# Participation in the compressed baryonic matter experiment at FAIR

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**Exploration of the high-density region of the phase diagram of strongly interacting matter will be performed in the compressed baryonic matter (CBM) experiment at FAIR. Some of the basic landmarks of the phase-diagram, e.g. transitions from the hadronic to quark gluon plasma phase, the region of first-order phase transition and the endpoint of the first-order phase transition known as the critical point will be explored. We propose to simulate, design, fabricate and operate a large part of the muon detection system of CBM. The system requires fast and high-resolution detectors and electronics to be operated in a high-radiation environment.**

**Keywords:** Chiral symmetry, compressed baryonic matter, FAIR, QCD phase diagram, vector mesons.

## Introduction and physics of compressed baryonic matter (CBM)

THE study of strongly interacting matter has been a subject of interest for several decades. One of the most challenging tasks of the modern day high-energy nuclear physics is to explore the phase diagram of strongly interacting matter. Statistical calculation of the quantum chromodynamics (QCD), the underlying theory of strong interaction, predicts that at high temperature and/or density strongly interacting matter undergoes a phase transition to a deconfined novel state called quark gluon plasma (QGP). In the confined phase, the constituents are the finite size colour-neutral hadrons, whereas in the deconfined phase the point-like colour charged quarks and gluons come into play. It is a matter of extensive research to find a proper system and observables by which we can explore this newly predicted state of matter. The very early universe and the core of neutron stars are the most suitable cases. According to the usual evolution equations giving its energy density as a function of age, the universe must have been in a state of QGP in the first few micro-seconds after the big bang. The core of the neutron stars is another possibility, and they may in fact consist of deconfined quarks. However, in the case of early universe QGP was at very high temperatures and vanishing small net-baryon density, mostly dominated by gluonic degrees of freedom, whereas QGP in the core of the neutron stars exhibits very large net-baryon densities and low temperatures. By now it is a well-accepted fact that the collisions of heavy nuclei at ultra-relativistic energies are the only way to form the state of QGP in the laboratory and thereby making them accessible to terrestrial experimental study. In the collision zone, matter is heated and compressed for a very short period of time. At relatively high temperature, a mixture of baryons, anti-baryons and mesons, all strongly interacting particles are produced in the collision zone which is generally called hadronic matter or baryonic matter if baryons prevail. At even higher temperatures or densities the hadrons melt, and the constituents, the quarks and gluons may move freely over the nuclear rather than nucleonic volume, forming a new phase, the QGP[1]. By varying the beam energy of the colliding nuclei, one can generate hot and dense nuclear matter, in the laboratory, over a wide range of temperatures and densities and thereby may, within certain limits, map the phase diagram of strongly interacting matter. The phases of strongly interacting matter are shown schematically in Figure 1.

As shown in Figure 1, nuclear matter exists in different phases as function of temperature and density, similar to water. The 'liquid' phase is realized in atomic nuclei at zero temperature and at saturation density ($0.17/fm^3$). The hadronic phase is represented by the white area in the figure. The transition from the hadronic white region to de-confined QGP region can take place over a range

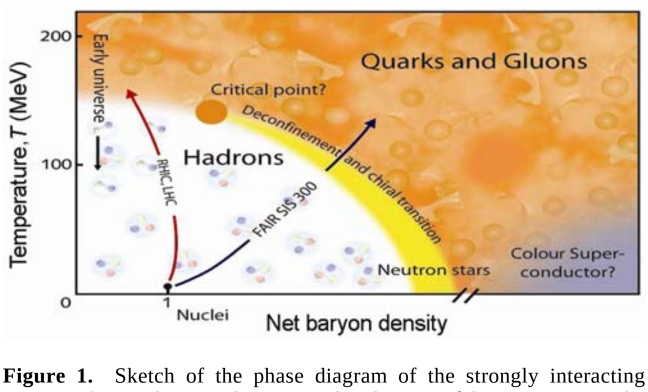


**Figure 1.** Sketch of the phase diagram of the strongly interacting matter. The net-baryon density is the density of baryons minus the density of anti-baryons.

