

Technical Design Report for the CBM

Time – of – Flight System (TOF)

The CBM Collaboration



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Summary

This document describes the technical design and the performance of the Time - of - Flight system (TOF) of the Compressed Baryonic Matter (CBM) Experiment at FAIR.

The detector system's prime task is to measure the arrival time of charged particles to allow for their identification after having matched the TOF - hit with the corresponding STS track obtained from the CBM silicon tracking system (STS). The system is designed to cope with all the reactions anticipated in the physics program of CBM. This ranges from heavy-ion reactions of different system size from C+C to Au+Au over a large incident energy range from 2A GeV to 45A GeV (35A GeV for the heaviest collision system) to proton - nucleus reactions up to a projectile energy of 90 GeV.

The physics motivation of CBM in general is presented in chapter 1. CBM aims to investigate rare probes such as charmed hadrons, multiple strange hadrons, di-electrons and di-muons as messengers of the dense phase of strongly interacting matter with unprecedented accuracy. This is achieved by designing all components of the experiment for an interaction rate of 10 MHz for the largest reaction systems. Since the experimental signatures of the probes can only be extracted after a full reconstruction, CBM features a data flow concept where all the data of all subsystems are pushed into a compute farm, the First Level Event Selector (FLES) in CBM terminology, where interesting events or slices in time are marked for storage after online analysis.

The general layout considerations following from the CBM concept are discussed in chapter 2. Since CBM is operated in fixed target mode the flux of charged particles is strongly varying with the polar angle. In order to fit to the forward acceptance of the CBM experimental setup that is based on an instrumented dipole magnet with particle identification detectors placed downstream of the target, a modular TOF wall is proposed whose elements, called modules in the following, are adapted to the granularity and rate requirements. To allow for sufficient separation power especially for the identification of charged kaons, distances of up to 10m and a system time resolution of 80 ps are necessary leading to an overall size of the TOF - wall of approx. $12 \times 9 \,\mathrm{m}^2$. To achieve the overall time resolution this area needs to get instrumented with timing detectors with an intrinsic timing resolution of better than 60 ps and an efficiency of better than 95%.

We propose to build the CBM - TOF wall on the basis of state-of-the-art Multigap Resistive Plate Chambers (MRPC). The basic element of this robust detector concept is a stack of resistive electrodes made out of glass or ceramics that are separated by thin gas gaps. At sufficiently high electric field strength avalanches are created in a very uniform manner and can be read out via capacitive coupling. As is demonstrated in chapters 7 this 10- years old detector technology is well advanced by now, largely due to the effort of the CBM - TOF group, and offers the flexibility to cope with the high demands posed by the CBM physics goals. Most notably, the proposed concept that requires a detector technology with a sustained rate capability in the order of 25 kHz/cm² became possible only by the development of a low-resistivity glass (see section 7.1.1) that is available for CBM - TOF by now through the CBM - TOF group at Tsinghua University, Beijing, China at reasonable costs.

The proposed structure of the CBM - TOF wall is based on detector layouts that have already been realized and tested in in-beam experiments and demonstrated MRPC counter timing resolutions below 60 ps with efficiencies above 95% at rates relevant for CBM (see chapter 7 for details). The basic element of the proposed wall are MRPC strip counters where a single avalanche is generating two signals at the two ends of a readout-electrode. The length of the readout - strip can be easily adjusted to the required granularity. The leading design goal of the proposed strip structures is operation stability and signal integrity. This is achieved by differential signal processing and the matching of the readout strip impedance to the input impedance of the newly developed preamplifier discriminator chip (PADI). Thus the number of spurious hits due to reflections is minimized and an optimal response of the detectors is guaranteed with minimal dead time. This aspect is considered to be especially important for the high rate running conditions of CBM where even independent events will be overlapping in time space and any additional spurious hit will deteriorate the system performance.

In order to minimize the number of components, the CBM - TOF wall is designed to be composed of 4 different types of MRPC counters only, arranged into 6 different types of modules. The proposed CBM -TOF system is described in detail in chapter 3.

The modules and counters are realized in 2 different technologies:

1. The modules placed at small polar angles close to the beampipe (M1 - M3) are housing counters (MRPC1,MRPC2) that employ a double stack HV - design. The counters are equipped with low resistivity glass and have electrodes of dimensions of $32 \times 10 \text{ cm}^2$ and $32 \times 20 \text{ cm}^2$, 10 gas gaps and a strip pitch of 4.7 mm. The front-end electronics in mounted outside of the gasvolume. A total of 36.608 electronics channels is needed to readout this part of the TOF wall.

The proposed design emphasizing the full coverage of the solid angle and is rather conservative in terms of data integrity since each hit is registered by 2 readout channels and allows to determine the hit position with an accuracy of a few mm in each direction.

More detailed measurements of the response under fully loaded conditions and time based simulations of the system response will show whether this strip solution could be replaced by a cheaper pad - type MRPC solution that is described in detail in the appendix E and requires only 27.792 electronic readout channels.

A decision will be taken at latest in Dec. 2015 after careful analysis of test beam data that will be taken at GSI in October 2014 and at CERN SPS in April 2015. With currently available HI - beam conditions close to the operating conditions of CBM will be realized.

2. For the remaining part of the wall (modules M4 - M6) two different sizes of a MRPC strip counter with active area of $32 \times 27 \text{ cm}^2$ and $32 \times 53 \text{ cm}^2$, and a strip pitch of 1 cm are proposed. These counters are equipped with low-resistivity glass or thin float glass electrodes according to the rate requirements and use a single HV stack with 8 gas gaps. In order to optimize the signal integrity the preamplifier is connected as directly as possible to the readout electrode and put into the gas volume of the modules. As largest benefit this arrangement offers the possibility to operate the detectors at lower discriminator thresholds and the lower pulse height results in turn also in a higher rate capability. The design of independent module units including the analog electronics also offers the necessary robustness to operate a system of 218 modules and 70.000 readout channels.

The disadvantage of the proposed single stack architecture is the need of two high voltages $(\pm 11 \text{ kV})$ causing substantial costs. An alternate design with a double stack configuration of the high voltage is available and can be operated at about 5.6 kV. However, this counter configuration needs more glass electrodes (12 instead of 9) and the cost benefit from the HV has to be compared to the additional cost caused by additional electrodes especially when these are made from low resistivity glass. Counters of this type that are described in appendix F.2.4 will be evaluated in comparison to the proposed ones also in the upcoming HI - test beam campaigns addressing the system features of the designs. A decision is will be taken at latest in Dec. 2015 after careful analysis of the test beam data.

The high performance electronics for the whole CBM - TOF wall is independent of the choice of a specific module or counter type and is based on the PADI and the GET4 - ASIC chips developed by the CBM - TOF group (see sections 3.3.3 and 3.3.5). The combination of both chips in conjunction with a custom - designed clock distribution system (section 3.3.8) offers the possibility to build a large scale system with an electronics contribution to the timing resolution of about 30 ps. This system was tested using a readout controller that implements the full CBMnet - protocol and allows for online inspection and control of the GET4 - data. The details of the readout-chain are described in section 3.3.

However, since up to now no long-term stably working GET4 - system could be demonstrated, an alternative backup solution is also included in this report. It is built on FPGA based TDCs that became available recently (see appendix G.2) and provides timing resolutions on the level of 10 ps. A free streaming readout chain is not yet available, but is planned to be realized in the near future. As a consequence the number of necessary readout controllers would be substantially reduced leading eventually to a more simple and cost effective system. More R&D is required in the direction of an FPGA - based digitizer / readout system, specifically considering the radiation environment (see chapter 2.5).

Since FPGA - based digitizers are offering a better resolution and more flexibility and would allow e.g. for an improvement of the double hit recognition the decision about the production of the GET4 - system will be taken only after a) the stability of the GET4 readout chain is proven, b) no competitive FPGA based solution is available until start of mass production (Dec.2015). Therefore R&D work on FPGA - based TDCs is continuing as part of the project.

The proposal of a high performance TOF wall would be incomplete without the discussion of the time - zero (t_0) - reference that is needed for any velocity measurement. Details can be found in chapter 4

demonstrating that for all of the anticipated running scenarios solutions are available. For most of the heavy-ion reaction running at the initial SIS100 accelerator the software based t_0 -extraction is sufficient (see section 4.2). This method can be calibrated by making use of the diamond based start detector system developed for the HADES experiment (section 4.4) that is operational up to interaction rates of 100 kHz.

As has been shown by Monte-Carlo simulations using the SHIELD event generator the quality of the t_0 - reference determination can be improved by installing the so called Beam Fragmentation T0 Counter (BFTC) as the innermost part of the TOF wall (see section 4.3). It should cover the region from about 20 to 60 cm from the beam pipe (overlapping with the PSD acceptance). Using a very simple algorithm without tracking information a t_0 -signal with a precision of better than 50 ps can be achieved. A detector concept, anticipated to be able to operate in this harsh environment with the fluxes being as high as 100 kHz/cm², built from very radiation-hard materials and possessing minimum gas aging characteristics, is suggested to be based on the ceramic electrodes (see section F.1). Single cell pads with the size of 2×2 cm² seem to fulfill the double hit, maximum rate and cross-talks requirements. Further R&D is necessary in order to prove the validity of the concept.

The very large dynamical range in terms of incident beam energies that has to be covered by the CBM experiment reflects itself by the movable wall concept where the whole TOF - system is mounted on rails and can be placed at various distances. The rail system is sketched in section 5.1. It allows e.g. to balance the decay losses for kaons against the purity of an anticipated online kaon multiplicity selection. It also enables the servicing of the components independently from the other subsystems of CBM during shutdown periods.

The TOF project is realized in close cooperation of institutes from China, Germany, Romania and Russia. The breakdown of the work packages (see section 8.3) demonstrates that the CBM - TOF group is well prepared to realize and maintain the proposed TOF wall.

A coarse planning of the timeline is given in section 8.6. The detector system will be constructed, installed into the CBM experiment and be ready for operation for the start of FAIR beams in the year 2020.

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Chapter 1

The Compressed Baryonic Matter Experiment

1.1 Exploring the Phase Diagram of Nuclear Matter

Quantum Chromo-Dynamics (QCD), the commonly accepted field theory of strong interaction, exhibits two well-known features: asymptotic freedom and chiral symmetry. The former labels the fact that for momentum transfers larger than the intrinsic QCD energy scale $\Lambda_{QCD} \approx 200$ MeV, the constituents of QCD, quarks and gluons, are weakly bound and perturbation theory becomes applicable. In the low-energy regime, on the other hand, the coupling is strong, and quarks and gluons are confined in colour-neutral clusters, the hadrons. Consequently, a transition from a hadronic medium to the so-called Quark-Gluon Plasma (QGP) is expected once a certain energy density is reached.

The chiral symmetry of QCD is approximate and exact only in the limit of vanishing quark masses. However, at low energy densities, the approximate chiral symmetry is spontaneously broken. This spontaneous symmetry breaking has a much larger effect, e.g. on the hadron masses, than the explicit symmetry breaking by the Higgs-masses of the quarks. Similarly to confinement, it is expected that chiral symmetry is (approximately) restored for matter at high energy densities.

In thermodynamic equilibrium, QCD matter can be characterized by two parameters, namely the temperature T and the net-baryon density ρ_B or its conjugate variable, the baryo-chemical potential μ_B . The critical energy density for the deconfinement or chiral transition can be reached by increasing both T or μ_B , i.e. by heating or compressing. At zero net-baryon density, it is possible to solve QCD on a space-time lattice. These ab-initio calculations confirm the qualitative expectations expressed above: they show a transition to deconfined and chirally symmetric matter at a critical temperature T_C of about 170 MeV. This transition seems to be a cross-over, meaning that the two phases are not distinguishable at T_C .

Lattice QCD, however, is restricted to vanishing or small net-baryon densities. At higher densities, one has to rely on effective, QCD-inspired models. Such models predict the chiral transition to be of first order at higher μ_B . Consequently, the regions of first-order phase transition and of cross-over must be separated by a critical point, where the transition is a second-order one. Moreover, while at $\mu_B = 0$, the chiral and deconfinement transitions seem to coincide, this need not be the case at higher baryo-chemical potentials. A non-congruence of both transition lines would give rise to a third phase, the so-called Quarkyonic matter, which is suggested by QCD models in the large N_C limit.

The situation is depicted in Fig. 1.1, showing a sketch of the phase diagram of strongly interacting matter. Cold nuclear matter - as found in normal nuclei with a net baryon density equal to one - consists of nucleons only. At moderate temperatures and densities, nucleons are excited to short-lived states (baryonic resonances) which decay by the emission of mesons. At higher temperatures also baryon-antibaryon pairs are created. This mixture of baryons, antibaryons and mesons, all strongly interacting particles, is generally called hadronic matter, or baryonic matter if baryons prevail. At very high temperatures or densities the hadrons melt, and the constituents, the quarks and gluons, form new phases, Quarkyonic matter or the Quark-Gluon Plasma. More exotic phases, like colour superconductivity formed by correlated quark-quark pairs, are speculated about at low temperatures and very high net-baryon densities. Such matter may exist in the cores of neutron stars.



Figure 1.1: Sketch of the phase diagram of strongly-interacting matter (from [6]).

The potentially rich structure of the QCD phase diagram at high net-baryon densities as suggested by theory surely calls for experimental verification. The discovery of the prominent landmarks like firstorder chiral and deconfinement phase transition and the critical point would be a major breakthrough in our understanding of the properties of nuclear matter. Experimentally, hot and dense nuclear matter is generated over a wide range of temperatures and densities by colliding nuclei at relativistic energies. The abundances of various hadron species produced in such collisions appear to be in chemical equilibrium, thus allowing to characterize them by the thermodynamic variables T and μ_B . The extracted values for T and μ_b at various collision energies form the so-called freeze-out line in the phase diagram as shown in Fig. 1.2. While nuclear collisions at the highest available energies (RHIC and LHC) appear to probe matter at high temperatures and small μ_B , the energy range accessible with the upcoming FAIR facility is best suited for the study of the regime of high net-baryon density. This is underlined by results of transport calculations as shown in Fig. 1.3. According to these calculations, densities up to a factor of seven higher than saturation density can be produced already at beam energies of 10A GeV. It should be noted that the freeze-out conditions depicted in Fig. 1.2 characterize only the final state of the collision. Detailed studies of finite-size systems with a highly inhomogeneous initial state configuration and of dynamical effects have to be carried out in order to access precise information on the properties and dynamics of each stage of the collision.

Currently, several experimental programmess are devoted to the exploration of the QCD phase diagram at high net-baryon densities. The STAR collaboration at RHIC scanned the beam energies in order to search for the QCD critical endpoint [8]. For the same reason, measurements are performed at the CERN-SPS with the upgraded NA49 detector (NA61) using beams of light and medium-heavy ions [9]. At the Joint Institute for Nuclear Research (JINR) in Dubna, a heavy-ion collider project (NICA) is planned with the goal to search for the coexistence phase of nuclear matter [10]. However, because of limitations in luminosity or detector design, these experiments are constrained to the investigation of abundantly produced particles. In contrast, the Compressed Baryonic Matter (CBM) experiment at the Facility for Antiproton and Ion Research (FAIR) in Darmstadt will be a high-rate fixed target experiment designed for precision measurements of multi-dimensional observables, including particles with very low production cross sections, using the high-intensity heavy-ion beams provided by the FAIR accelerators.





Figure 1.3: Baryon density as function of elapsed time for central Au+Au collisions at different beam energies as calculated with the HSD transport code [11]

Figure 1.2: Experimentally measured freeze-out points (from [7]) extracted from particle yields assuming thermal equilibrium.

