-RICH in CERN PS infrastructure.

CBM-DAQ is based on the CBM Net protocol. It is used, for example, to read TRD and STS. The protocol resides in front end ASICs of FEE, readout drivers ROC (readout controller), FLIS board of FLES interface, and direct connections between the FPGA (GbTx SFP). The modernized CBMNetv3 includes mechanisms described above immunizing against radiation, link layer, different implementations of the physical layer, and the extensive network functionalities. Laboratory readout experiments with the beam were carried out for three SPADIC boards and ROC controller, including testing the implementation of the physical layer FLIB. A dedicated analog-digital ASIC HUB MIXED, designed for readout and data aggregation is under tests. The system includes four voltage CMOS channels, serializer/deserializer with multiplexers, PLL, band reference, data and clock signal recovery (CDR), communication and networked data aggregation, I2C readouts, and LVDS.

V. CBM-ICT Computing Layer

The ICT layer of the CBM experiment contains many functional units as graphical user and operator interfaces, component database CDB for the entire CBM detector and all sub-detectors - STS, magnet, PSD, RICH, ToF, MUCH, MVD, TRD, ECAL, simulation models of individual detectors, the process of building the event, FLES reconstruction packet, trajectory reconstruction in the CBM-MUCH, events selectors, reconstruction algorithms, event-by-event extraction, etc. The CDB has a tree structure. The leaf of the tree is connected to a tabular set of components. Tests, certificates, and status of the components is stored in the form of cross-references. Component tests are in form of images. Implementation of the CDB is based on the interaction of client - server. Authorized access to the CBM Component database is via a web interface.

VI. Involvement of IES WUT in Preparation of CBM

Institute of Electronic Systems (IES) of Warsaw University of Technology WUT is involved in the preparation of the CBM experiment since 2008. In that year, we participated in the preparation of the grant „Preparatory and Design Work on Read-Out Board – Components of the Data Acquisition System for the CBM Spectrometer (in Polish: Prace przygotowawcze i projektowe Read-Out Boards ¬ elementów układu zbierania danych dla spektrometru CBM). Unfortunately, this grant has not been approved by Polish funding agencies. However, we were still involved in analysis related to the design of the readout system for the CBM experiment, particularly for the STS detector.

We have participated in the „ CBM DAQ Workshop" in December 2008, in „CBM FEE/DAQ Workshop" in November 2010, in „17th CBM Collaboration Meeting" in April 2011. In December 2012, the Institute of Electronic Systems applied formally for membership of the CBM collaboration and was accepted in 2013.

Currently, we are involved in the preparation of the part of the CBM Readout and Data Acquisition System. The subsystems designed by us will be used to provide slow and fast control for front-end electronics (FEE), to deliver reference clock and time synchronization for FEE and to receive, aggregate and distribute the received data, finally transmitting them to the First Level Event Selector (FLES). Currently, IES team is performing a research project „Development and implementation of a readout and control protocol between STS-XYTER and data processing board (DPB) for FAIR" financed by GSI. In the future, we are going to continue our involvement as the Polish in-kind contribution to the CBM project in the framework of the Femtofizyka consortium.

Current results of our cooperation are very promising [8-9]. Our involvement in the preparation of CBM experiment was very inspiring and resulted in interesting international cooperation and many publications. Early studies on a processing of the data received from the FEE resulted in parametrized and scalable implementation of the heap sorter in the FPGA, which is able to perform real-time sorting of received data stream with optimal internal memory usage [10].

Research on possibilities to provide efficient control and data transmission via standard COTS network infrastructure resulted in the development of high-speed reliable network protocol optimized for communication with FPGA [11]. Additionally, studies on possible improvement of FEE control via high speed but high latency links have been performed [12]. Work on the development of the STS-XYTER protocol and its testing setup resulted in cooperation with AGH University in Krakow and with GSI. The obtained results were published in a few articles describing the developed protocol [13-14] and designed prototypes of the DPB boards [15-16].

Studies on the possibility to utilize the existing GBT technology developed at CERN to provide the deterministic latency communication with FEE give us opportunity to cooperate with Variable Energy Cyclotron Centre (VECC) in Kolkata, India. In May 2015, we have hosted Mr Swagata Mandal from VECC, who cooperated with us on development of the GBTx emulator [18]. Our CBM involvement also creates interesting research and design topics for our PhD students. The ISE PhD students were involved in research on implementation of the time-deterministic multigigabit serial links and clock recovery and time synchronizations in the DPB prototypes [16-17].