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of temperatures and density space. At zero net-baryon density, the transition temperature is around 170 MeV. On the other hand, in highly compressed cold nuclear matter, the baryons lose their identity and dissolve into quarks and gluons. The critical density, at which this transition occurs, however, is not known. At very high densities and low temperatures, beyond the de-confinement phase transition, a new phase is predicted: the quarks are correlated and the di-quark bound states form the colour super conductor. At zero net-baryon density, according to lattice QCD calculations, the transition from hadronic phase to partonic phase is a cross-over transition. At low temperatures and high net-baryon density region, the transition is believed to be of first order. The exact location of the critical point where the transition changes its character is however still unknown. In the present theoretical studies, the co-ordinates of the critical point in the phase diagram are highly uncertain. Along with the deconfinement phase transition, another transition known as the chiral phase transition is believed to take place leading to the restoration of spontaneously broken chiral symmetry (a fundamental symmetry of QCD in the massless limit), as the matter goes from the hadronic state to the partonic state. The chiral transition is expected to be associated with the light quark (*u*, *d*) masses and hence the study of the mechanism of chiral symmetry breaking is related to the yet unsettled issue of the origin of hadron masses. At zero net-baryon density, the first principle lattice QCD simulations have been performed by different groups. Calculations done by F. Karsch *et al*. (BNL-Bielefeld group) indicate that the two transitions coincide at zero net-baryon density and occur at the same temperature (~ 170 MeV). However, lattice QCD results obtained by Fodor *et al.*[2] (Wuppertal-Budapest group) find two significantly different values of $T_c$ for the critical temperatures of the deconfinement and the chiral phase transition.

In the heavy-ion experiments at the relativistic heavy ion collider (RHIC) and BNL, the QCD phase diagram has been studied in the region of high temperatures and low net-baryon densities. The experimental results have provided circumstantial evidence for a new phase of matter dominated by the partonic collectivity. In the experiments at the large hadron collider (LHC) at CERN, this research programme is being continued towards higher temperatures and smaller net-baryon densities. Thus these experiments are suitable to reproduce the conditions which prevailed in the early universe as it underwent a phase transition from quark–gluon matter to hadronic matter in the first micro-seconds after the big bang.

A complementary experimental approach is to explore the properties of matter at high baryon densities and low temperatures. This region of the QCD phase diagram – which is to a large extent unexplored in detail both experimentally and theoretically – can be reached in heavy-ion collisions at intermediate beam energies. Such reactions create fireballs with moderate temperatures and net-baryon densities several times the density of the normal nuclear matter (i.e. density in the core of the nuclei). The transport calculations performed employing different transport models predict that the highest net-baryon densities (6–12 times the normal nuclear matter density) are expected for nuclear collisions in the beam energy range between 10 and 40 GeV/u. FAIR will provide beams in the range of 2–45 GeV/u.

As noted by Nobel Laureate, F. Wilczek, the exploration of the high baryon density regime will put a new challenging perspective on the problems of the confinement and the chiral symmetry restoration. The focal point of the proposed CBM experiment is to produce and study the super-dense nuclear matter in the reaction volume of the relativistic heavy-ion collisions.

The energy range up to 15 GeV/u was pioneered at AGS in BNL. In CBM (second generation fixed target experiment) the energy range from 10 to 40 GeV/u will be scanned for studying the following observables.

- In-medium modification of hadrons in dense nuclear matter, predicted to be related to the signature of the chiral phase transition.
- Indications of de-confinement phase transition at high baryon densities.
- The critical end point providing direct evidence for the phase boundary.
- Exotic states of matter such as condensates of strange particles.

The approach towards these goals is to measure simultaneously observables which are sensitive to high-density effects and phase transitions. In particular, we plan to focus on the following.

- Short-lived (lifetime shorter than that of the fireball) vector mesons which decay into lepton pairs.
- Strange particles, in particular baryons (anti-baryons) containing more than one strange (anti-strange) quark, so-called multi-strange hyperons.
- Mesons containing charm or anti-charm quarks.
- Collective flow of all observed particles.
- Event-by-event fluctuations.

Di-leptons stemming from the decay of low mass vector mesons (LMVMs) as well as from charmonia are very promising diagnostic probes to characterize the dense baryon matter. If the LMVMs decay inside the dense collision zone, their in-medium spectral functions are reflected in the invariant mass spectrum of the lepton pair. Due to their long mean free path, the information carried by them is not distorted by the surrounding medium and they provide almost unscathed information about the interior of the collision zone where they are being created. The deduced modification of the spectral function might be related to the expected restoration of chiral symmetry in the dense medium. It is important to note that no measurements have been performed so far on di-lepton production in heavy-ion collisions in the beam energy range between 2 and 35 AGeV. Thus di-lepton data from CBM will be highly welcome. In Figure 2, we show the prediction for the spectral function of $\rho$ meson with different in-medium scenarios[3] where it is seen that at a density of about four times the nuclear density, $\rho$ almost melts completely. The vacuum lifetime of $\rho$ is 1.3 fm/c which leads $\rho$ to decay inside the dense fireball and the decay leptons which remain undistorted carry the information from the fireball.

Another key observable for the CBM experiment is the hidden charm or charmonia that can also be measured through its decay in the di-lepton channel. The created cc-bar pairs inside the medium either propagate as charmonium (hidden charm) or pick up light quarks to form pairs of D and D-bar mesons (open charm). The charmed hadrons have a much larger mass than the ordinary hadrons and it is expected that charmonia might only be formed in the very early phase of the heavy-ion collisions. The 'anomalous suppression' in charmonium production (in addition to 'normal nuclear absorption' also present in p + A collisions), in heavy-ion collisions, has long been predicted as a 'smoking gun signature' for the formation of colour de-confined medium[4].