1.2 The CBM Physics Programme

In order to gain insight into the properties of compressed baryonic matter created in heavy-ion reactions, the collision products have to be experimentally detected and characterized with respect to their yield and phase-space distribution. Different types of particles provide access to the different stages of the collision as illustrated in Fig. 1.4:

- Because of their large mass, exceeding the temperature of the fireball by far, charm quarks can only be created by first-chance collisions of the incoming projectile and target nucleons. Charmed hadrons thus serve as a probe for the very early, high-density stage of the collision.
- After a short time span, an equilibrated medium is formed in the centre of the fireball. During its expansion and cooling, it emits hadrons and photons. The produced hadrons interact both elastically and inelastically. Multi-strange hyperons and the ϕ meson decouple early from the dense medium because of their low hadronic cross section. They thus carry information on this hot and dense, yet hadronic stage of the reaction.
- Finally, also the interaction between the bulk particles (π , K, p, Λ) ceases (freeze-out), and the particles stream freely into the detectors.
- Throughout the collision, vector mesons (ω, ρ, ϕ) are produced by $\pi\pi$ annihilation and decay either again into pion pairs or electromagnetically. As leptons do not suffer from hadronic final-state interactions, the lepton pairs from vector meson decays carry information on all stages of the reaction. Of particular interest here is the ρ meson which, because of its small life time, decays predominantly in the hot and dense medium.

By a comprehensive measurement of the diagnostic probes described above, CBM intends to address the following physics topics:

• What is the equation-of-state of nuclear matter at densities close to that in the core of neutron stars?

The collective motion of produced particles ("flow") results from the conversion of spatial density gradients into pressure gradients. Flow thus gives direct access to the equation-of-state of the hot and dense medium. Moreover, the production of multi-strange (anti-)baryons, in particular at or even below the threshold in elementary collisions, is sensitive to the baryon density of the medium.



Figure 1.4: Three stages of a U+U collision at a laboratory beam energy of 23A GeV as calculated with the UrQMD model [12]: The initial stage where the two Lorentz-contracted nuclei overlap (left), the high density phase (middle), and the final stage ("freeze-out") when all hadrons have been formed (right). Different particles are created in different stages of the collisions or escape from the interaction region at different times (see text). Almost 1000 charged particles are created in such a collision, most of them being pions.

• What are properties of hadrons in a dense medium?

The restoration of chiral symmetry in the dense medium will reflect in the modification of hadron properties (mass, width). These are accessible by the measurement of lepton pairs resulting from the decay of short-lived vector mesons, in particular the ρ meson. It was also proposed that a modified mass of charmed hadrons (D mesons) will affect their production yield. The measurement of open charm thus potentially also gives inside in the in-medium modification of hadron properties.

• Where and of which type is the phase transition from hadronic to partonic matter at high net-baryon densities?

Should there be a first-order phase transition, there must be a co-existence phase with latent heat. The phase transition thus should manifest in discontinuities in the excitation functions of sensitive observables, such as yields, spectra and flow of strange or charmed hadrons and of lepton pairs. Moreover, fluctuations in event-by-event observables reflecting conserved quantities (baryon number, strangeness, net charge) are expected and must be studied.

• How is charm produced close to threshold and how does it propagate in dense nuclear matter?

The answers to these questions are basically unknown, and experimental data on charm at low energies is scarce (J/Ψ) or entirely lacking (D mesons). In order to address this subject, the measurement of yields and spectra of both open and hidden charm in nuclear collisions is required. For the understanding of the data, reference measurements in p+p and p+A collisions are indispensable.

• What are the properties of multi-strange hyper-nuclei, and do strange do-baryons or other exotic strange objects exist? The experimental knowledge on multi-strange hyperons is poor. In heavy-ion collisions, such objects can be produced by coalescence of Λ with nuclei or light fragments. The FAIR energy range is particularly suited for the production of hypernuclei; the maximum production yield is expected around 10*A* GeV. The existence of exotic strange objects as collapsed states of matter is still an issue in high-energy physics; heavy-ion collisions with abundantly produced strangeness offer a tool to create such multi-strange composites. They would be detected via their decay chain with one or multiple Λ in the final state.

CBM intends to perform the measurements described above in a large acceptance, which high accuracy and statistics, and systematically as function of beam energy and system size. This includes a fine-grained energy scan as well as the measurement of different collision systems, ranging from heavy-ions (Au) over light ions to p+p reactions. The experimental challenge is to measure multi-differential observables and particles with very low production cross sections such as multi-strange (anti-)hyperons, particles with charm and lepton pairs with unprecedented precision. The situation is illustrated in Fig. 1.5, showing predictions for the product of multiplicity and branching ratio for various particle species produced in central Au+Au collisions at a beam energy of 25 AGeV. The data points are calculated using either the HSD transport code [13] or the thermal model based on the corresponding temperature and baryonchemical potential [14]. Mesons containing charm quarks are about 9 orders of magnitude less abundant than pions (the ψ ' meson is even more suppressed). The dilepton decay of vector mesons is suppressed by the square of the electromagnetic coupling constant $(1/137)^2$, resulting in a dilepton yield which is 6 orders of magnitude below the pion yield, similar to the multiplicity of multi-strange anti-hyperons.



Figure 1.5: Product of particle multiplicities and branching ratio for particles created in central Au+Au collisions at 25A GeV as calculated with the HSD transport code [13] and the statistical model [14]. For the vector mesons $(\rho, \omega, \phi, J/\psi, \psi')$ the decay into lepton pairs was assumed, for D mesons the hadronic decay into kaons and pions.

Up to date, only the bulk particles were measured in heavy-ion collisions in the FAIR energy range. Diagnostic probes of the dense stage of the fireball such as multi-strange baryons, dilepton pairs and charmed particles will be measured for the first time by the CBM experiment in this energy domain. In order to produce high statistics data even for the particles with the lowest production cross sections, the CBM experiment is designed to run at reaction rates of up to 10 MHz. Such rates, unprecedented in heavy-ion experiments, are highly demanding in terms of detector technique and data processing, but give way to a unique discovery potential for CBM.

A substantial part of the CBM physics topics will already be addressed with beams from the SIS100 synchrotron, which will come into operation first, at incident beam energies up to 10A GeV. The intended measurements at SIS100 including the results of simulations and count-rate estimates are described in [15]. A general review of the physics of compressed baryonic matter, the theoretical concepts, the available experimental results and predictions for relevant observables in future heavy-ion experiments can be found in the CBM Physics Book [16].

1.3 The Facility for Antiproton and Ion Research (FAIR)

The international Facility for Antiproton and Ion Research (FAIR) in Darmstadt will provide unique research opportunities on the fields of nuclear, hadron, atomic and plasma physics [17]. The research program devoted to the exploration of compressed baryonic matter will start with primary beams from SIS100 (protons up to 29 GeV, Au up to 11A GeV, nuclei with Z/A = 0.5 up to 14A GeV) and will be continued with beams from SIS300 (protons up to 90 GeV, Au up to 35A GeV, nuclei with Z/A = 0.5

up to 45A GeV). The layout of FAIR is presented in Fig. 1.6. The beam extracted to the CBM cave will reach intensities up to 10^9 Au ions per second.



Figure 1.6: Layout of the Facility for Antiproton and Ion Research (FAIR) [17].

1.4 Experimental Setup

To cope with the experimental challenges described in section 1.2, the CBM experimental setup was designed according to the following considerations:

- Almost complete acceptance from mid- to beam rapidity,
- high rate capability and radiation hardness,
- identification of hadrons and leptons,
- sensitivity to weak decay topologies,
- sensitivity to open charm decays.

The experimental setups are shown in Figs. 1.7 and 1.8 with electron detectors and the muon detection system, respectively. They comprise the following components:

• Dipole magnet

The dipole magnet will be superconducting in order to reduce the operation costs. It has a large aperture of $\pm 25^{\circ}$ in polar angle and provides a magnetic field integral of 1 Tm.

• Micro-Vertex Detector (MVD)

The MVD will provide excellent position resolution and low material budget required for the identification of open charm particles by the measurement of their displaced decay vertex. It consists of four layers of MAPS detectors located from 5 cm to 20 cm downstream of the target in vacuum. The detector arrangement provides a resolution of secondary vertices of about 50-100 μ m along the beam axis.

1.4. EXPERIMENTAL SETUP



Figure 1.7: The CBM experimental facility with the electron detectors RICH and TRD.



Figure 1.8: The CBM experimental facility with the muon detection system.

• Silicon Tracking System (STS)

The task of the STS is to provide track reconstruction and momentum determination of charged particles. The system consists of eight tracking layers of silicon strip detectors and provides a momentum resolution of about 1.5 %.

• Ring-Imaging Cherenkov Detector (RICH)

The RICH detector will provide the identification of electrons by the measurement of their Cherenkov radiation in a standard projective geometry with focusing mirror elements and a photo detector. The detector will be positioned behind the dipole magnet about 1.6 m downstream of the target. It consists of a 1.7 m long gas radiator and two arrays of mirrors and photo detector planes.

• Muon Chamber System (MUCH)

The concept of the muon detection system is to track the particles through a hadron absorber system and thus perform a momentum-dependent muon identification. The actual design of the muon detector system consists of 6 hadron absorber layers and 18 gaseous tracking chambers located in triplets behind each iron plate.

• Transition Radiation Detector (TRD)

Three Transition Radiation Detector stations each consisting of 3 detector layers will serve for particle tracking and for the identification of electrons and positrons with p > 1.5 GeV/c ($\gamma \ge 1000$). The detector stations are located at approximately 5 m, 7.2 m and 9.5 m downstream of the target, the total active detector area amounts to about 600 m². The pion suppression factor obtained with 9 TRD layers is estimated to be well above 100 at an electron efficiency of 90%. For measurements at SIS100 only one station with 3 detector layers will be used as an intermediate tracker between the STS and the TOF wall.

• Time-of-Flight System (TOF)

For hadron identification an array of Multi-Gap Resistive-Plate Chambers will measure the timeof-flight of the reaction products. This TOF wall is planned to cover polar angles from $2.5^{\circ} - 25^{\circ}$ spanning an active area of about 120 m²; it will be located between 6 m and 10 m downstream of the target depending on the physics needs. The required full system time resolution (including the contribution of the t₀-reference) is of the order of 80 ps. For 10 MHz minimum bias Au+Au collisions the innermost part of the detector has stand rates up to 25 kHz/cm² which is not feasible with common float-glass detectors. Prototypes with low-resistive glass have been developed which deliver excellent time resolutions (about 60 ps) even at these rates. At small deflection angles the granularity is about 5 cm² corresponding to an occupancy of below 5% for central Au+Au collisions at 25A GeV beam energy. The basic features of this TOF Wall, R&D on prototypes and electronics, results of performance simulations as well as the proposed technical realisation are subject of the present report and will be presented in detail in the following.

• Electromagnetic Calorimeter (ECAL)

A "shashlik" type calorimeter as installed in the HERA-B, PHENIX and LHCb experiments will be used to measure direct photons and neutral mesons (π^0, η) decaying into photons. The ECAL will be composed of modules which consist of 140 layers sandwiched of lead and scintillator sheets. The shashlik modules can be arranged either as a wall or in a tower geometry with variable distance from the target.

• Projectile Spectator Detector (PSD)

The PSD will be used to determine the collision centrality and the orientation of the reaction plane. Such a precise characterization of the event is of crucial importance for the analysis of event-byevent observables. The detector is designed to measure the number of non-interacting nucleons from a projectile nucleus in nucleus-nucleus collisions. The PSD is a full compensating modular lead-scintillator calorimeter which provides very good and uniform energy resolution. It comprises 44 individual modules, each consisting of 60 lead/scintillator layers.

The high event rates envisaged by the CBM experiment of up to 10 MHz require an online data reduction by a factor of 100 or above, in order to arrive at a manageable archival data rate. Because of the complex event topologies and the complexity of signal signatures, the CBM DAQ system will not employ a hierarchical trigger system with first-level hardware triggers. Instead, all read-out electronics will run autonomously and push signals above threshold with time stamps to the data acquisition system. Data selection will be performed exclusively in software on a high-performance computer farm equipped with many-core CPUs and graphics cards, located several 100 m distant from the experiment in the GSI Green-IT Cube. This concept requires partial event reconstruction in real time and thus highly efficient and performant reconstruction algorithms. Track reconstruction, which is the most time consuming combinatorial stage of the event reconstruction, will be based on parallel track finding and fitting algorithms, implementing the Cellular Automaton and Kalman Filter methods. Observables that do not require extreme event statistics or where no event selection signature is available can be measured in dedicated runs with moderate interaction rate or simultaneously with rare probes by archiving randomly selected minimum-bias events.

Chapter 2

The Time-of-Flight System

As one of the core detectors of the CBM experiment, the Time-of-Flight (TOF) system provides particle identification for all charged hadrons emitted in beam-target interactions into the acceptance of the setup. The detector will be operated in all experiments of the CBM physics program at SIS100. This includes proton beams with laboratory energies up to 29 GeV, and heavy ions with lab energies from 2A GeV up to 14A GeV as well as in later SIS300 campaigns protons up to 90 GeV and ions up to 45A GeV.



Figure 2.1: Populated phase space in Au + Au reactions calculated with the URQMD generator at beam energies of 4 (left), 10 (middle) and 25 A GeV (right) for protons (1st top), pion (2nd row), positively charge kaons (3rd row) and antiprotons (bottom row). The colors represent the particle yield on a logarithmic scale. Red (blue) lines are locations of constant laboratory momentum (polar angle).

The populated phase space in minimum bias heavy ion reactions is depicted in Fig.2.1 for 3 reference systems representative for the wide physics program addressed by CBM. As can be seen from Fig.2.1 the bulk of all produced hadrons (pions, kaons, antiprotons) is located at laboratory momenta below

8 GeV/c even at the higher SIS300 energies. A high performance TOF - detection system offers the opportunity to solve the particle identification task by a single subsystem for all hadrons.

2.1 TOF - PID - Method

2.1.1 Standard method



Figure 2.2: Distribution of m^2 versus momentum for positively charged hadrons. The distance between target and TOF detector is 10 m, the time resolution 80 ps.



Figure 2.3: m^2 spectrum for positively charged particles at $p_{lab} = 6$ GeV/c. The solid line shows the fit to the spectrum, the dotted lines the contribution of the single particle species (π, K, p) .

The principle of particle identification by time-of-flight relies on simultaneous measurement of momentum and velocity of a particle. Assuming that a track trajectory is reconstructed from the interaction vertex to the TOF system, the measured time-of-flight allows to calculate the velocity β of the particle. Together with the momentum p from the tracks' curvature, the (squared) mass of the particle can be calculated as

$$m^2 = p^2 \left(\frac{1}{\beta^2} - 1\right) \tag{2.1}$$

In most cases, the TOF resolution σ_t dominates the error in the squared mass over the contributions of momentum and track length inaccuracies. Then, the error in m^2

$$\sigma_{m^2} = \frac{2p^2}{\beta^2} \frac{\sigma_t}{t} \tag{2.2}$$

is independent on m and is a quadratic function of the momentum. Because of this quadratic dependence, the PID capability quickly decreases with increasing momentum as shown for an ideal detector in Fig. 2.2 for positively charged particles.

For the quantitative PID, the two-dimensional probability density function (PDF) has to be derived as the sum of the single particle functions:

$$PDF(p,m^2) = \sum_{\alpha} PDF^{(\alpha)}(p,m^2) \quad , \tag{2.3}$$

where the summation runs over the contributions of pions, kaons and protons. The single particle function can be written as

$$PDF^{(\alpha)}(p,m^2) = r_{\alpha}(p)f_{\alpha,p}(m^2) \quad , \tag{2.4}$$

where $r_{\alpha}(p)$ is the momentum spectrum of particle α after the detector acceptance. For illustration, assuming a purely Gaussian contribution of each particle with a momentum dependent width :

$$f_{\alpha,p} = \frac{1}{\sqrt{2\pi}\sigma_{m^2}(p)} exp \left\{ -\frac{(m^2 - m_{\alpha}^2)^2}{2\sigma_{m^2}^2} \right\}$$
(2.5)

The PDF is constructed by fitting the measured m^2 distribution in momentum bins, in this case by the sum of three Gaussians as demonstrated for simulated events in Fig. 2.3.