VII. Conclusions

This paper describes the Compressed Barionic Matter experiment (CBM), for which the research infrastructure is built in the FAIR and GSI Research Centres in Darmstadt. CBM will investigate the areas of existence of quark – gluon plasma QGP, possible quark matter, phase transitions and critical points in strongly interacting matter. Young researchers from the Institute of Electronic Systems WUT design and build software, firmware and hardware for DAQ of the CBM experiment. The cooperation is very profitable for all sides involved. Generally, such a cooperation is extremely important for small university based teams, which may contribute actively with their intellectual potential relevant for the debated field, for the common success of the experiment.

References

[1] B. Friman, et.al., (Edit), The CBM physics book, Lecture Notes in Physics, vol.814, 2011

[2] V,Friese, Ch.Sturm (Edit.), The CBM Collaboration, Compressed Barionic Matter experiment at FAIR, Progress Report 2014, GSI, Darmstadt, April 2015, ISBN 978-3-9815227-2-3

[3] R.S.Romaniuk, Visions for the future of particle accelerators, Proc. SPIE, art.no.890324 (2013) doi: 10.1117/12.2035418

[4] R.S.Romaniuk, LCLS – large laser infrastructure development and local implications, International Journal of Electronics and Telecommunications, vol.60, no.2, pp.187-192 (2014) doi: 10.2478/eletel-2014-0023

[5] R.S.Romaniuk, Intrenational Linear Collider global and local implications, International Journal of Electronics and Telecommunications, vol.60, no.2, pp.181-185 (2014) doi: 10.2478/eletel-2014-0022

[6] R.S.Romaniuk, Fusion 2050 – European and Polish perspective, International Journal of Electronics and Telecommunications, vol.60, no.1, pp.85-91 (2014) doi: 10.2478/eletel-2014-0011

[7] R.S.Romaniuk, CBM experiment (in Polish), Elektronika, vol.56, no.09, pp.87-93 (2015) doi: 10.15199/13.2015.9.21

[8] W.Zabołotny, et al., Towards the data Processing Boards for the CBM experiment, in [2], page 97

[9] K.Kasiński, W.zabołotny, J.Lehnert, et al., STS-HCTSP, an STS Hit&Control Transfer Synchronous Protocol, in [2], p.96

[10] W. M. Zabołotny, Dual port memory based Heapsort implementation for FPGA, Proc. SPIE, art.no.80080E (2011) doi: 10.1117/12.905281

[11] W.M.Zabolotny, Low latency protocol for transmission of measurement data from FPGA to Linux computer via 10 Gbps Ethernet link, J. Instrum., vol. 10, no. 07, pp. T07005–T07005, Jul. 2015.

[12] W.M.Zabołotny, Improvement of FPGA control via high speed but high latency interfaces, in Proc. SPIE, art.no.96623G (2015) doi: 10.1117/12.2205441

[13] K.Kasinski, W.Zabolotny, and R.Szczygiel, Interface and protocol development for STS read-out ASIC in the CBM experiment at FAIR, in Proc. SPIE, art.no.929028 (2014) doi: 10.1117/12.2074883

[14] K.Kasiński, STS-HCTSP: Silicon Tracking System Hit & Control Transfer Synchronous Protocol using GBT's e-link for the CBM experiment at FAIR, presented at the iWoRiD-2015 - 17th International Workshop on Radiation Imaging Detectors, DESY, Hambug, Germany, 28-Jun-2015.

[15] W.M.Zabołotny and G.Kasprowicz, Data processing boards design for CBM experiment, in Proc. SPIE, art.no.929023 (2014) doi: 10.1117/12.2073377

[16] W.M.Zabołotny, Versatile prototyping platform for Data Processing Boards for CBM experiment, presented at the TWEPP-2015 - Topical Workshop on Electronics for Particle Physics, Lisbon, Portugal, 28-Sep-2015.

[17] M.Gumiński, W.Zabołotny, G.Kasprowicz, K.Poźniak, and R.Romaniuk, Time and clock synchronization with AFCK for CBM, Proc. SPIE, art.no.96622V (2015) doi: 10.1117/12.2205798

[18] S.Mandal, W.Zabolotny, S.Sau, A.Chkrabarti, J.Saini, S.Chattopadhyay, and S.K.Pal, Internal monitoring of GBTx emulator using IPbus for CBM experiment, Proc. SPIE, art.no.96622Q (2015), doi: 10.1117/12.2205595