At FAIR, charm production will be studied at beam energies close to the kinematic threshold and the production mechanisms of charmonium are expected to be sensitive to the conditions inside the early fireball. If, for example, the medium undergoes a QGP phase, the charmonium might well be dissolved leading to different yields and momentum distributions as in the vacuum case. Predictions have been made on $J/\psi$ survival probability and $\psi'/\psi$ ratio for central AA collisions. It has been found by a theoretical calculation performed by employing a transport model Hadron String Dynamics (HSD) that at FAIR energy, the process of the origin of the measured survival probability can be clearly distinguished between two possible scenarios, e.g. the co-mover absorption (hadronic scenario) and the threshold melting (partonic scenario). The ratio of $\psi'/\psi$ shows a very different energy dependence, it increases with energy in the hadronic scenario and decreases in QGP scenario. Apart from the total relative abundances of charmonia, their collective properties are also of interest. Since the charm quarks are produced early in the reaction, their collectivity (radial and elliptic flow), in Au + Au collisions, if observed, would indicate that early time dynamics is governed by partonic collectivity[2].

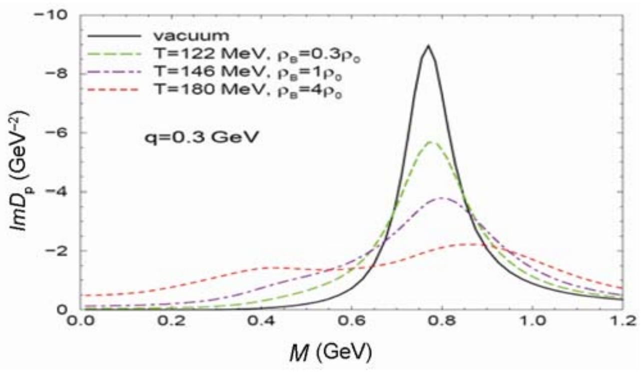


**Figure 2.** Predictions for the fate of the $\rho$ meson spectral function at different temperatures and densities[3].

## The CBM experiment

The layout of the CBM experiment suitable for di-muon measurement is shown in Figure 3. The main tracking device is a set of (7–9) silicon tracking stations (STS) placed inside a dipole magnet and just after the target. The tracks measured in STS are used for particle identification and momentum determination. The muon system (MUCH) consists of a set of sliced absorbers with high-resolution tracking stations (up to 18) sandwiched between them. The absorbers in MUCH are employed to stop charged particles other than muons. The softer di-muons from LMVMs will be selected by the requirement of the tracks passing through a smaller number of stations, whereas the tracks of di-muons from charmonia will require to pass through a thick absorber of about 1 m thickness giving a larger number of hits. The experimental difficulty is to identify soft muons from rare decays in the environment of heavy-ion collisions with up to 1000 charged particles per collision. This will probably be the first time that a system with tracking stations inside sliced absorbers is to be used. Due to the production of secondaries in a large number, the detection of charged tracks inside the absorber is a real challenge. Muon

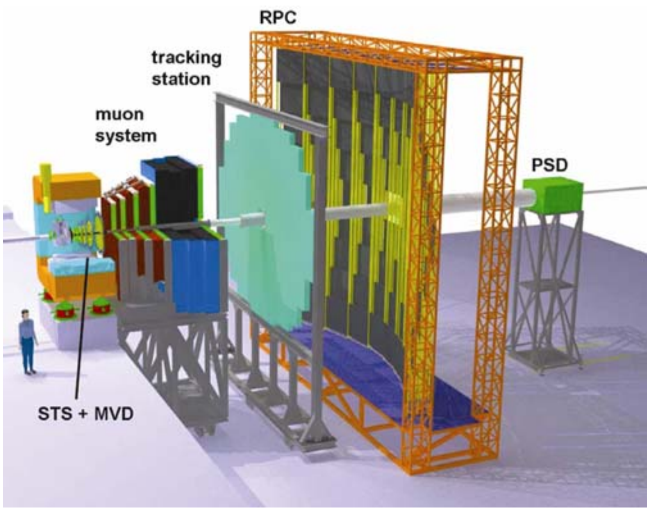


**Figure 3.** (From left) Dipole magnet, STS and muon detection system. D-mesons and hyperons can be identified via their decay topology with STS only.