It should be mentioned that the Ansatz written down above implies an uniform resolution over the full active volume of the TOF system without any dependence of the detector response on the particle species (specific energy loss). More complicated response function can, however, be incorporated in a similar fashion.

2.1.2 Particle identification by Bayesian method

The standard particle identification (PID) method presented in the previous paragraph, called also $n\sigma$ -approach, selects different species based on the number of standard deviations by which a signal differs from the expected detector response. There are special types of analysis where an alternative Bayesian approach is worth to be considered. The Bayesian method produces probabilities for each identity hypothesis that depend not only on the detector response but also on the relative particles abundances. This dependence is described by the following formula:

$$w(i|s) = \frac{r(s|i)C_i}{\sum_{k=e,\pi,K,p} r(s|k)C_k}$$
(2.6)

where w(i|s) is the probability to have a particle of type i if a signal s is obtained and r(s|i) is the probability to obtain, in the corresponding detector, a PID signal s if a particle of type i is detected (further referred to as detector response functions). The C_i factors are derived from the relative particle abundances and represent the a priori probabilities of finding a particle of type i (further referred to as priors). It can be considered as a very good approximation that the detector response functions depend only on the properties of the considered detector and that the priors depend only on the analysis details. The detector response functions are determined, as it was described in the previous paragraph, during the reconstruction phase from the experimental data with no dependence on Monte-Carlo (MC) simulations. If there are MC models that reproduce the relative yields of different species then, the priors could be taken from MC. As in general this is not the case, the priors can be determined from data using an iterative method.

Applying any TOF - particle - identification method one has to distinguish 2 cases:

- 1. particle identification on a track by track basis,
- 2. inclusive particle identification on a spectral basis.

The first track-wise particle identicifation can typically be applied when the separation of the mean values of the respective masses is larger than $3 \times \sigma_{M^2}$ that in turn depends on the timing resolution of the system and the flight path, over which the time difference is measured. The dependence of the 3σ -separation power is plotted in Fig. 2.4 as function of the detector distance to the target and the system time resolution.

Comparing to the iso-momentum lines in Fig. 2.1 one has to conclude that a TOF - system is the natural choice for the core particle identification method in the FAIR energy regime.

For optimal performance (as discussed in detail in chapter 6) the ToF system has to be flexible enough to cope with different tasks, e.g.

- for antiproton measurements, the best separation power is supposedly achieved with the largest possible distance of the TOF wall to the target,
- at the lower beam energies, when searching e.g. for rare strange clusters, there are hardly any kaons with momenta above 4 GeV/c, asking for the shortest possible distance of the TOF wall to the target in order to minimize decay lossses.

The system proposed here accommodates these different use cases by the possibility to change the distance to target, i.e. it is made movable along the beam direction (see section 5.1).



Figure 2.4: Dependence of separation power of TOF systems as function of momentum, time resolution and flight path length.

2.2 TOF - Requirements

The TOF Wall identifies hadrons i.e. pions, kaons and protons in the angular range covered by the STS detector $(2.5^{\circ}-25^{\circ})$. Placed at a distance of 10 m from the primary interaction point it covers an active area of about 120 m², approximately rectangular in shape (9 m high, 13.5 m wide).

In order to distinguish kaons reasonably well from pions and protons for the major part of the cross section in the geometrical acceptance, a full-system time resolution of at least 80 ps is needed (see section 6.2) This figure includes all possible contributions such as electronics/digitization jitters and the relative calibration of tens of thousands individual channels, but also the resolution of the T_o -time reference that can be obtained by different methods (see section 4.4). Hence, the typical time resolution of the single channels should not exceed 60 ps. At the same time the individual detection efficiency should reach at least 95%. At present a system of Multi-gap timing Resistive-Plate Counters, MRPCs, is considered the only possible solution that can meet these requirements at affordable costs.

In order to accumulate enough statistics of rare probes such as J/Ψ and Ψ' , the CBM detector has to run at ion beam intensities up to 10^9 /s. This beam rate is neede - with a standard 1% target - to achieve a target interaction rate of about 10 MHz; together with the high particle multiplicity per event this yields considerable rates in the TOF wall. Fig. 2.5 shows the simulated average track-density rates in kHz/cm² for minimum-bias events in Au+Au at 25A GeV with the TOF wall placed at a distance of 10 m from the interaction target representing typical operating conditions at SIS300 (cf. Fig. 1.7) Also shown (blue histogram) are the fluxes calculated for Au + Au reactions at an incident energy of 10 AGeV and a distance of 6 m with the reduced setup where only the RICH detector is placed in between the STS and the TOF wall. It can be seen that the distance of the TOF wall to the target can be shortened for the lower incident energies (SIS100) substantially without exceeding the rate requirements imposed from the SIS300 operation.

As demonstrated by the figure 2.5 the flux load on the TOF Wall varies by almost two orders of magnitude over the active surface. Counters placed in the innermost part of the wall positioned typically at a distance of about 50 cm from the beampipe have to stand particle fluxes as high as 100 kHz/cm² without deterioration of their key properties. Note that the extremely high rates at small positive x-position in Fig. 2.5 up to 1 MHz/cm² are an artefact of the eventgenerator that does not describe fragment



Figure 2.5: Calculated particle flux in the CBM TOF wall placed 10 m (red) and 6 m (blue) behind the primary interaction point using as event generator URQMD and a target interaction rate of 10 MHz minimum bias Au+Au reactions at two different incident energies, depicting the running conditions at SIS300 (red) and SIS100 (blue). The particle flux includes the contribution of secondary particles produced in the upstream material of CBM. Upper part: Flux as function of X at Y=0 (i.e. left/right of the beam axis), the X-axis also defines the deflection plane of the particles' trajectories in the magnetic field. Lower part: Flux as function of Y at X=0.

production in the spectators properly, but rather disintegrates spectator nuclei into free protons and neutrons. These rate requirements are no longer achievable with RPCs built in the standard technique with float glass electrodes; the electrodes have to be of lower-resistive material such as semi-conductive glass or ceramics. Over the larger part of the wall surface, however, standard detectors can do the job which will reduce the overall detector costs.

Fig. 2.6 demonstrates the track density in a single central Au+Au event at 25A GeV again as function



Figure 2.6: Hit density (hits/ cm^2 /event) of primary and secondary charged particles in central Au+Au collisions at an incident energy of 25A GeV with the TOF wall at a distance of 10 m from the interaction target (red) in comparison to the situation at 10 AGeV, 6 m. (top panel: as function of X, bottom panel: as function of Y, cf. Fig. 2.5).

of the distances X,Y to the beam axis. As shown the innermost part of the wall will be exposed to track densities of about $2 \cdot 10^{-2}$ particles/cm²/event. The granularity of the TOF wall should be high enough ensure clean measurements. We base the following design on the requirement to keep the ratio of possibly distorted double-hits to clean single hit below 5%. Under these conditions the effective area of a single cell (strip or pad) should not be larger than 5 cm² in the center part of the wall. Allowing for some charge sharing between neigboring cells the effective load is increased and thus an even smaller cell size is required. Therefore we start with a cell size of 4 cm² at the small polar angles.

Since the track density drops rapidly with increasing distance from the beam axis, the effective cell size at the large polar angles could be made as large as 100 cm². Therefore a fixed target experiment like CBM needs a counter and system design that can be adapted to the strongly varying granularity requirements. We try to follow the granularity requirements by designing modules with different granularity and rate



Figure 2.7: Layout of the ToF wall (baseline option) in the xz - plane.

capability and placing the same type of module into areas facing similar conditions. The differt type of modules are equipped with the same type of MRPC counters each.

2.3 Detector system layout

The detector system concept tries to accomodate the different requirements caused by the large range of incident beam energies that need to be covered. The TOF wall has to be operational at beam energies ranging from $E_{beam}=2A$ GeV to $E_{beam}=45A$ GeV. For a forward spectrometer like CBM a planar geometry is advantageous, offering the possibility to adjust to the different beam energies by placing it at different distances to the target.

The number of different module types should be kept as low as possible in order to allow for easy exchange and minimal number of spares. In addition keeping the number of different counter sizes small reduces the overall production costs.

The solution presented below is a modular TOF wall consisting of 6 different modules that are located at fixed position in x - direction (the deflection plane of the dipole magnet) and that can be adjusted in vertical (y) direction according to the actual distance of the wall in order to minimize dead areas.

The schematic design of the CBM - TOF wall as implemented in the simulation environment is shown in Figs. 2.7 and 2.8.

In the proposed scenario the full wall consists of only 4 different types of MRPC counters that are arranged into 6 different types of modules. These modules are described in detail in chapter 3 and are mounted into a common frame as discussed in chapter 5.1.

The structure and contents of the individual modules will be described in chapter 3.1, the performance that can be reached with this design is discussed in chapter 6.

2.4 CBM experimental setups with the TOF system

As indicated above the demands of the various physics use cases on the TOF system are quite different. Reference scenarios have been defined in order to study the feasibility of certain experiments.

• Setup A: in order to optimize the kaon efficiency at the lowest SIS100 energies the TOF wall is positioned as close as possible to the target (at a distance of 6 m).



Figure 2.8: Planar projection of the TOF wall in the xy - plane.



Figure 2.9: Setups of the CBM - experiments: for measurments of hadrons at low SIS100 energies (left), antiproton and di-electron measurements at full SIS100 rigidity (middle) and SIS 300 configuration including a fully equipped TRD subsystem (right)

- Setup B: in order to measure stable rare particles as cleanly as possible, the TOF wall is positioned at a distance of 10 m to the target. An additional tracking layer (TRD) is inserted.
- Setup C: Final CBM setup including a fully equipped TRD and RICH subsystem for simultaneous electron and hadron measurements at SIS300.

The actual setup will be chosen depending on the physics goals of a specific running period. The performance will be discussed in chapter 6.

It should be mentioned that the TOF wall will also be used in the di-muon campaigns of CBM (see chapter 1). MC studies show that a substantial reduction of the background can be achieved by time

time difference cuts on the muon pairs. Being shadowed from the primary particle flux by the absorber material this mode of operation does not pose any additional requirement on the TOF system and will not be discussed here any further. The physics performance for this use case will be included in the MUCH - TDR.

2.5 Radiation Environment

As CBM is aiming at unprecedentedly high interaction rates, selection and placement of electronic components and semiconductors have to be compatible with the expected fast hadron flux as well as with the radiation dose that both vary strongly with the polar angle.

Hazardous radiation effects in semiconductors depend mainly on the manufacturing process (Metal Oxide Semiconductor (MOS), Silicon on Insulator(SOI), ...) as well as on the device architecture (90nm, 45nm, 32nm, ...) and can be qualified as follows:

- Cumulative Effects (destructive)
 - due to energy deposition, the critical parameter is the Total Ionizing Dose (TID) (in Gy or rad)
 - due to lattice displacement, the relevant parameter is Non-Ionizing Energy Loss (NIEL) (in 1 MeV - neutron equivalent fluence, $n_{eq}/cm^2/year$)
- Single Event Effects (non destructive)
 - due to upsets in transistors, the relevant parameter is high-energy hadron fluence (in $1/cm^2/s$)
 - due to transient glitches on signal lines, the relevant parameter is high-energy hadron fluence (in $1/cm^2/s$)

2.5.1 Simulations with FLUKA

Fast hadron fluence, radiation dose and neutron equivalent flux were evaluated with the FLUKA package. The results of FLUKA calculations in terms of neutron equivalent flux are shown in the appendix B, the other quantities are documented in [18]. Data have been generated for the following experimental conditions employing Au + Au reactions:

- TOF wall at 6 m, beam energy 4A GeV,
- TOF wall at 6 m, beam energy 10A GeV,
- TOF wall at 10 m, beam energy 25A GeV.

Different settings of the magnetic field in the CBM magnet were analyzed and, more importantly, various positions of the projectile-spectator detector PSD were assumed. The PSD delivers the biggest contribution to the radiation background in the Wall area. As far as fast hadrons are concerned, the difference between the last two items is not very essential, as the influence of the longer distance is counterbalanced by the higher beam energy, which has been shown before, see Figs. 2.5.

2.5.2 Placement of SRAM-based FPGAs

Front-end processors like Read-Out Controllers (ROC) usually employ SRAM-based Field-Programmable Gate Arrays (FPGAs) because of their general advantages that are, however, suffering the following radiation effects.

Cumulative Radiation Effects According to FLUKA simulations for TOF, critical TID values are reached long before the critical NIEL values (see [18], pp. 31/32). Therefore, e.g. modern SRAM based Xilinx FPGAs using 90nm CMOS architecture can be operated up to 3000 Gy (300 krad) (see [19]) which is accumulated at TOF (expecting 1 m distance to the beamline) after ten CBM-years. Several device annealing effects, taking place at room temperature when the particle beam is switched off, are not considered here. As they further relax the TID requirement cumulative effects are not considered to be critical for the placement of SRAM-based FPGAs at TOF.

It should be noted, that this statement only applies for the central processing FPGA chip itself. Supporting boards for the Read-Out Controllers consist of many different components which all need to be qualified for the expected total dose.

Single Event Radiation Effects Single event effects are radiation induced changes in the data matrix of a semiconductor device and therefore the qualification is different in comparison to cumulative effects. Single event effects do not damage the device, they can lead to an unpredictable behaviour if the ionization effect is caused underneath a powered transistor or beside a metal signal line. In its worst but rarest case, this leads to a device reset. SRAM-based FPGAs suffer severely from Single-Event Upsets (SEUs) that are mainly caused by high-energy hadrons which can change the electrical properties of transistors, altering a single one can change the storage value of the whole SRAM cell. Hence the decision where to place SRAM FPGA devices is a balance between the reliability of the device and the urge to save cabling and cost.

There are several techniques to successfully mitigate these single event effects, but for complex systems, full reliability cannot be guaranteed. Proven to be very effective is a permanent refresh of the FPGA's configuration memory in background at runtime (a technique called "scrubbing"), combined with a redundant logic design.

Commonly, it is assumed that SRAM based FPGA device can be operated when the fast hadron rate is below 10 kHz/cm² (with some effort even up to 100 kHz/cm² should be thinkable) and the total ionizing dose is below 200 krad [20]. For the TOF - wall, this requirement translates to positions where |x| > 2 m (horizontal) and |y| > 1 m (vertical). These positions coincide with the outer surfaces of the M3 - modules. For the outer modules M4, M5 and M6, SRAM based FPGA electronics can be directly placed onto the modules.

Further consideration about the placement of digital readout components can be found in section 3.3.7.

Chapter 3

TOF wall components

The Tof - detectors system is organized in a modular way in order to minimizes the number of components. The basic units are modules that are mechanically and electrically independent units that are placed into a mechanical structure, the space frame. These modules contain the MRPC counters and the associated electronics. The following components are part of a module:

- MRPC counters
- Front-end electronics
 - Preamplifier and Discriminator
 - Digitizer
- Clock System
- Readout Controller

In the following the six different types of modules that constitute the baseline design of the CBM - TOF wall are described in detail.

Then the MRPC counters of which we employ 4 different types and that are housed in the modules are described as well as their associated front-end electronics.

In addition we present the design of the clock system and the current status of the components of the readout chain specific to the TOF wall system.

The prototype tests that the designs are based on, can be found in chapter 7 and are referenced individually below. Wherever applicable open design choices and milestones toward the final decision are mentioned.