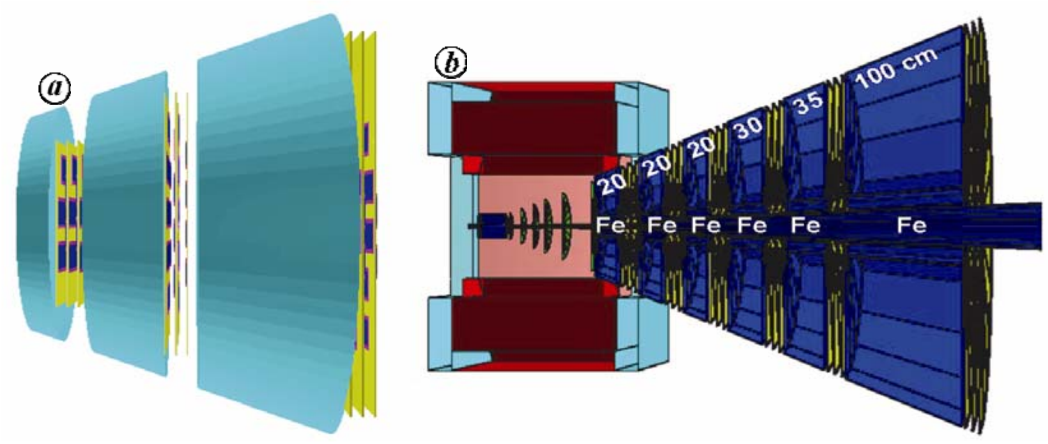


**Figure 4.** ***a***, SIS-100 MUCH geometry (magnet not shown); ***b***, SIS-300 MUCH geometry (with magnet and silicon tracker).

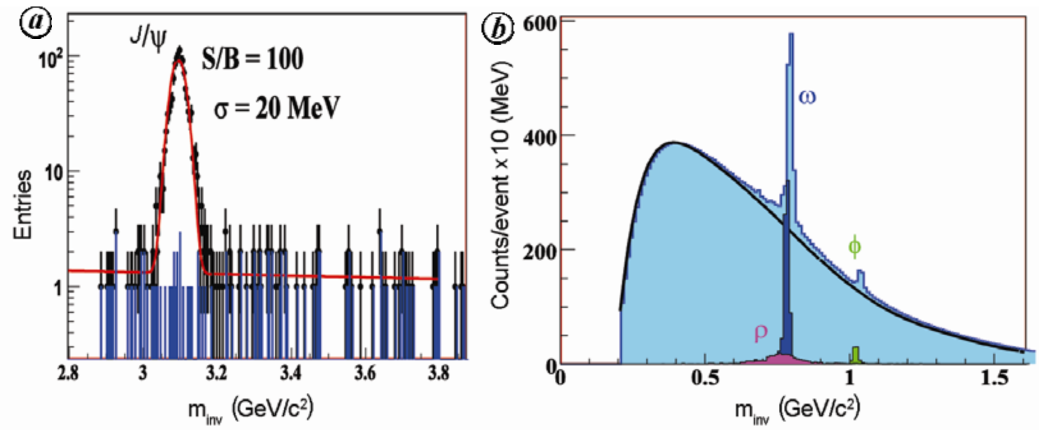


**Figure 5.** Invariant mass spectra for $J/\psi$ (***a***) and LMVM (***b***) for central Au + Au collisions at 25 A GeV using UrQMD as an event generator for simulating the background and Pluto for simulating the signal. SIS-300 geometry is used for di-muon measurement. The combinatorial background is estimated using super event analysis. Signal multiplicities are taken from the HSD event generator.

measurements seem to provide an excellent signal-to-background ratio for charmonia, but poses a challenge to be efficient also for soft muons.

## Muon tracking stations system for CBM, Indian contribution

We propose to simulate, design, fabricate and operate a large part of the muon detection system as a part of the Indian contribution to FAIR. Two main challenges in this effort are to develop and fabricate high granularity, high-resolution detectors for detection of muons which can operate at high particle density, high radiation environment. Another significant component of our contribution to the CBM muon system is the design, development and fabrication of the entire readout electronics for the muon detection system at CBM. This will involve Indian industry in a big way.

We have performed simulation for optimization of MUCH geometry for Au–Au and pA collisions to be delivered by SIS-100 at 10 and 30 GeV/u and AA collisions at a maximum of 45 GeV/u by SIS-300 accelerators at FAIR. For a possible gap between the startup periods of two rings and to make best possible use of the evolving technology, we plan to have two versions of MUCH as shown in Figure 4. Figure 4 *a* and *b* shows the proposed SIS-100 and SIS-300 MUCH geometries consisting of 9 and 18 detector stations respectively. This geometry consists of layers of thin absorbers at the beginning for detection of LMVM and a thick (~ 1 m) absorber for the detection of $J/\psi$. In SIS-100 configuration, there are three absorber layers and in SIS-300 configuration, the number of absorber layers is six.

Figure 5 demonstrates the feasibility of measuring LMVM and charmonium in CBM set-up as seen by clear peaks in the simulated fully-reconstructed invariant mass spectra.

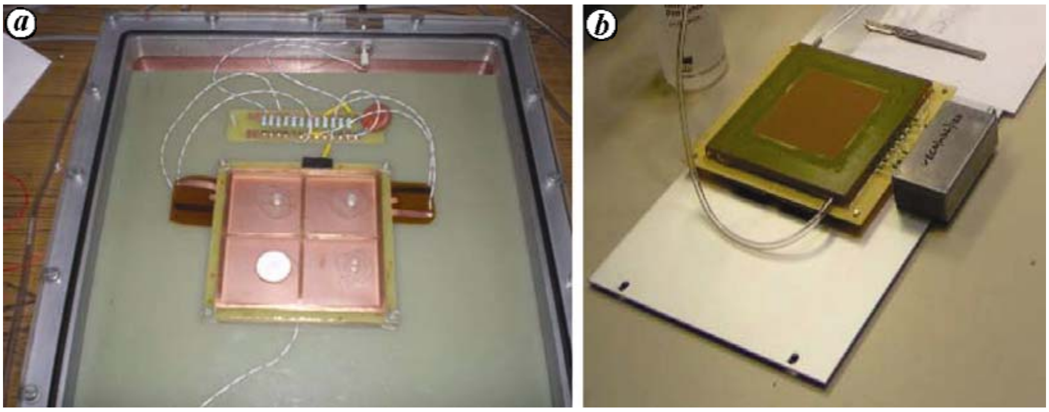

**Figure 6.** ***a***, 2-GEM assembly; ***b***, A triple GEM detector.

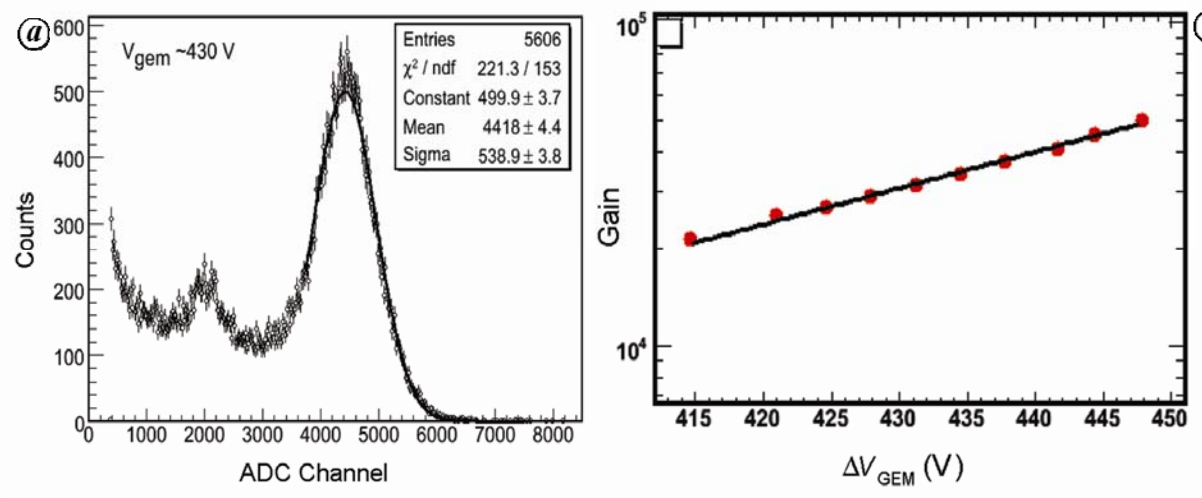


**Figure 7.** (***a***) Pulse height spectra and (***b***) variation of gain with applied voltage for Fe-55 source.

The unique feature of FAIR is that it will deliver an unprecedented beam intensity to meet the challenge of the requirement of a large number of collisions for a statistically significant measurement of the rare probes in a reasonable time. The high beam intensity however poses a challenge to the detector-system which requires fast response. In addition, high track density demands detectors with high position resolution. The experimental and technical challenges are therefore to design and build a large area, high-position-resolution detector-system which has to be operated at a particle density of up to 1 hit/cm$^2$ per event, with an event rate of up to 10 MHz.

At present, no detector technology is available to deal with this challenge and only option available is to perform extensive R&D on detector technology for achieving the goal. We are working on a technology, known as the gas electron multiplier (GEM)-based gaseous detector, which has the potential to deliver the desired performance at an affordable cost[5].

The amplifying elements of GEM-foils are made out of a 50 μm thick polyimide foil coated with a thin layer of metal on both sides. A regular array of holes are chemically pierced which are about 50–70 μm in diameter and 140 μm in pitch. On applying a potential difference ($V \sim 400$ V) across the two conducting surfaces, a very high field is generated inside the holes which can produce large multiplications of electrons, thus producing an avalanche when placed inside a gas volume. This signal can be read out using pads or strips. Multiple layers of such GEM planes can be arranged in the form of a stack to produce higher amplification thus producing larger signals.