3.1 Modules

The CBM ToF wall is composed of 6 different types of modules called M1 to M6. The arrangement of these module types within the ToF wall is depicted in Fig. 3.1. The drawing shows only the rough position and size of the modules. The exact sizes, the number of modules of each type, and other relevant quantities are listed in Tab. 3.1. The total number of modules is 226.

								1
	M6	M5	M5	M4	M5	M5	M6	
M6		M5	M5	M4	M5	M5		M6
M6	M6	M5	M5	M4	M5	M5	M6	M6
	IVIO	M5	M5	M4	M5	M5	.210	
	M6	M5	M5	M4	M5	M5	M6	M6
M6		M5	M5	M4	M5	M5	WIO	
		M5	M5	M4	M5	M5	MG	
M6	IVIO	M5	M5	M4	M5	M5	IVIO	M6
	MC	M5	M5	M4	M5	M5	MC	
M6	IVIO	M5	M5	M4	M5	M5	IVIO	M6
		M5	M5	M4	M5	M5		-
M6	IVID	M5	M5	M4	M5	M5	IVI6	M6
		M5				M5		
M6	IVID	M5	1			M5	M6 M5	M6 M6
	M5	M5	M3	M1	M3	M5		
M6	M5	M5	1			M5	M5	
	M5	M5				M5	M5	M6
M6	M5	M5	M2	M2	M2	M5	M5	
	M5	M5	1			M5	M5	
M6	M5	M5				M5	M5	M6
	M5	M5	1			M5	M5	
M6	M6	M5	M3	M1	M3	M5	M6M	M6
		M5	1			M5		
M6		M5	M5	M4	M5	M5		M6
	M6	M5	M5	M4	M5	M5	M6	
M6		M5	M5	M4	M5	M5		M6
	M6	M5	M5	M4	M5	M5	M6	
M6		M5	M5	M4	M5	M5		M6
	M6	M5	M5	M4	M5	M5	M6	
M6		M5	M5	M4	M5	M5		M6
	M6	M5	M5	M4	M5	M5	M6	
M6		M5	M5	M4	M5	M5	M6	M6
	M6	M5	M5	M4	M5	M5		
M6		M5	M5	M4	M5	M5		M6
NO	M6	M5	M5	M4	M5	M5	M6	
								6

Figure 3.1: Arrangement of the different module types M1 - M6 in the CBM ToF wall.

Module	Number	Module size	Number of	Number of	Number of	Number
notation	of		MRPCs	MRPCs	cells per	of cells
	$\operatorname{modules}$	mm^{3}	per module	in total	module	in total
M1	2	$1270 \times 1417 \times 239$	32	64	2048	4096
M2	2	$2140 \times 705 \times 239$	27	54	1728	3456
M3	4	$1850 \times 1417 \times 239$	42	168	2688	10752
M4	24	$1802 \times 490 \times 110$	5	120	160	3840
M5	132	$1802 \times 490 \times 110$	5	660	160	21120
M6	62	$1802 \times 740 \times 110$	5	310	160	9920
Sum	226			1376		53184

Table 3.1: Numbers and dimensions of the modules.

Considering the naming convention in CBM the modules are named as shown in Fig. 3.2. The yellow colored modules contain MRPCs equipped with low resistive glass as electrodes. The blue colored modules contain MRPCs with float glass as electrodes since this area is exposed with incident particle fluxes below 1 kHz/m^2 . The name of the module is composed of 5 digits. The first digit represents the x-direction. L stands for Left, C for Central and R for Right. The second digit represents the column number beginning with zero counting from inside to outside. The third digit stands for the y-direction beginning with T (Top), C (Center) and B (Bottom). The last two digits represent the row number starting again with zero and counting from the center to the periphery.

For the area covered by the modules M1 to M3 an alternative solution employing MRPC counters with pad readout electrodes has been developed that eventually could save some cost due to the reduced number of readout channels (see appendix E).

The baseline TOF - wall is composed of four types of MRPCs named "MRPC1" to "MRPC4" described in subsection 3.2.1 and 3.2.2. Their position in the wall is depicted in Fig. 3.3 starting with MRPC1 (red) in the innermost region surrounded by MRPC2 (yellow) and MRPC3a (light green). This MRPCs are

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10707	L2T09	L1T16	LOT12	COT12	R0T12	R1T16	R2T09	R3T07		
L3107		L1T15	LOT11	COT11	R0T11	R1T15				
L3T06	L2T08	L1T14	LOT10	C0T10	R0T10	R1T14	R2T08	R3T06		
		L1T13	LOT09	C0T09	R0T09	R1T13				
	L2T07	L1T12	L0T08	C0T08	R0T08	R1T12	R2T07			
L3T05		L1T11	L0T07	C0T07	R0T07	R1T11		R3T05		
	12T06	L1T10	L0T06	C0T06	R0T06	R1T10	R2T06	R3T04		
L3T04		L1T09	L0T05	C0T05	R0T05	R1T09				
	12T05	L1T08	L0T04	C0T04	R0T04	R1T08	R2T05			
L3T03		L1T07	L0T03	C0T03	R0T03	R1T07	112100	R3T03		
	1 2704	L1T06	L0T02	C0T02	R0T02	R1T06	R2T04			
L3T02	22104	L1T05	L0T01	C0T01	R0T01	R1T05	112104	R3T02		
	12702	L1T04				R1T04	P 2TO2			
L3T01	L2105	L1T03	LOTOO	COTOO	POTOO	R1T03	K2103	R3T01		
	L2T02	L1T02	20100	COTOO	KUTUU	R1T02	R2T02			
L3T00	L2T01	L1T01				R1T01	R2T01	R3T00		
	L2T00	L1T00			R0C00	R1T00	R2T00			
L3C00	L2C00	L1C00	L0C00			R1C00	R2C00	R3C00		
	L2B00	L1B00				R1B00	R2B00			
L3B00	L2B01	L1B01				R1B01	R2B01	R3B00		
	L2B02	L1B02				R1B02	R2B02			
L3B01	L2B03	L1B03	LOBOO	COBOO	R0B00	ROBOO	RUBUU	R1B03	00000	R3B01
		L1B04				R1B04	R2B03			
L3B02	10004	L1B05	L0B01	C0B01	R0B01	R1B05		R3B02		
	L2B04	L1B06	L0B02	C0B02	R0B02	R1B06	R2B04			
L3B03		L1B07	L0B03	C0B03	R0B03	R1B07		R3B03		
	L2B05	L1B08	L0B04	C0B04	R0B04	R1B08	R2B05			
L3B04		L1B09	L0B05	C0B05	R0B05	R1B09		R3B04		
	L2B06	L1B10	L0B06	C0B06	R0B06	R1B10	R2B06			
L3B05		L1B11	L0B07	C0B07	R0B07	R1B11		R3B05		
	L2B07	L1B12	L0B08	C0B08	R0B08	R1B12	R2B07			
L3B06		L1B13	L0B09	C0B09	R0B09	R1B13	R2B08	R3B06		
	L2B08	11814	L0B10	CB10	R0B10	R1B14				
L3B07		11815	L0B11	CB11	R0B11	R1B15		R3B07		
13807	L2B09	11816	10812	CB12	R0B12	R1B16	R2B09	1.5507		
		CT010	LOOIL	0012	10012	11010				

Figure 3.2: Module names

equipped with low resistive glass. MRPC3b (dark green) and MRPC4 (blue) are the most peripheral and have electrodes made of float glass. The main properties are shown in Tab. 3.2.

MRPC notation	MRPC1	MRPC2	MRPC3a	MRPC3b	MRPC4
Number of MRPCs	40	246	580	200	310
Active area [mm ²]	300×100	300×200	320×270	320×270	320×530
Number of Strips per MRPC	64	64	32	32	32
Strip length [mm]	100	200	270	270	530
Granularity (cell size) [mm ²]	472.4	944.8	2700	2700	5300
Number of gas gaps	10	10	8	8	8
Gap size μm	140	140	220	220	220
$Glass size [mm^2]$	320×100	320×200	330×280	330×280	330×540
Glass thickness [mm]	0.7	0.7	1.0	0.5	0.5
Number of glass plates	12	12	9	9	9
Glass type	low res.	low res.	low res.	float	float
Total glass surface $[m^2]$	15.36	188.93	482.33	166.32	497.18

Table 3.2: Numbers and dimensions of different MRPC counters.

All MRPC types have strips as read-out cells, that means they are read out from both sides. The strip length vary from 100 mm in MRPC1 to 530 mm in MRPC4. In the same extent the granularity increases from 472.4 mm^2 to 5300 mm^2 .

Fig. 3.4 depicts the front view of the wall in a 3-dimensional drawing in order to check for dead zones. The modules are marked by dark lines, the red crossed boxes denote the non-overlapping active areas of the single MRPC detectors. The yellow frames (hardly seen) represent the overlap of the MRPCs.

Fig. 3.5, 3.6 and 3.7 show the top, side and the oblique rear view of the ToF wall. The modules M1 to M6 are indicated by the different colors. Expecially the top and the oblique rear view show the staggering of the modules forming a parabolic shape of the wall.



Figure 3.3: MRPC arrangement in the ToF wall. M1 to M3 are composed of MRPC1 and MRPC2. M4 and M5 are composed of MRPC3a and MRPC3b. M6 contains counters of the type MRPC4.

In the following each module type is described individually.



Figure 3.4: Front view of the ToF-wall. Modules are marked by dark lines, the red crossed boxes denote the non-overlapping active areas of the single MRPC detectors inside. The yellow frames represent the overlap of the MRPCs.



Figure 3.5: Top view of the ToF wall. The different types of modules are indicated by different colors.



Figure 3.6: Side view of the ToF wall. The different types of modules are indicated by different colors.

Figure 3.7: Oblique rear view of the ToF wall. In this view the staggering of the modules become visible.
3.1. MODULES

3.1.1 M1

The module M1 contains 32 MRPCs arranged in 4 columns and 8 rows. The first two rows, facing to the beam, are composed of 8 counters called "MRPC1" with an active area of $300 \times 100 \text{ mm}^2$. The other rows are composed of 24 counters called "MRPC2" with an active area of $300 \times 200 \text{ mm}^2$. Both counters have 64 readout strips with a pitch of 4.72 mm and a length of 100 mm and 200 mm, respectively. Details of MRPC1 and MRPC2 are presented in 3.2.1. The MRPCs are staggered in 4 layers in order to avoid dead zones. The horizontal overlap is 9 mm between MRPC1 and between MRPC1 and MRPC2 and 18 mm between MRPC2. The vertical overlap is 10 mm for all MRPCs. The total active area of M1 is 1170 \times 1292 mm². This yields to an overlap of 9.83 % of the total module area. The arrangement of the counters is depicted in Fig. 3.8.



Figure 3.8: 2D view of the M1 module. The counters of type MRPC1 and MRPC2 are staggered in 4 layers with some overlap in order to guaranty a contonuous coverage.



Figure 3.9: 3d view of MRPC configuration within M1 module.

The counters are mounted in a gas tight box (see Fig. 3.9) with the dimension $1270 \times 1417 \times 239$ mm³. The lateral and front walls of the gas tight module boxes are made of 10 mm thick honeycomb sheets, sandwiched between two stesalit plates of 0.4 mm. The inner sides of the walls are covered by a copper plated 0.13 mm thick PCB. The 12 mm thick aluminum back plate supports the whole inner structure of the module. Short twisted pair cables transport the signals from the readout electrode PCBs to the connectors soldered on the feed-through PCBs which are glued into the back plate, each serving 8 channels. The preamplifier cards (see section 3.3.4) are plugged directly into the connectors on the outer side of the flange. The total number of readout channels is 4096 yielding in a total power consumption of the preamplifier of about 70 W. The arrangement of the preamplifiers is similar to M3 and is visualized for M3 in Fig. 3.13. The discriminated LVDS-signals are sent via 3 to 4 m long twisted pair cables to the TDCs.

3.1.2 M2

The module M2 contains 27 counters arranged in 7 columns. The two columns facing to the beam contain 12 MRPC1 counters. The other 5 columns contain 3 rows of MRPC2 (15 counters). The total active area of M2 is $2040 \times 580 \text{ mm}^2$ comprising 1728 read-out cells and thus 3456 electronic channels consuming about 60 W of LV-power. The overlap in horizontal direction is 4 mm for MRPC1 and 10 mm for MRPC2. The overlap in vertical direction is 10 mm for both counter types. The total overlap is 6.01 % of the module area. The arrangement of the counters is done in four layers similar to M1 (see Fig. 3.10).



Figure 3.10: 2D view of the M2 module. The counters of type MRPC1 and MRPC2 are staggered in 4 layers similar to M1.

Figure 3.11: 3d view of the M2 module tight gas box.

The dimension of the gas box (see Fig. 3.10) is $2140 \times 705 \times 239 \text{ mm}^3$. The technical design is equivalent to the M1 box.

3.1.3 M3

The module M3 contains 42 counters from type MRPC2 arranged in 6 columns and 7 rows (cf. Fig. 3.12). The overlap between the MRPCs is 18 mm in horizontal and 10 mm in vertical direction resulting in an total overlap of 10.06 %. The total active area of the module is $1750 \times 1292 \text{ mm}^2$ comprising 2688 read-out cells and thus 5376 electronic channels. The total consumption is about 100 W. The dimension of the gas box is $1850 \times 1417 \times 239 \text{ mm}^3$. The technical design is equivalent to the M1 box.

3.1.4 M4

The module M4 establish the central colum of the ToF wall. It comprises 5 counter of the type MRPC3a or MRPC3b (see subsection 3.2.2) depending on the module position. The total active area of M4 is $1520 \times 270 \text{ mm}^2$. The overlap between the counters is 20 mm corresponding to two MRPC read-out strips. This is sufficient to avoid edge effects. The counters are arranged in 1 row with 2 layers; 3 counters in front and 2 counters in the back. In total M4 comprises 320 read-out channels consuming 5.5 W which is dissipated inside the module. A 2d view with showing some detailed dimensions of M4 is depicted in Fig. 3.14. The box size is $1802 \times 490 \times 110 \text{ mm}^3$. A 3d view of the opened module is shown in Fig. 3.15. The preamplifiers (labeled b) are connected directly to the MRPC3a/b (labeled a). The discriminated signals are transmitted via twisted pair cables to the feed-throughs PCBs (labeled d). Outside the module the feed-throughs PCBs contain connectors were the 10 TDC-PCBs (labeled f in Fig. 3.17) with 32 channel each are plugged. The TDC-PCBs are fixed in a crate (labeled e in Fig. 3.17) which is mounted on the gas box. A FPGA based data combiner board is sitting near the TDC crate and collecting the data from each TDC and sends it via optical fiber to the next processing unit. The threshold setting of the preamplifiers is done via slow control commands to the TDCs where an SPI Master is implemented. The feed-throughs for HV, gas and grounding are positioned on top and below the feed-throughs PCBs and are denoted by c. Per module one HV supply for positive and one for negative polarity is foreseen. Inside the module the HV is split via an HV-filter and distributed to the counters. The infrastructure of a module contains 2 gas pipes, 2 HV cables, 2 cables for LV, 2 different



Figure 3.12: 2D view of the M3 module.



Figure 3.13: Backside view of the M3 module flange (similar to M1 and M2) with the connectors for the front-end electronics and the feed-trough for HV and gas.



Figure 3.14: 2d view of M4



Figure 3.15: 3d view of the opened M4 module looking from the front. Single MRPCs are denoted by (a), the preamplifier cards which are connected directly to the read-out electrodes by (b), feedthroughs for HV, gas and low voltage by (c) and feed-through PCB with connectors by (d).

clock cables and one optical fiber for the data. The construction principle of the gas box is the same as for M5 and M6 and is described in more details in subsection 3.1.6.