Presently, R&D on GEM-based detectors at VECC-Kolkata is being persued. Present source of GEM foils is CERN and we can procure them in two sizes, 10 cm × 10 cm and 30 cm × 30 cm. For MUCH, we have been performing R&D based on 10 cm × 10 cm GEM for which a small status report is given here. At the same time, we are working on the design of large stations based on largest possible GEMs available from CERN. We are also pursuing at CERN through a collaboration programme, the possibility of development of large and custom-size

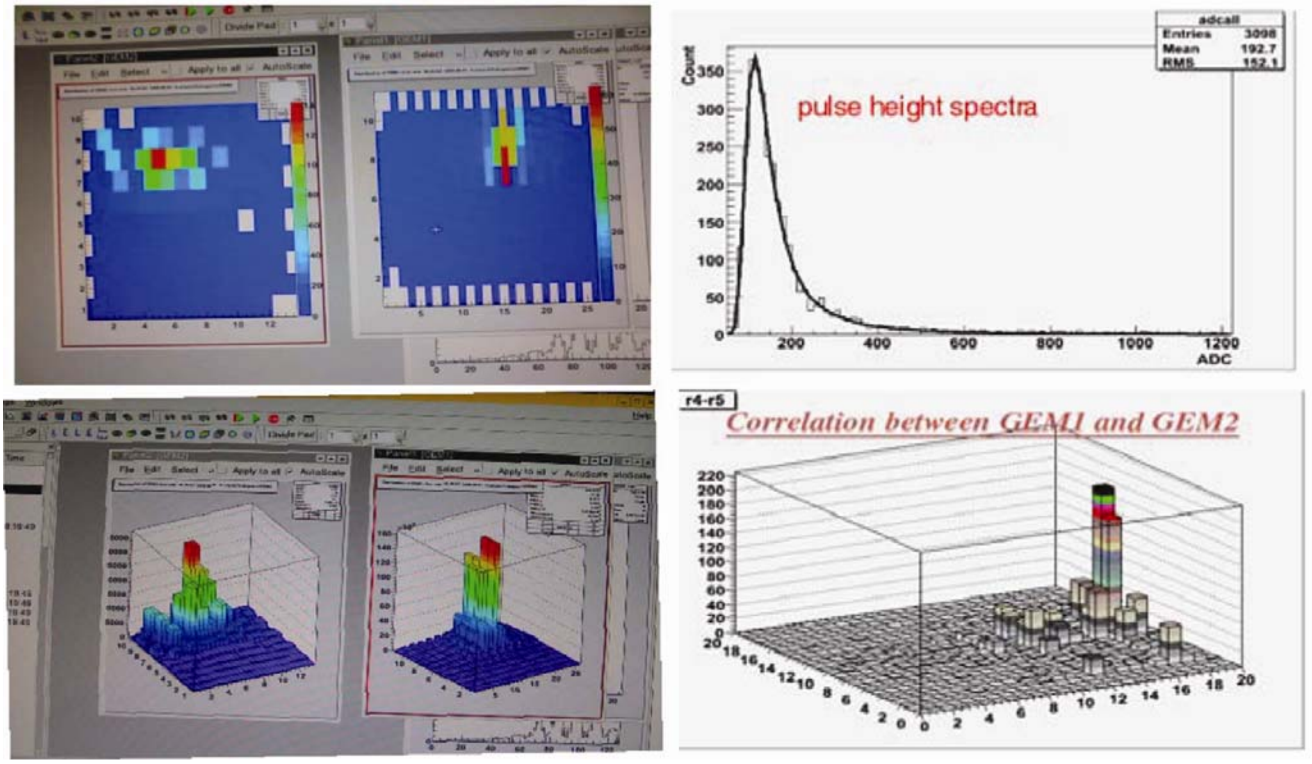


**Figure 8.** (Left) Beam spots for two detectors (right, top) minimum ionizing spectra, (right, bottom) correlation between two detectors.

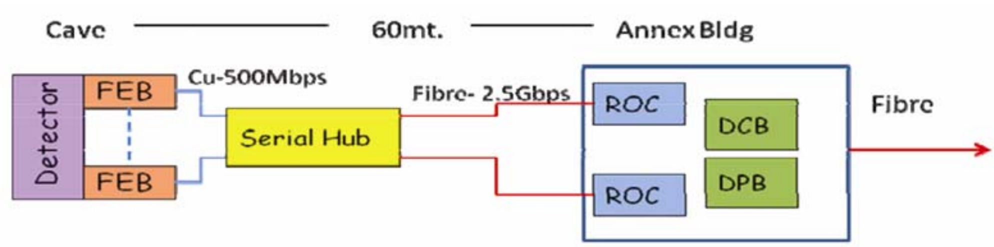


**Figure 9.** Layout of the MUCH readout scheme. Detector is followed by the front-end board (FEB). Signals from FEB will be transported via a serial hub ASIC to the FPGA-based readout controller before going to the tape.