3.1.5 M5

The module M5 is basically constructed as M4 with the only difference that the staggering of the counters inside the module is changed (cf. Fig. 3.16). The counters are rotated by 8.7° in respect to the module box leading to a roof tiles structured staggering. This rotation was chosen in order to compensate the

angle of the incident particles since the M5 modules are not placed in the central column. However, the rotation angle is fixed for all M5 modules and is predetermined by the counter and module box thickness. The overlap between the counters in the rotated frame is 20 mm (2 strips) while looking perpendicular to the module the overlap is 12.81 mm. The total active area of the module is 1530.3 \times 270 mm². Considering the active area of the individual counters (MRPC3a or MRPC3b) the overlap inside the module is 4.36 %. Fig. 3.17 shows a 3d drawing of a from the back side opened M5 module. The bars holding the counters are not shown. The labels in the figure are the same as for Fig. 3.15. Additionally a crate which holds the TDC cards is shown. The create is screwed to the box and can be removed completely with the TDCs. The module comprises 320 read-out channels dissipating 5.5 W of power inside the module (preamplifier) and about 20 W outside (TDCs + FPGA-board + clock distribution).



Figure 3.16: 2d drawing of module M5. The counters are rotated by 8.7° and staggered in a roof-tile fashion.



Figure 3.17: 3d view of the opened M5 module looking from the back. Single MRPCs are denoted by (a), the preamplifier cards which are connected directly to the read-out electrodes by (b) and feedthroughs for HV, gas and grounding by (c). The TDC cards labeled (f) are sitting in a crate labeled (e) and are plugged directly on the feed-through PCB labeled (d) in Fig. 3.15.

3.1.6 M6

The module M6 is located in the most peripheral region of the ToF wall and contains 5 counters of the type MRPC4 with the largest granularity of 530 cm². The total active area is 1527.8 \times 530 mm² with an total overlap of 4.51 %. The counters are rotated by 7.6° and overlap by 2 cm (2 strips) in the rotated frame. Looking perpendicular on the module the overlap between counters is 14.54 mm. The preamplifiers (labeled b in Fig. 3.19) are similar to M4 and M5 connected directly to the counter (labeled a) dissipating 5.5 W which is distributed over 320 read-out channels inside the module. The TDCs are sitting in a crate (labeled e) outside the module box similar to M4. The crate design is exactly the same as for M4 and M5 which minimizes construction costs.

The module box size is $1802 \times 740 \times 110 \text{ mm}^3$ and is constructed identical to the box of M4 and M5. The box of M6 as well as of M4 and M5 are made of aluminum and built in the same way. An explosive drawing of the M6 module box is shown in Fig. 3.20. The backbone of the box are two rectangular, 8 mm thick frames which are mounted together in the corners by rods. On their inner sides they have milled groves into which the narrow side walls are glued. Three of these are just 1 mm thick to minimize straggling of the penetrating particles; one is 10 mm thick: this side carries all connectors and feed-throughs, it is hidden behind the active zone of the module in front. The front and back sides of the boxes are closed by 0.5 mm aluminum foils which are glued on 3 mm thick frames; together they are screwed against the rectangular frames, tightened by O-rings. In case the material budget should be



Figure 3.18: 2d drawing of module M6. The counters are rotated by 7.6° and staggered in a roof-tile fashion.



Figure 3.19: 3d view of the opened M6 module looking from the front. Single MRPCs are denoted by (a), the preamplifier cards which are connected directly to the read-out electrodes by (b) and feedthroughs for HV, gas and grounding by (c). The TDC cards are sitting in a crate labeled (e) and are plugged directly on the feed-through PCB labeled (d) in Fig. 3.15.



Figure 3.20: Explosive view of the M6 module box. The box of M4 and M5 have the same design.

reduced even more, the front foil can be replaced by a 75 μ m polyimid foil. The back side cover could be exchanged against a water-heated version if necessary. The feed-throughs of the detector signal and all controls sit on a multilayer PCB which is pressed by frames against O-rings. The module boxes are fixed to the aluminum profiles of the main frame by means of 4 "ears" on their front or back frame. The total weight of an empty chamber is about 15 kg.

3.2 MRPC counters

More than 40 years ago, counters working in the spark regime [21, 22], operated at 12 bar with a highly quenching gas mixture and a gap size of 0.1 mm between a conductive electrode and a semiconductive glass plate of $5 \times 10^9 \ \Omega$ cm, showed time resolution well below 100 ps. The streamer is followed by a spark which is quenched very quickly. The output signals are high, they can be processed directly by a double-threshold discriminators [23] which guarantee a walk-free timing. These spark counters have been investigated for many years. About 40 counters, each of 30 x 4 cm² size, have been used successfully in the NA49 experiment at CERN [24]. Ninety centimeters long prototypes (area 380 cm²), developed at GSI, have reached time resolutions of about 60 ps [25]. These counters are read out on both sides via 16 individual anode strips; the TOF is derived from the mean of the two times recorded at the two ends. The time difference yields a spatial resolution of few mm along the strip while across strips a $350 \ \mu m$ resolution is reached by weighting the charges recorded on neighboring strips fired in an event. The measured time spectra are not completely Gaussian, they develop an exponential tail to the side of longer times. Detailed studies of this effect have shown that it is at minimum if the counter is operated with a Ne-based gas mixture [25]. There are also technological difficulties in building Pestov detectors, e.g. the preparation of the electrodes, the technique of the 0.1 mm high spacers, the gas vessel holding 12 bar and the extreme requirements in cleanness during mounting and operation.

A RPC [26] is a parallel plate chamber with resistive electrodes. With a proper gas mixture the streamer development is strongly suppressed and sparks no longer ignite at the operation voltages typically used. Therefore, these chambers operates in avalanche mode and need fast amplifiers for signal processing. For fast timing applications normally a gap size of 0.3 mm is chosen. In order to obtain a reasonably high primary signal at a pressure of about 1 bar one uses a stack of resistive plates separated by gaps. Since the intermediate resistive electrodes are transparent for the fast signals, the resultant signal is formed by the sum of the avalanches in the individual gaps. The principles of a multigap structure (MRPC) based on melamine resistive electrodes and its timing performance which is potentially better than that of a one-gap chamber of same total active thickness are discussed in [27]. On one side of the stack the HV is connected to a metallic electrode, the signal is taken from a conductive plate on the other side. A symmetric design with the anode in the middle of the stack, requiring one HV electrode on the top and another at the bottom, based on resistive glass electrodes was proposed in [28]. The work has concentrated on single-cell chambers of not more than 20 cm^2 real size based on a symmetric design with the anode in the middle of the stack. For example with a 3×3 cm² detector a time resolution of 44 ps and an efficiency of 99% has been measured [26, 28]. In such small single cells, the position dependence of the timing may be kept within certain limits; edge effects, on the other hand, could influence the time resolution as well as the efficiency. To bypass the construction of a huge number of individual cells, the ALICE collaboration has begun studies of prototypes where individually read out anode pads are placed on large-area glass stacks [6]. Time resolution of 62.5 ps and 95% efficiency have been obtained with such a geometry. However, a position dependence of the time resolution and efficiency is similar to those observed for single cells.

During the R&D activities for upgrading the ToF barrel of FOPI experiment at GSI, the idea to combine the advantages of MRPC principle and of the Pestov counters was introduced. The first prototypes of MSMGRPC (Multi Strip Multi Gap RPC) were produced with active areas of 120 cm² and 400 cm² and read out via multistrip anodes very similar to the Pestov detectors, i.e. having 16 (or 12) strips over the 40 mm width, each strip being read out at both ends. This completely novel detector concept was realized for the first time and is documented in [29].

The MSMGRPC-RPCs offer a very good homegenity of their response and allow for a 2-dimensional position reconstruction of the hits. Delivering two coincident signals from both sides of the readout strip they also allow for noise rejection in the frontend electronics by requiring coincident signals within the propagation time of the signal. Due to the high demands on signal integrity for the CBM free streaming readout concept this type of MRPC represents the baseline choice for the CBM - TOF wall.

3.2.1 MRPC1 and MRPC2

The two types of MRPC have the same architecture, presented in Fig. 3.21. In order to achieve the required high granularity two types of MRPCs have been designed: MRPC1 type with cell length of 100 mm and MRPC2 type of 200 mm, as it is shown in Fig. 3.22. Both types of MRPCs have the same

3.2. MRPC COUNTERS

length which is limited by the size of the low resistivity glass, available only to a maximum length of 320 mm and thicknesses of 1 mm and below. The counters have fully differential, symmetric, double stack arhitecture with strip readout electrodes, signals being readout at both strip sides. They feature 64 electrode strips with a pitch of 4.72 mm (2.18 mm width/2.54 mm gap) which define an active lenght of 302 mm for both counters.



Figure 3.21: 3D image of MRPC2 counter; the inner structure of MRPC1 counter is identical

APLAC simulations predict an impedance close to 100 Ω for such a transmission line and hence a good matching with the input impedance of the front-end electronics. The central readout electrode has the copper strips sandwiched between two 0.5 mm thick FR4 PCB layers. The cathodes have copper strips on the inner side of a 0.5 mm FR4 plate.



Figure 3.22: Left side, strip RPC prototype (pitch 4.72 mm); right side, cross sections showing the sizes of geometrical and active area, respectively, of the two types of counters: MRPC1 (100 mm wide) and MRPC2 (200 mm wide). For details see text.

MRPC1 counters cover polar angles from 46 mrad up to 154 mrad in horizontal direction and up to 78 mrad in vertical direction and MRPC2, angles from 154 mrad to 361 mrad in horizontal direction and from 78 mrad to 255 mrad in vertical direction.

The back flange of each module carries the front-end electronics (FEE) cards. Figure 3.23 shows a MRPC2 prototype fully equipped on the back flange of the gas box with PADI8 (see section 3.3.4) together with



Figure 3.23: A prototype counter of type MRPC2 which the back flange fully equipped with PADI8 and the associated baseboards.

the associated baseboards. The PADI8 cards, connected to the baseboards, are plugged in the connectors on the back flange.

3.2.2 MRPC3a, MRPC3b and MRPC4



Figure 3.24: Sectional drawing of MRPC3b and MRPC4 equipped with a stack of 9 float-glass plates.

The counter types MRPC3a, MRPC3b and MRPC4 have the same construction principle and are therefore described in a common subsection. The counters are designed in a fully differential single stack configuration with strip read-out i.e. the signals are read out on both sides. The strip pitch is 1 cm with a strip width of 0.7 mm. The read-out electrode is a 1.6 mm thick PCB with the above described copper



Figure 3.25: Cross section of the MRPC3a, MRPC3b and MRPC4. The figure is drawn to scale.

strips. At the end of the strips transmission lines of about 2 mm width transmit the signals to L shaped pin-connectors (cf. Fig. 3.24).



Figure 3.26: 2d drawing of MRPC3a/b (left) and MRPC4 (right).



Figure 3.27: 3d view of the MRPC4 counter with the preamplifiers attached on the read-out electrode.

On the backside of the PCB a grounded copper layer covers the area where the transmission lines are routed in order to guarantee a transmission-line impedance of 50 Ω . The connectors has 9 pin where the odd pins have ground connection and the even pins the signal connection. Every signal pin is connected with a 200 k Ω SMD resistance to a ground pin. On top of the read-out strips a 75 μ m thick Kapton[®] serves as electrical insolation between HV electrode and read-out electrode. A second 75 μ m thick Kapton[®]-foil is coated with an industrial spray called Licron[®] serving as HV electrode. The surface resistivity of this layer is about 200 M Ω/\Box and is facing to the glass. The same mirrored structure is covering the glass stack from the other side forming the single stack configuration. The glass plates forming the stack are separated by 220 μ m thick fishing lines. The number of gapes depends on the glass thickness which depends on the kind of the glass (low resistive or float). Values are summarized in Tab. 3.2. These values are based similar to MRPC1 and MRPC2 on APLAC simulations which predict an impedance close to 100 Ω in order to match the impedance of the transmission line (differential) and the input impedance

of the preamplifier. An impedance of 100 Ω was confirmed by measurements with the reflectometer. The MRPC3 comes in two versions: MRPC3a contains low resistive glass as electrode material while MRPC3b contains float glass plates of 0.5 mm thickness. MRPC4 is essentially a copy of MRPC3b but with longer read-out strips. Fig. 3.26 shows the different dimensions of MRPC3a/b and MRPC4 in a 2d drawing. The cross section of these three types is shown in Fig. 3.25. A 3d drawing of an MRPC4 counter is depicted in Fig. 3.27.

3.3 Readout Chain

The readout chain has to provide sufficient bandwidth to allow for a free-streaming data taking even at the highest assumed rates. The requirement for the full TOF system is a time resolution in the order of or better than 80 ps. The design goal of a time resolution in the order of 50 ps for the start time system leads to a requirement in the order of 60 ps for each channel of any counter and its electronics. Assuming that MRPC detectors can reach time resolutions as good as 50 ps, this leaves at most 38 ps for the electronics (including the clock system). This maximal electronics contribution to the time resolution can be roughly shared between the preamplifier and the Time-to-Digital Converter (TDC, including the clock system contribution) with 20 ps and 32 ps, respectively. Of course, any additional margin obtained on the readout chain side relax the constraints on the detectors.

The specifications for the development of the readout chain are therefore the following:

- it should be free-streaming,
- it should provide Time over Threshold measurement,
- it should contribute to the time resolution of the full CBM TOF system for at most 38 ps per single channel, with 20 ps or less due to the preamplifier and 32 ps or less due to the digitizer (including clock distribution).

The current design is based on the experience gained with the PADI - GET4 - ROC prototype chain which is described in section 3.3.2 (Fig. 3.31). All these specifications are worst case values and there is a realistic chance that better performances will be achieved (see sections 3.3.4 and 3.3.5).

The first part of this section explains what a free-streaming readout chain is and what is the current concept of such a readout chain for the TOF wall case (functional level). It is followed by a description and performance evaluation of the baseline choices for the components of the readout chain specific to the TOF system. Finally, some estimations on the numbers of each component required to build the complete TOF readout chain are extracted from simulation of heavy ion collisions.

3.3.1 Free-Streaming Readout

In a triggered readout the front-end electronics or any first readout component stores the data in a buffer and waits for a trigger signal. In some cases it even waits for the trigger to start the digitization of stored analogue quantities. The trigger signal has to be generated using a sub-set of the data or dedicated signals and is then propagated back to the front-end. There it selects the data in the buffer according to their arrival time i.e. a predefined time window around that time is required. Thus, only relevant data are transferred to the computer farm, where higher-level (more complex) triggers can be used and where the remaining data can be prepared for storage.

In a free-streaming readout, no global trigger signal is propagated backward to the front-end. All signals passing the front-end thresholds are digitized, time stamped and stored in an input buffer. The digitizer sends data from the input buffer to the readout-controller as soon as they become available. The readout controller that implements the data combiner functionality (DCB) has to have sufficient bandwidth and buffer depth to accommodate the data flow from the front-end boards. Itself the aggregation node sends its data to the data processing level (implemented in the case of CBM on the Data Processing Boards (DPB)) where first-level data manipulations like noise reduction, rough calibration, time ordering and per-formatting can take place. On this level the data from many channels can be aggregated further in order to fill the bandwidth to the online computer farm that is called First Level Event Selector (FLES) in the CBM context. There the data from all sub-detectors in a given time period are grouped together and partially reconstructed (tracks, vertices, etc.). The necessary degree of reconstruction depends on the

3.3. READOUT CHAIN

targeted physics signals. If an interesting signal is detected after reconstruction, either the reconstructed data or the raw data are prepared for storage and saved for off-line analysis.

One advantage of such a scheme is that also complex physics signals can be used for event selection, since all raw data are present at the computing farm and can be fully reconstructed. High interaction rates of the order of MHz can be achieved, because no "readout dead-time" exists. As long as the data transport between layers and the buffers at each level are properly dimensioned, the only remaining dead-time is the intrinsic one of the front-end electronics. Combining these advantages with high precision detectors allows high-statistics measurement of rare probes, as described in section 6.

The main constraint in such a system is that all boards performing the time tagging of the digitized data have to be synchronized at a nanosecond level on the full experiment scale. Another constraint is the limitation in the amount of transmitted data by the bandwidth of the links between the different readout levels. This means that a single oscillating front-end channel could saturate each readout level and corrupt all events if it goes undetected. Finally, these huge amount of data have to be digested almost in real-time. This means that the processing farm has to be properly dimensioned in terms of input bandwidth, internal network and processing power. The dimensioning of the FLES farm and the software modules are subject of the separate Online TDR of CBM.

3.3.2 Chain Concept

Fig. 3.28 summarizes the general concept of a free-streaming readout chain. A free-streaming readout chain is usually composed of up to seven main functional blocks, six of which forming the data readout path. The type of data transport link used between each of these functional blocks (copper, optical fibers, internal bus, ...) is highly dependent on the hardware on which the functions are implemented. The first block when starting from the detector output is the Front-End Electronics (FEE), which converts the detector signals to digital messages including a time stamp. The second one is an optional aggregation of the output links from a few FEE elements to a common transport link. This is followed by a readout controller, which provides the interface between the FEE and the experiment control system (configuration, data taking control, ...) on one side and the data taking system on the other side. After this element, another optional aggregation can be done between a few data transport links. The next element in the readout chain is a preprocessing step, which can e.g. perform a cleaning of the data or a change in their format. Finally, the data reach the online event building, analysis and selection system before being archived.

Aside from the data readout path, a free-streaming readout chain must also include a clock system in order to insure that all time-stamping elements (FEE or readout controllers) are staying synchronized and using the same time frame. This is a prerequisite for building events without a trigger signal.



Figure 3.28: General concept of a free-streaming readout chain. The "Aggr." functional blocks represent optional aggregation steps. The background colors of the blocks correspond to their functions and are re-used in Figures 3.29, 3.31 and 3.30.

Fig. 3.29 shows the application of this general description to the case of the CBM TOF wall. For the CBM TOF wall, the FEE is composed of two stages, first a preamplifier discriminator and then a Time-to-Digital Converter (TDC), as presented in section 3.3.3. The TDC will be readout and configured using a controller implemented as a module in an FPGA, called ROC for ReadOut Controller. Local preprocessing methods can also be used early on the ROC to reduce the amount of data to be transferred, like charge (for Time over Threshold) cuts, timing window on signals from both ends for the strip counters, etc. They will need some initial calibration values (offsets, gains, cuts, ...) which have to be loaded, but the possibility to transfer the full raw data will be kept. After calibration, these components could also automatically detect noisy/ringing channels and disable them before they saturate the full transport chain.



Figure 3.29: Concept of a free-streaming readout chain for TOF. The time orders ("ps", "ns") indicate the required time-synchronization quality.

For the time stamp used for event building and selection, CBM needs only a clock synchronization in the order of ns. On the other hand, in order to provide the time resolution needed for proper PID, the TOF system need a synchronization of the clocks provided to any of its elements in the order better than 10 ps. Therefore, the CBM TOF wall will include a clock system (generation and distribution) using the less precise CBM clock to generate a TOF specific clock. As the CBM and TOF time frames are then locked to each other, the time measured by the TOF system can be used directly at the event building stage without needing an additional time stamp.

More sophisticated data preprocessing and data formatting will be performed just before sending the data over a \sim km long optical fiber to the First Level Event Selector (FLES). These will be performed in an element called DPB for Data Processing Board, which will be a module loaded on an FPGA. The distribution of the preprocessing tasks between ROC and DPB will depend on the available resources and available information at each of these readout levels. Some details on the foreseen preprocessing steps can be found in Appendix G.4.



Figure 3.30: Current concept of the free-streaming readout chain for the CBM TOF wall. The frequencies indicate the required clock properties.

Fig. 3.30 presents the current system concept for the full CBM TOF readout chain. The discriminator will be the PADI chip, the TDC is realized by the GET4 chip and the clock system will be built upon the CLOSY system described below. However, the clock generation will be modified to operate in slave mode, deriving the two frequencies needed for the TOF system from the more general CBM clock. The ROC will be implemented on a dedicated FPGA board to optimize the input and output connectors to the TOF wall needs. It will be followed by CERN GBTX chips [30, 31], which will act both as data combiners and as converters to optical data transmission. The number of ROCs connected to each GBTX will be adapted depending on the input data rate to optimize the bandwidth usage of the output 4.8 Gb/s optical link, thus providing optimal support for the different data rates in the different parts of the TOF wall. From the DPB, optical fibers are used to transport the data from the CBM cave to the GSI/FAIR computing center, the Green Cube, where the First Level Event Selector is located. The input to the FLES will be based on FPGA board called FLES Input Boards (FLIB), each receiving data from 4 to 8 optical fibers.

Fig. 3.31 shows the prototype chain used to obtain the results presented in this document. In this prototype, the discriminator is the PADI ASIC presented in section 3.3.4 and the TDC is the GET4 ASIC presented in section 3.3.5. Up to 8 GET4 chips are readout and configured through an LVDS serial



Figure 3.31: Prototype of the free-streaming readout chain for TOF. The frequencies indicate the currently used clock properties.

interface by a ROC based on the SYSCORE v2 FPGA board (see G.1 for details on this component). The clock generation and synchronization is done using the CLOSY2 board, which provides a 156.25 MHz clock for the GET4 chip and a phase locked 250 MHz clock for the ROC. The CLOSY2 was operated in this prototype as a clock master. From the ROC, the data are transferred by optical fiber to a PCI-E FPGA development board, the Active Buffer Board (ABB), hosted in a computer. On the computer, the data acquisition system was the DABC DAQ framework from GSI [32], while the data analysis was done using either the GO4 framework [33] or the CBMROOT framework [34], both based on the CERN ROOT framework [35]. Preliminary data preprocessing tasks were already implemented on the FPGA of the SYSCORE v2 board. This is represented in the figure by the mixed background color of the ROC block.

The hardware used to implement the general CBM and specific CBM TOF readout network as well as the data formats and algorithm present in the final CBM acquisition system will be described in more details in another document, the "CBM Online Systems" TDR. The release of this document is currently planned for 2015. For this reason, following subsections describe only the components specific to the TOF wall readout chain.

3.3.3 Frontend electronics

The front-end electronics (FEE) is based on the PADI ASIC as preamplifier and discriminator which will be placed as close as possible to the read-out electrodes. The design is kept fully differential in order to minimize the sensitivity to common-mode noise. For the digitisation of the signal the event-driven TDC ASIC GET4 is chosen; they have been especially developed for CBM ToF, cf. chapters 3.3.4 and 3.3.5 and are shown on the photos of Fig. 3.32

These front-end ASICs are readout via an FPGA-based readout controller, ROC, which transfers the data to the acquisition system; further information about this readout controller can be found in this paper [36]. A very precise clock generator provides the two main frequencies of the system: The ROC itself requires 250 MHz, the TDC a phase-coupled frequency of 156.25 MHz. A third signal is send out by CLOSY2 upon every 5th coincidence between the clocks in order to make sure that all components are synchronized. The clock distribution CLOCKDISTRIBUTION2 spreads these three signals by means of a 1:10 splitter. The specifications of CLOSY2 and CLOCKDISTRIBUTION2 are listed in chapter 3.3.8. A second prototype version was tested in parallel using an FPGA TDC instead of GET4, which is the baseline solution. Principle information on these TDCs can be found in the papers [37] and [38]. Results from laboratory tests are presented in Appendix G.2. These TDCs exhibited good time resolution and would provide more freedom for maintenance and upgrading thanks to the programmable nature of FPGAs. Their development will therefore be pushed further to ensure they can be integrated in the readout chain (free-streaming mode readout). Should they exhibit better performance than the GET4 for a similar price before December 2015, they would then be selected as baseline option. One important step is to prove that an FPGA TDC can coup with the radiation environment of CBM-ToF. In addition the channel dead time after collecting a hit signal should go down too. Both issues are addressed and we will see in the near future how this will work out.

3.3.4 PreAmplifier DIscriminator (PADI) FEE

The time of flight measurement poses completely different demands on the readout system than on other sub-detectors. The signal amplitude is only of interest for the time correction (in the leading edge discrimination case), so demands on the amplitude resolution are relatively modest. The demand on the



(a) PADI6 ASIC



(b) GET4 V1.0

Figure 3.32: ASIC developments: PADI-6 chip (left), GET4 TDC (right).

time resolution however is extremely high. For conditions expected in the TOF wall with the full-system time resolution of 80 ps with more than 100k readout channels and an event rate of several 100 kHz, we have developed the customized ASIC called PADI, that is described below.

The typical RPC signal

The RPC is a gaseous detector which can deliver very fast signal pulses when an ionization particle passes through. Typical characteristics of detector signals for 50 Ω impedance of the detecting strip (FOPI case) are presented in Table 3.3. The amplitude pulse height spectrum is continuous with a peak value in the range of 2-4 mV (or 30-60 fC) [39].

Parameter	Value
Rise Time	0.3 ns
FWHM	1-2 ns
Fall Time	0.3 ns
Amplitude	0.5 - 30 mV

Table 3.3: Typical characteristics of RPC signals for very dense strips, 50 Ω (FOPI case).

The strip-electrode structure offers half the sensitivity in comparison with the pad-electrode structure. Moreover, if the strips are too dense, the charge sharing between adjacent strips will supplementary reduce the signal amplitude. The preamplifier has to cope with short rise times at low amplitudes by keeping the amount of electromagnetic pickup small. For the ToF system upgrade of FOPI [39], we have designed a 16 channel preamplifier-discriminator card, FEE5 [40]. It consists of discrete elements and features a maximum gain of 220 at a bandwidth of 1.5 GHz. The noise referred to input is below 25 μV_{RMS} with an intrinsic time resolution of $\sigma_{tE} = 15$ ps at 5 mV input signal. The crosstalk between neighbouring channels is less then -43 dB and the power consumption 0.51 W/channel.

While the use of conventional integrated circuits to process primary RPC signals has its advantages, for a high-density systems only acceptable solution is to reduce the price and power consumption per channel, by implementation of a customized ASIC design. The NINO architecture [41, 42] used in ALICE, with its full differential structure, containing a 8 channels amplifier-discriminator, offers a very attractive design and was the starting point for our design. In order to study advantages of the ASIC approach an 8 channel PCB containing the NINO ASIC and compatible with our TACQUILA2 [43] digitizer was designed. From comparative test of this PCB and standard FEE5 we have draw conclusion that for an

successful ASIC design compromises have to be made: lower gain and bandwidth in comparison to the solution using the best discrete integrated circuits available.

In Fig. 3.33 a comparison between two possible solutions is shown: very dense strips (2.5 mm pitch), 50 Ω impedance, readout at both ends by single-ended FEE5 (FOPI) and true differential detection PADs, read differentially with 100 Ω impedance NINO-FEE (ALICE). In these two cases, the dynamics of detector signals are well matched to the used FEE and the time resolution reach the same good figure. The use of ASIC imposes the increase of the detector signal amplitudes; therefore relative to specific FOPI case the decrease of the strip pitch (to reduce the charge sharing between adjacent strips), the increase of the strip characteristic impedance to 100 Ω (more voltage to the same charge), and the true differential PAD/strip detection structure (which has two times bigger charge responsivity) is mandatory.



Figure 3.33: Comparison between two existing solutions: very dense strips, 50 Ω impedance, single-ended readout at both ends (FOPI) and PADs, read differential with 100 Ω impedance (ALICE). The plotted data are obtained with the same digitizing system TACQUILA2 and with two PCBs: FEE5 and FEE-NINO comprising two NINO ASICs.

The fast PADI ASIC

The new design was driven by the specific needs of the TOF wall. An R&D project was started within the EC FP6 Hadron Physics consortium, aiming, among other, at the development of a new four channel ASIC, in 0.18 μ m CMOS technology, called PADI, with following key parameters: fully differential design, 50 Ω input impedance, preamplifier gain 100, preamplifier bandwidth \geq 300 MHz, peaking time 1 ns, noise related to input \leq 25 μ V_{RMS}, comparator gain \geq 100, DC feedback loop for offset/threshold stabilization, and threshold range related to input between 0.5 and 10 mV. Our main criterion for optimization was to obtain the best time resolution for low signals, e.g. to have the possibility to accommodate for different MRPC electrode structures and to utilize full detector signals without reflections to the FEE.

The project has over years yielded a series of prototypes: PADI-1 (described in [44], PADI-2,-3 (described in [45], PADI-6,-7 and finally PADI-8 (the throughout evolution is described in [46]). Here we will present two variants, PADI-6 and PADI8, which have been successfully used in our latest experiments. PADI-8 is the final preamplifier for CBM-ToF.

PADI-6 ASIC

The block diagram of PADI-6, houses 4 identical channels and a common current biasing circuit (IB). Each channel consists of a preamplifier (PA), a discriminator (DI), and a Buffer stage (source followers) for monitor tasks. The common bias block supplies four currents IB and uses an external resistor as reference. The PA stage biasing, controlled by this current, guarantees an input impedance close to 50 Ω . To match the output signal to the user's needs, we implemented a second external programmable resistor which steers the biasing of the last discriminator stage (VB). In the default configuration the differential output signal is close to the LVDS standard. All others biasing voltages are generated at channel level.



Figure 3.34: The Block schematics of the PADI-6 (see text).

The threshold voltage is obtained from a DC bridge realized by six resistors R. This bridge is supplied from VDD and can be controlled internally by two 10-bit DACs or externally, by a potentiometer connected between VREF+ and VREF- pads and having the cursor at ground potential. These pads are common for all channels and one potentiometer can control the thresholds of all channels. The two DACs are complementary commanded and the common mode voltage is not affected by the DAC code value. We used SPI (Serial Protocol Interface) which is simple and robust. Fig. 3.35 shows the simplified AC scheme of the PADI-6 preamplifier stage. Its structure is close to the one of NINO [41, 42]. The input currents IAC1 (IAC2) lead to the cascode amplifiers CA1 – CA3 (CA2 – CA4). Their currents provide over the R1-Cp1 groups the voltage at the next stage, the transconductance amplifiers TA1 and TA2. TA3 is the first amplifier of the DC feedback loop, TA4 the second one. We use the feedback to stabilize the DC working points of all MOS transistors. The dominant pole of the loop is realized by the Rf-Cf group. The amplifier TA3 uses the VTHR threshold voltage to shift the output voltage of the preamplifier. Due to this design the discriminator can be set in DC to be in the one state and only the amplitudes larger than the threshold value will fire the complementary state.

The feedback path is unique for signals and threshold voltage. The whole schematic can be evaluated like a full differential operational transconductance amplifier (OTA), having two inputs (VTHR and Signal)

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Figure 3.35: The simplified ac schematic of the preamplifier stage (see text).

and one output. The resistive feedback realized with four identical resistors (R4) assures a linear DC transfer function. Except Rf, all resistors in schematic are physical resistors. This solution achieves a maximum preamplifier bandwidth with good Monte Carlo results in matching of components when taking into account the technological dispersions. In Fig. 3.36 the transient response at preamplifier output and at time output in dependence to QIN is shown.



Figure 3.36: Simulation: Transient response at preamplifier output (left) and at time output (right) in dependence to QIN.