GEMs. If available, we can build sector or slat type GEM chambers keeping the amount of dead space at minimum.

Starting from a double GEM chamber of 10 cm × 10 cm size with a single-pad readout, we have built a large number of chambers of varying configurations, e.g. double and triple GEM chambers, varying the distances between GEM layers, drift plane to GEM layer and GEM layer to readout plane, varying the pad readout configurations from staggered pads of 1.6 mm × 16 mm to 3.5 mm × 8 mm dimensions to rectangular pads of 3 mm × 3 mm and 4 mm × 4 mm dimensions. Figure 6 shows a 2-GEM assembly and a triple-GEM with staggered readout pads. The chambers have been tested with radioactive sources and proton beams. Figure 7 shows the pulse height spectra and the variation of chamber-gain measured from X-rays emitted from Fe-55 source with the applied voltage.

A set of chambers were tested with 2.5 GeV/c proton beam at SIS-18 beamline at GSI. Figure 8 shows the beamspot as seen on two chambers. The left picture shows both 2D (left) and a lego (right) plot of the pads hit. The pulse height spectrum for the minimum ionizing particle (MIP) is fitted with a Landau distribution function. The correlation in position between two back-to-back detectors is shown in Figure 8 (bottom-right).

Even though basic response of the detectors to MIP and X-rays is satisfactory, detailed R&D is necessary to obtain desired efficiency, position resolution, rate handling capability and radiation hardness of the materials used for building the GEM detectors. We are also working on designing the chambers-mechanics, readout electronics, layout of connectors among others based on the largest GEM available currently.

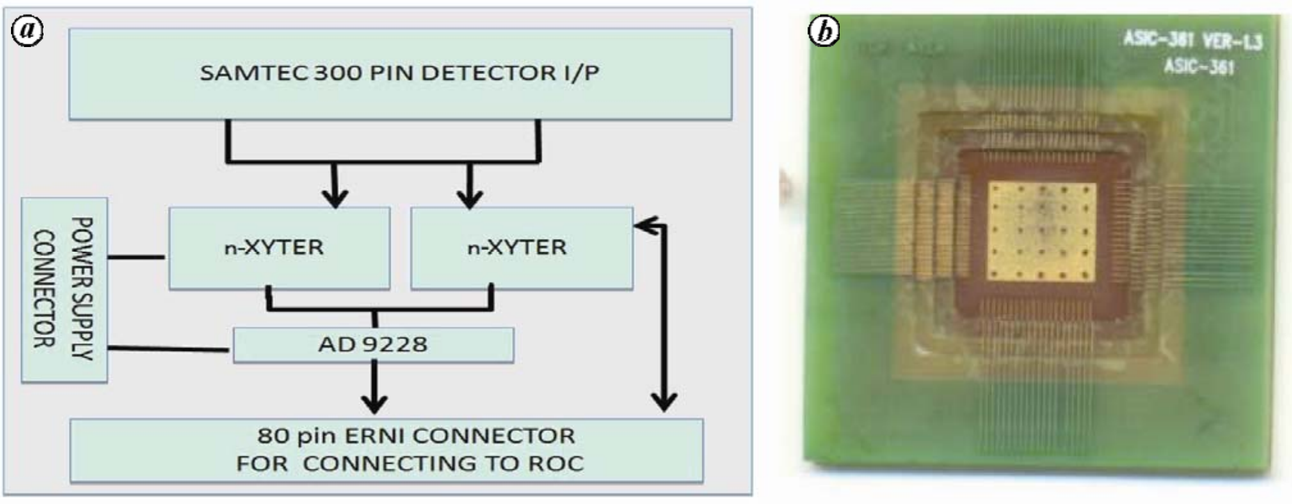


**Figure 10.** (***a***) Design of a FEB; and (***b***) a PCB scooped for mounting a bare ASIC by wire bonding.

## Electronics

MUCH detectors need to operate at high rates in a high-radiation environment. The associated readout electronics therefore need to deal with such requirements. These electronics need to be radiation hard, and the front-end board (FEB) sitting directly on to the detector has to be highly integrated for cost and space reasons. Detailed R&D is therefore required to design and optimize the application specific integrated circuits (ASICs) and FPGA-based electronics for these jobs.

As a part of the contributions towards building muon detection system for CBM, we plan to build the entire electronics readout system for MUCH. In the following discussions, we describe the challenges and plans for the design and production of these electronics boards. The schematic layout of the readout system is shown in Figure 9.