In Fig. 3.37 the simulation of the time walk (arrival time -1 ns) and the time over threshold (ToT) are presented as function of the input charge QIN for different threshold voltages VTHR. In Fig. 3.38 the single channel time resolution (two channels difference) versus input signal amplitude measured with a 6 GHz analogue bandwidth Tektronix DSO equipped with Advanced Jitter Measurements software is shown.

PADI-8 ASIC

The main goal of the PADI-8 design in comparison to PADI-6 was to increase the number of channels on the chip from four to eight. In general the block layout is very similar to the one of PADI-6 (Fig. 3.34) with the following new features:

- 1. Each channel has only two 10-bit DACs which are directly connected to the threshold-voltage pins for an independent threshold control (the former DC bridge with 6 resistors is removed).
- 2. Only one channel contains the Buffer stage and the analogue output EOUT.



Figure 3.37: Simulation: time walk (left) and of time over threshold (right) as function of QIN for different VTHR.



Figure 3.38: Measurement: single channel time resolution versus input signal amplitude dependence to VTHR.

3. The POL pin is missing. Each channel has a small logic cell which sends the signal to the OR cell; depending of the value of bit 9 (DAC 10 bit, MSB) this signal is inverted or not. With this scenario, we can have any type of signal polarity at the channel inputs; the TOUT keeps the correct discrimination phase and the OR output is automatically adapted to have the needed phase (NIM standard).

Fig. 3.39 compares the simulated and measured dependence of the input impedance ZIN on R_{EXT} . In tests with PADI-6 we have seen that the ZIN = 50 Ω can be settled with low dispersion, but the DC offset of the preamplifier baseline has a nonlinear increase; for ZIN = 200 Ω this offset becomes normal. In order to decrease this effect in PADI-8, we have decreased the current density of input transistors two times by increasing their width with the same factor. As a result, ZIN = 50 Ω can be settled without degradation of the baseline offsets.

The setup for measuring the input impedance uses the HP808A pulse generator, the Directional Bridge HP8721A and the TDS7104 Tektronix scope. We have decreased the test pulse amplitude to 10 mV, which corresponds to a pulse current of 0.2 mA into 50 Ω load (the maximum biasing current of the input cascode is 0.7 mA). The reflected signal is measured on the 1 mV scale by using the gated measurement of the mean values.

The measured and simulated values agree almost perfectly for $R_{EXT} \ge 120\Omega$. For lower R_{EXT} (which correspond to high currents) the two curves deviate. This experimental saturation for $R_{EXT} \le 120\Omega$ is not fully understood. To avoid this region, we set the working point into a safe region $\sim 60 - 70 \Omega$ and tune the needed impedance for detectors with ZIN $\le 50\Omega$ with a parallel resistor.



Figure 3.39: Measured and simulated dependence of the input impedance on R_{EXT} .

Fig. 3.40 shows the dependence of the analog outputs (full symbols, left ordinate) and the errors related to linear fit of data (open symbols, right ordinate) on the DAC code for two PADI8 channels (black and red symbols). The errors with respect to the linear fit are ± 2 LSB.



Figure 3.40: Measured DAC integral non-linearity for two PADI-8 channels (located on different chips).

Another important feature of the channels is depicted in Fig. 3.41; it shows the two-channel time resolution for seven channel pairs on one PADI-8 chip. At the set threshold voltage (-124 mV) all channels are at the discrimination limit for the smallest test pulse amplitude (attenuation -50 dB is equivalent with 0.79 mV). An evaluation of the channel noise is difficult because only the discriminated signals are accessible. We have tried to determine the threshold-voltage limits for the discrimination of noise signals. For single channel we find these limits at \pm 36.9 mV for single discrimination in about 10 s. If we evaluate this rate for a normal distribution to 6σ , the related noise value is 6.15 mV_{RMS} which is close to the simulated value of 5.5 mV_{RMS}. If we set the same DAC code to all channels and look to the OR output, we find new limits at \pm 40.4 mV for single discrimination in \sim 10 s. This demonstrates that all eight channels have comparable noise properties and also a low dispersion of the DC baseline offset (the simulated σ of the offset is 1 mV).

Table 3.4 summarizes the main parameters of the most important PADI generations. The quantities denote simulated results (nominal conditions: 25°C temperature, 1.8 V supply voltage, NMOS-PMOS-resistors-capacitors having typical parameters). PADI-6 and PADI-8 are very similar in their features, except the baseline DC offset which has been decreased further in the latter; they fulfill all requirements



Figure 3.41: Left: single channel time resolution versus input signal amplitude in dependence to VTHR; Right: measured time resolution for different channel combinations on one chip (channel one against seven remaining). The test pulse (0.25 V amplitude and 3 ns width) is attenuated by the specified values.

Main parameters comparison	PADI-1	PADI-2	PADI-6	PADI-8
Channels per chip	3	4	4	8
PA Bandwidth (MHz)	280	293	416	411
PA Voltage Gain	74	87	244	251
Conversion Gain (mV/fC)	6.3	7.8	35	30
Baseline DC offset σ (mV)	6.7	21.9	5.9	1
PA Noise (mV_{RMS})	3.37	2.19	5.82	5.5
Equivalent Noise Charge (e_{RMS})	3512	1753	1039	1145
Threshold type	Extern	Extern	Ext. & DAC	DAC
Threshold dynamics $(\pm \text{ mV})$	Non.lin. 280	Non.lin. 300	Lin. 500	Lin. 750
Input Impedance Range (Ω)	30-450	37 - 370	38 - 165	30 - 160
$\begin{tabular}{lllllllllllllllllllllllllllllllllll$	21.6	17.4	17.7	17

for the TOF wall and can readily be mass-produced.

Table 3.4: Main parameters of the PADI chip family.

PADI front-end boards

In order to reach the best performance the PADI ASIC have to be mounted as close as possible to the MRPCs, hence in module types M4, M5, and M6 they are placed directly on cells inside of the modules. Due to the large density in the module types M1, M2, and M3 there is not enough space inside of the module, so the boards are placed outside of the modules directly on the enclosing boxes.

In the current development the FEE-board layout comprises a base-board for power distribution, SPI-Interface, and a connector for the Hit and OR-signals from PADI; it carries add-on boards with PADI chips (PADI card) and the connectors to the counters. In Fig. 3.42 we show the prototype of the baseboard fully equipped with add-on PADI cards. The design is kept fully differential in order to minimize the sensitivity to common-mode noise.

A prototype module with built-in FEE is shown Fig. 3.43. In this case the design of the MRPC connectors is such that the PADI cards can be mounted directly on the counter. The output signals are fanned out of the module trough the gas-tight feed-trough multi-pin connectors.

Another prototype PADI8 FEE for outside placement for module M1, M2 and M3 is shown in Fig. 3.44. One base board can serve 4 addon PCBs, where each addon PCB host one PADI-8. The FEE board shown in Fig. 3.44 has 32 channels.



Figure 3.42: Prototype of a FEE-board (base board equipped with four add-on PADI cards carrying two PADI-6 chips each) serving 32 channels).



Figure 3.43: A MRPC prototype inside of the gas box, fully equipped on both sides with FEE boards.



Figure 3.44: Prototype of a FEE-board (base board equipped with four add-on PADI cards carrying one PADI-8 chip each) serving 32 channels).

Outlook PADI Hardware

New frontend cards are development with specific layouts for each detector. New PCBs for Modules M4, M5 and M6 equipped with PADI8 are under development. In addition it is planned to package the ASIC to reduce the complexity of the PCBs as well as the cost of the PCBs. This have the affect that the PCB and the PCB assambling will be cheaper and in addition no addon PCBs with expensive connectors are needed anymore, due to the fact that reworking of broken ASICs is than possible.

3.3.5 Time to Digital Converter (TDC): GET4

GET4 (Gsi Event-driven Tdc) is a 4-channel TDC ASIC with an event-driven readout which fits into the DAQ environment of the CBM experiment. It is developed by the GSI ASIC design group which is part of the experiment-electronics department. The ASIC is logically divided into a TDC core and a digital readout. The TDC core is a DLL-based TDC with a clock-driven hit register.



Functional description

Figure 3.45: Block diagram of the GET4 TDC ASIC.

Fig. 3.45 shows a block diagram of the GET4 ASIC. On the left side the TDC core is depicted in a blue box, the green box on the right contains the token-ring readout.

TDC core

The main part of the TDC core is a 128 stages delay locked loop (DLL) circuit. The 156.25 MHz system clock passes the delay line of 128 identical voltage controlled delay elements. A phase comparator compares the input clock signal and the clock signal propagated through the delay line. In lock state the clock propagation through the delay elements is controlled in that way that both inputs of the phase comparator are in-phase, i.e. the delay of the whole delay chain is an integer multiple of the clock cycle time.

In case of GET4 the total delay is equal to the clock cycle time. Thus the delay of a single delay element is $\tau = T_{cyc}/128$ or

$$\tau = \frac{1}{f_{cuc} \cdot 128} \tag{3.1}$$

With a clock frequency of $f_{cyc} = 156.25$ MHz one gets a delay of $\tau = 50$ ps.

For each channel 128 d-type flip-flops build up the clock-driven hit register. The input signal which is connected to the data input of all flip-flops is sampled by the 128 phase shifted clock signals from the DLL core. So the hit register covers an image of the time structure of the input signal with a binning of 50 ps. Altogether a history of 6.4 ns is stored in the hit register.

After the hit register the hit pattern is divided into two parts of 64 samples corresponding to time intervals of 3.2 ns. Edge-detecting data encoders are used to get fine-time data and hit-detect flags for leading and trailing edges.

Due to the division into two parts the encoder can cope with one event in a 3.2 ns time interval which corresponds directly to the worst-case double-hit resolution. The hit-detect flags and the fine-time data are stored in d-flip-flop registers.

The control voltage of the DLL is monitored by two comparators. Their threshold voltage is generated by two 10-bit DACs. In lock state the DLL control voltage should lie in the window defined by the threshold voltages of the comparators. In out-of-lock state the control voltage of the DLL tends to the power rails so the comparators can recognize lock errors of the DLL.

Ringing or noise on input channels in a self-triggered DAQ is a major problem as these channels might overload the data links from the digitizer to the DAQ back end completely. To avoid this GET4 can

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disable selectively the input channels. This can be done by a configuration word transmitted on the serial up-link. In the default configuration all four channels are enabled after reset.

After initialisation of the readout system all channels are disabled; they are enabled after the first epoch event to get a defined start condition for the time-over-threshold calculator.

Time definition

The trigger less DAQ architecture of CBM does not provide a global trigger signal as time reference, hence a common clock signal is used as reference. One edge of the clock signal is arbitrarily defined as origin of the time line. This edge is called *epoch start*. The event time is completely determined by the number of clock cycles from the epoch start to the event and the time fraction between the previous leading edge of the clock signal and the hit signal as depicted in FIG. 3.46. The time fraction is the *fine time* delivered by the encoder of the TDC core. The number of clock cycles is counted in the *time stamp* counter.



Time stamp and epoch counter

The main clock is directly connected to a 12-bit *time stamp counter*. From the clock cycle time and the width of the counter one obtains the time interval of a counter epoch $t_{epoch} = 26.2144$ µs. At each time-stamp counter overflow a second counter is incremented, the 24-bit *epoch counter*. This way a time period of $t_{dyn} = 439.805$ s (7 min. 19.805 s) is bijectively given by the time stamp and the epoch counter.



A major task in a system where more than one GET4 work in parallel is the synchronization of all timestamp and epoch counters. Therefore GET4 has a dedicated *Sync* input to synchronize the time-stamp counter. Fig. 3.47 shows the timing of the synchronization. When a leading edge on the sync line is detected the time-stamp counter will be cleared by the next leading edge of the system clock.

If the counter is already in phase with the external synchronization source the last counter state before synchronization should be 4095. If it differs from that state a counter sync error signal is generated which is inserted into the data stream.

To synchronize the epoch counter a counter initialization value can be send to the GET4 ASIC by the serial up-link. This value will be loaded into the epoch counter on the next external time-stamp counter synchronization. If the epoch counter was not synchronized before i.e. it is in a different state an epoch-counter sync error will be generated and inserted into the data stream.

Derandomization

The first-level data acquisition is located directly behind the TDC core; it has to write the data coming from this core into the derandomization FIFOs. For each edge encoder of each channel a separate FIFO exists that means eight independent FIFOs are implemented. The data word written into the FIFO contains fine time and hit data from both half cycle encoders. In addition the time stamp and flags for external synchronisation, DLL lock state and epochs are part of the FIFO data word. To avoid data corruption by single-event upsets inside the event FIFOs the last flags are hamming encoded.

In case of epoch events the time stamp is zero by definition and instead of the time stamp information the least significant 12 bits of the epoch counter are written into the FIFO. In order to avoid data corruption of the epoch counter information during data storage in the FIFO also these data are hamming protected. The event FIFO has a depth of seven entries and are protected against overrun. One FIFO entry is always reserved for epoch event entries. Special dead time counters recognise the full state of the FIFOs and count the clock cycles during these states.

Token Ring readout

For readout of the eight event FIFOs a token ring readout is implemented as shown on the right site of figure 3.45. the token ring readout provides 24 bit event data with channel number, edge, time stamp and fine time for each detected edge at its output. The logic guaranteers that the events are ordered by epochs. Data events of different epochs are separated by epoch events containing the epoch number.

GET4 Backend

Figure 3.48	B: Block	diagram	of	the
GET4 backen	d.			



Fig. 3.48 shows a block diagram of the GET4 back end. Two read-out modes are available: a 32-bit and a 24-bit mode. The 24-bit mode is mainly implemented to be compatible with the first GET4 prototype of 2008. The 32-bit mode provides the full functionality of the GET4 chip.

In the 24-bit mode the data from the token-ring read-out are directly sent out with a 24-bit serialiser. In the 32-bit mode these data are processed in the time-over-threshold calculator, a data reduction at a very early stage. This module calculates pulse widths from the leading and trailing edges and generates a 32-bit event word with time stamp and fine time of the leading edge and an 8-bit pulse width. Resolution and dynamic range of the pulse width are configurable. The options are given in Table 3.5.

	rai	nge	$\operatorname{resol}\iota$	tion
TOT Configuration	$_{\rm bins}$	\mathbf{ns}	$_{\rm bins}$	\mathbf{ps}
0	255	12.7	1	50
1	510	25.5	2	100
2	1020	51.0	4	200
3	2040	102.0	8	400

Table 3.5: Possible configuration options for resolution and range of the time-over-threshold measurement.

Behind the time-over-threshold calculator module the data words coming from the slow-control read out are introduced into the data stream. This module is able to read out frequently from some counters

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incoming pulse, dead time or detected single-event upsets in hamming protected registers. Also data read from SPI devices are processed by the slow control readout.

The data stream can be split into two streams sent out by two 32-bit double data rate serialiser with 320 MBit/s each. For the configuration of GET4 a serial receiver with a data rate of 20 MBit/s is used as slow control up-link. The 32-bit data words contain a 5-bit module address, a 3-bit sub-module address and 24 bits data.

The GET4 ASIC provides a flexible configurable SPI master interface which can configure front-end electronics e.g. a DAC for setting discriminator thresholds. The PADI-6 chip which is designed to operate in conjunction with GET4 can be configured by the mentioned SPI. It can be programmed by the slow control up-link.

For electronics testing and monitoring a flexible internal test pattern generator is implemented which operates with a free running configurable ring oscillator asynchronously to the system clock. The test pattern generator provides a wide spectrum of tests such as bin-width measurements, linearity tests, time-resolution measurements etc.

Development Status

Figure 3.49: Die picture of the GET4 ASIC.