### *FEB*

This board will be connected directly to the detector chamber and will consist of an ASIC for performing channel by channel processing of signals. At present, the design of a 128-channel self-triggered mixed-signal ASIC (n-XYTER) is being modified such that the requirements of different CBM detectors can be met. In India, we have been working on building a prototype FEB using the available n-XYTER. The geometry of the ASIC die-size is 8779.70 μm × 7950.85 μm, number of pads = 361, pad pitch ~ 100 μm and it is a bare ASIC. The effective pitch on one side with two staggered rows is less than 50 μm. It has posed a challenge to have a PCB with this conductor width and spacing with the presently available PCB technology. The ASIC is to be wire-bonded with the PCB pads with space and length constraints of the wires. PCBs unlike normal ones need to be laser cut to have more number of pads accommodated. We have designed a board with two n-XYTERs (Figure 10 *a*) and approached many vendors in India for fabrication and solution to this problem. From an initial market survey, it appears to be a very challenging job for the available industry in India. Even in Germany, the yields of these boards are very low. We are in the process of launching extensive R&D towards this.

The design of such a board and the making of a PCB made locally is shown in Figure 10.

### *Serializer ASIC (HUB)*

The objective of the stage is to develop a high speed data link from detector FEB to the downstream CBM data acquisition chain as well as for the upstream chain for the communication of the control signals to FEB. The custom building blocks for this ‘Communication HUB ASIC’ would need to contain the following:

- High speed transmit serializer (2.5 Gbps).
- Transmit 2.5 GHz clock multiplication unit.
- Output driving logic, impedance matched.
- Low jitter clock and data recovery unit for the deserializer.

For anything to be integrated on the readout chips, the UMC 0.180 μm process is foreseen. Design of such an ASIC is extremely challenging and difficult to get it made by the industry even at a high cost. The preliminary design-work by a group from IIT-Kharagpur has been reviewed and accepted by the CBM collaboration and a plan is therefore made to have the first prototype ready by the end of 2011.

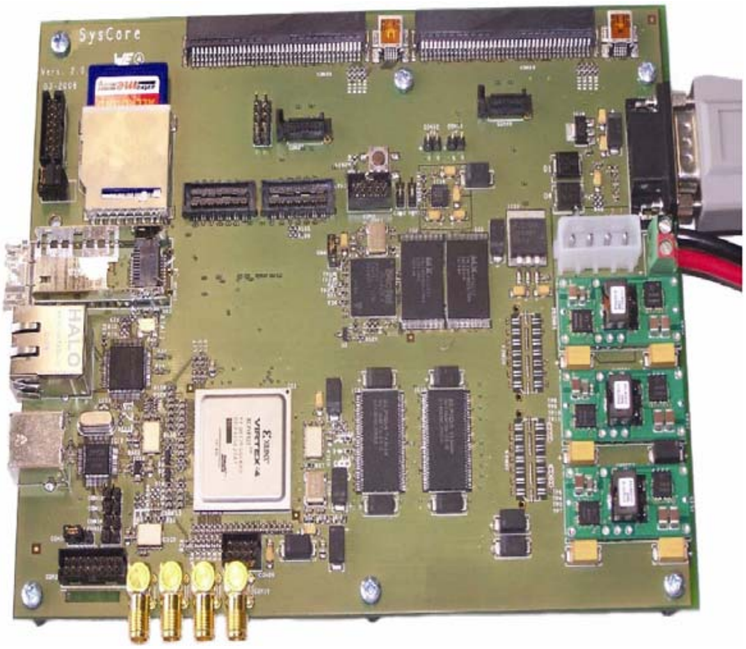

**Figure 11.** A ROC board fabricated by the Indian industry.

*Readout controller board*

At present, the scope of the readout controller (ROC) board is not well defined as it depends on the detector functionality, on-board data processing requirements and final design of HUB-ASIC. However, it is anticipated that the board will consist of an FPGA for heavy digital processing. We have therefore explored our ability to build such a complex board by building a ROC being used by the test experiments. One such board is shown in Figure 11.

## Summary and discussion

The study of the strongly interacting matter at extreme conditions is fascinating both theoretically and experimentally. Although in theory, high-temperature and low-density phase can be understood by the lattice-QCD simulation, however, high-density phases are still debatable. Therefore, the only way to pinpoint the landmarks of the phase-diagram is by creating nuclear media at extreme conditions in the laboratory by colliding two heavy ions at varying energies. Over the last several decades, high-temperature and low-density phases are being explored extensively in RHIC and LHC. The CBM experiment in the upcoming FAIR facility will be the first place where the high-density phase will be studied in great detail. Equipped with the high-beam intensity at FAIR, CBM focuses on detecting probes with extremely low production cross-section, e.g. open and hidden charms, multi-strange particles and other exotica. A nationwide collaboration has been formed in India to participate in the CBM experiment in terms of building and operating a large portion of the di-muon detection system. The requirements of high-resolution, fast and radiation hard detector-system and electronics will allow us to explore a new technological domain. The experience of building high-resolution detectors will have its application in other areas like medical imaging and radiography among others.


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