The first time the four channel DLL based TDC core was implemented on a prototype ASIC was in 2008. This prototype ASIC was tested intensively and it was used to show feasibility of fulfilling the CBM requirements with the GET4 TDC concept. After the design of two additional test ASICs to improve the converter linearity of the TDC core the first fully equipped TDC ASIC GET4 V1.10 as described in section 3.3.5 was taped out in 2012. Whereas the TDC core is a full custom design to guarantee the maximum level of symmetry for best converter performance the read out logic was synthesised from 17647 lines of VHDL code and automatically placed and routed. The whole TDC is realised on 3240 µm by 2250.12 µm in UMC 180 nm CMOS technology. A Die picture is shown in figure 3.49.

Also this ASIC was tested in the laboratory as well as in beam time at GSI in 2012 together with an RPC. Some minor bugs have been found which are corrected in the design.

A first GET4 ASIC based on a corrected VHDL code was submitted in early 2013. Unfortunately this ASIC was not operational due to a mistake in clock tree synthesis. So in September 2013 the latest version of the design, GET4 V1.24 was taped out which is now under test.

The performance measurements presented below are done with this latest GET4 V1.23 if not otherwise mentioned.

Performance

Rate capability

The rate capability of GET4 is mainly given by the serialiser speed. Short bursts of up to 320 MHz event rate can be buffered by the event FIFOs. The token ring readout can cope with up to 80 million edges per second. To study the rate capability of the GET4 read out logic in detail functional simulations of GET4 with a random hit stimulus have been done with different event rates and read out bit rates. The results of these simulations are shown in figure 3.50.



Figure 3.50: Simulation results of data rate capability in 24-bit (left side) and 32 bit read out mode (right side).

On the left side the simulation results for the 24-bit read-out mode are shown. For two bit rates (40 MBit/s and 160 MBit/s) the rate of the read out data and of the error events is plotted against the input hit-rate. Both rates are summed up for all channels. At low rates the data rate is equal to the input rate, so no hits are lost. At input rates above 0.6 MHz for 40 MBit/s and 2.5 MHz for 160 Mbit/s, respectively, the system is not longer able to transport all data, hence dead times become larger and event losses higher. Finally the read out data rate saturates at 660 kHz for 40 MBit/s and 2.77 MHz for 160 MBit/s. At larger input rates the serial link has to be shared with an increasing number of lost-event error events.

The results of a similar simulation for the 32-bit read out mode are shown on the right side of figure 3.50. Three read-out speeds are plotted, 40 MBit/s and 320 MBit/s with one serialiser and 640 MBit/s with two serialisers. As expected the highest possible data rates are larger than in 24-bit mode, namely 815 kHz for 40 MBit/s, 7.19 MHz for 320 MBit/s and 13.28 MHz for 640 MBit/s. The improvement of 23.5% for 40 MBit/s is slightly smaller than the theoretical improvement of 30%. This might be caused by inefficiencies of the time-to-threshold calculator at higher rates, but further investigations are necessary. All results of the simulations are summarized in Table 3.6.

A laboratory test with pulser signals in 24-bit read-out mode at 160 MBit/s gave results matching the simulation [47].

Data Rate	Event Ra	te / MHz	Table 3.6: Simulated max-
$\mathrm{MBit/s}$	24 Bit mode	32 bit mode	imum event rates. The
40	0.660	0.815	event rates are summed up
160	2.77		for all 4 channels (event
320		7.19	rate/ASIC, see text for de-
640		13.28	tails).

Radiation Hardness

In irradiation tests the GET4 ASIC was proven to be sufficient radiation tolerant for the CBM-ToF environment. More details on radiation hard electronics can be found in section 3.3.6

Lock Range

To obtain the best possible time precision the design of the DLL delay elements is very close to limit of the used CMOS technology. Nevertheless some safety margin is needed for stable operation with PVT¹ variations.

 $^{^{1}\}mathbf{P}$ rocess **v**oltage and **t**emperature

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With GET4 V1.23 measurements have shown that the DLL locks with 1.8 V core voltage and in a room temperature environment in a frequency range up to 162.8 MHZ. At the design frequency of 156.25 MHz the ASIC can operate at temperatures up to 80 degrees centigrade measured on the pcb close to the ASIC.

Linearity



Figure 3.51: Measured differential (DNL, red) and integral (INL, blue) non-linearity of the GET4 TDC Core.

Figure 3.51 shows the differential and integral non linearity of an arbitrarily chosen channel. Differential as well as integral non linearity is in the range of ± 50 ps which is the bin size. Due to this excellent value linearity corrections for time measurements are not needed to fulfill the CBM requirements in time precision.



Figure 3.52: Left side: Spectrum of the time difference of correlated signals on two channels. Right side: Spectrum of measured pulse spacing of two pulses.

Time Precision

To measure the time resolution the internal test pattern generator was configured to generate two synchronous pulses on all channels. The differences of the measured leading-edge times of channels 0 and 1 are plotted into a histogram on the left side in Fig. 3.52. The RMS deviation of the plotted distribution is $\sigma_{2ch} = 23.76$ ps. The time resolution of a single channel is obtained by division by $\sqrt{2}$:

$$\sigma_{1ch} = \frac{1}{\sqrt{2}} \sigma_{2ch} = 16.76 \text{ ps}$$
 (3.2)

The single channel time resolution is very close to the theoretical limit $\sigma_{1ch} = 50 \text{ps}/\sqrt{(12)} = 14.45 \text{ps}$ supporting the small DNL contribution.

A time resolution better than 20 ps was also measured on the other channels.

Double hit resolution

The double hit resolution of the GET4 ASIC is given by the internal architecture of the hit encoders. These encoders can cope with one hit in a half clock cycle period. This leads to a double hit resolution of 3.2 ns. The right side of Figure 3.52 shows a pulse spacing spectrum of double pulse generated with an arbitrary waveform generator with a time interval between the leading edges of 3.2 ns.

Pulse width resolution



Figure 3.53: Spectrum of the pulse with of discriminated AWG signals. Left side: The AWG signal well above the discriminator threshold, Right side: The AWG signal with added noise close to the discriminator threshold.

Fig. 3.53 shows two pulse width spectrums. In both cases the signal of an arbitrary waveform generator was fed into a discriminator. The discriminator output was used as signal input of the GET4 TDC. An AWG signal well above the discriminator threshold leads into a pulse width spectrum as shown on the left side of figure 3.53 with a well defined peak at 2.95 ns pulse width.

To get smaller pulse widths the signal amplitude of the AWG signal was reduced and to widen the spectrum some noise was added to the AWG signal. The result is plotted on the right side of figure 3.53. It is clearly visible that the GET4 TDC is able to measure pulses below 1 ns pulse width.

GET4 front end board

The test PCB for the GET4 chip comprises a base-board for the clock distribution and the different supply voltages (5V, 12V and 48V) and separate add-ons for the TDC chips. One baseboard (Fig. 3.54) can carry four PCBs each being equipped with four GET4.



Figure 3.54: Test board for GET4 TDCs; each of the add-on boards carries 4 GET4 chips, 64 channels altogether.

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Each add-on PCB has a 16-channel input connector for the Hit signals as well as a connector for the SPI-DAC-Interface. Each GET4 can be used as an SPI Master for setting the threshold of PADI or to send commands to other SPI components. In upper right corner of the base board (see Fig. 3.54) there are the different power inputs, the two clock and the sync-signal inputs are placed in the lower corner. In between the connector for the readout controller is placed.

In order to characterize the system, the time resolution between two channels is measured with an external pulser: a) on the same chip (chip-level) b) on different chips on the same add-on-PCB (PCB-level) and c) on 2 different add-on PCBs (PCB-PCB-level). The results are listed in Table 3.7.

	$\sigma_{2ch} \ / \ \mathrm{ps}$	$\sigma_{1ch} \ / \ { m ps}$
chip-level	27.35	19.33
pcb-level	27.69	19.58
pcb-pcb-level	28.70	20.29

Table 3.7: External pulser test of GET4 (time resolution between two channels); the different levels are explained in the text.

Outlook GET4 Hardware

The new version of GET4 ASIC was first tested with the existing hardware since there was no change in the pin layout and it fulfills the requirement for CBM-ToF. The new generation of hardware allows to connect GET4 directly to the detector box without cables (Fig. 3.55). One Baseboard is equipped with two addon PCBs where each host 4 GET4 ASICs.



Figure 3.55: Base board for GET4.

Like for PADI it is planned to package the GET4 ASIC to reduce the complexity of the PCBs. New PCBs for packaged GET4s and the modules M1, M2 and M3 are under development.

3.3.6 Radiation Tolerance of Electronics

Radiation damages to electronic components are an important issue for the CBM experiment. Here, distinction must be made between Commercial Off-The-Shelf (COTS) components (e.g. power regulators, line drivers, FPGAs) and application specific integrated circuits (ASICs). The last-mentioned components are self-developed components in which the electronic circuit, the circuit layout and the used technology are well known.

For the CBM experiment one of the preferred technology for ASIC developments is the UMC 180 nm CMOS process. In the ToF read out system this technology is used for PADI as well as for the GET4 ASIC. In this regard the ASIC design group of the GSI Experiment Electronic department has already launched research projects in 2007[48] and the subsequent years. With dedicated test chips the effects of total ionizing dose accumulations as well as single event effect cross sections have been measured[49].

These studies showed that the used technology is sufficient radiation hard relating to total ionising effects in the context of CBM-ToF.

The SEU cross sections gotten in these measurements can be used to estimate failure rates of ASICs designed in the UMC 180 nm technology but to assure the radiation tolerance of PADI and GET4 a PADI6 and a GET4 V1.10 were irradiated with 2 GeV protons at the COSY accelerator facility at FZ Jüllich in July 2013.

ASIC	proton density		Accu	mulated dose
PADI	$2.31 \cdot 10^{12}$	$\rm cm^{-2}$	665	$Gy(SiO_2)$
GET4	$2.23\cdot10^{12}$	cm^{-2}	642	$Gy(SiO_2)$

Table 3.8: Proton densities and accumulated total ionising dose for different ASICs during COSY beam test[50].

Both ASICs were placed directly into beam. At a proton energy of 2.0 GeV the total number of delivered protons was $\approx 3.88 \cdot 10^{12}$, with a proton flux between $1.5 \dots 3.0 \cdot 10^8 \text{ cm}^{-2} \text{s}^{-1}$. The proton beam diameter was around 1cm (3mm sigma). The proton densities and calculated total ionising doses for the beam positions of the different test devices are listed in table 3.8.

For the PADI ASICs the analog threshold voltages were measured. Within the 2 days beam on target the precision between 2 channels of PADI was measured with the GET4 ASIC of around 27 ps.

With the GET4 no SEU induced malfunction have been observed. Eight bit errors have been detected by integrated hamming error correction units.

Due to total ionising dose accumulation a slight decrease of the control voltage was observed that disappears after some hours of annealing. Based on these tests the GET4 ASIC is proven to be sufficient radiation tolerant for the CBM-ToF environment.

Other components, especially those that will be used in critical areas, will be tested in further radiation campaigns in 2014.

3.3.7 Placement of Electronics

Electronics Assembly for Modules M1 to M3

In the part of the wall closer to the beam pipe (modules of type M1, M2 and M3), the number of electronic channels is high and the available space very restricted. Hence it is not possible to mount the preamplifiers inside the Module boxes directly on the RPCs. Boards equipped with PADI-8 ASIC can be mounted on the back side of the boxes. The TDC boards are mounted at the moment outside of the inner wall region. Their distance to the PADI FEE must not exceed 4 m, otherwise performance might get lost. All described components are under development. An in-beam test is planned for end of 2014.

Fig. 3.56 shows the backside of a prototype module (with 4 detectors inside) with the electronics in place.

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Figure 3.56: PADI-8 FEE mounted behind a prototype for Modules type M1 to M3 (128 channels).

For the readout electronics of this part of the wall the expected radiation level is an issue, especially for FPGA based readout controllers. The radiation environment can be evaluated with the simulations presented in Chapter 2.5. The code loaded in the FPGAs has to be designed radiation-hard and must employ fast recovery procedures. Test have shown that up to a certain point of radiation this is very well doable. To see how near we can get to the inner region of the ToF-Wall we will see in the near future. For the next iteration of FEE cards we will equip PADI and GET4 TDC on the same PCB. In this case we have to transmit only the digitized signal over a longer distance to the readout controller.

The FPGA boards in later stages of the readout chain e.g. those for aggregation and pre-processing can be placed further away from the detectors, where the radiation levels are much lower.

Electronics Assembly for modules M4 to M6

Fig. 3.57 sketches the readout chain for modules of type M4 to M6 with the readout chain mentioned before.



Figure 3.57: Simplified mounting scheme of the readout electronics on a module of type M4 to M6 (320 channels).

The PADI boards are attached directly on the five RPCs inside the gas box. Each board is connected via a flat-band cable to the feed-through connectors on the right side. The TDC boards are plugged outside onto this connectors. Via these boards also the slow control commands for the threshold setting are transmitted to the PADI chips.

The support frame of the outer board houses in addition the clock and power distribution. Data from the TDCs are sent to a data-combiner / readout-controller board via flat-band cables. As readout-controller board for GET4 we use SYSCORE V2 [36] at the moment.

3.3.8 Clock System CLOSY

A very precise clock generation and distribution system, called CLOSY, has been designed for time measurements with the CBM ToF wall. The main card (CBM-CLOCK-SYTEM) is based on a frequency-synthesizer chip to create two independent output frequencies that are phase-coupled. An additional downstream fast CPLD creates a synchronization signal, which is needed as a periodically epoch marker. The concept of the CBM Time-of-Flight detector requires two phase-coupled frequencies of high performance [51]. One is directly used for time measurements with an event-driven TDC (FEET-board, GET4 TDC chip), c.f. 3.3.5 and [52], the other reasons of synchronous data-transport (Read Out Controller board, ROC), see section G.1. The front-end boards with the GET4 chip require a frequency of about 160 MHz with very low jitter (less than 5 ps RMS). The ROC board need a 240 MHz clock, with less strict demands, however, as far as jitter is concerned.

To synchronize these frequencies over a long distance and to create epoch markers ($t_{epoch} = 26.2144 \ \mu s$), an additional signal is created. All three signals will be cascaded over two stages and distributed over distances of about 20 m to cover the whole ToF wall area. This approach of distributing clock signals with LVDS levels was already applied successfully at the FOPI experiment at GSI [53], see Fig. 3.58.

CLOSY Circuitry

Based on a programmable any-rate XO (Silicon Laboratories, Si570), a low-jitter synthesizer and jitter cleaner (Texas Instruments, CDCL6010) and a fast CPLD (Xilinx, XC2C32A) an impedance-controlled six-layer board has been developed that delivers two phase-coupled signals (for the prototype system with 250 MHz and 156.25 MHz) and an additional synchronization signal (SYNC) (see Figs. 3.59 and 3.60).

In stand-alone operation CLOSY2 uses the on-board XO as clock source, but it also accepts an external LVDS signal (EXTIN). One of these inputs is directed over a crosspoint switch (Texas Instruments, SN65LVDS122) to the frequency synthesizer. Optionally this signal can be monitored by a control output (CNTRL).

Inside of the frequency synthesizer an integrated jitter cleaner with the option of a narrow external PLL loop filter also offers the opportunity of using a non-optimal external clock source. To define the suitable output frequency a rational fraction of 5/8 from 250 MHz i.e. 156.25 MHz, would be a good choice to get a

3.3. READOUT CHAIN

fixed frequency relation for the TDC chip and the ROC board. The SYNC signal has to be generated in a fast CPLD outside the CDCL6010, since the synthesizer does not deliver such a signal. It is generated in the simple way of generating two patterns by sampling the lower frequency with the leading and trailing edges of the higher frequency. In the case of a repeated sequence by comparison of these patterns, an

the SYNC signals (see Fig. 3.61). To monitor the temperature stability of the XO a temperature sensor (Texas Instruments, TMP101) has been placed close to the oscillator. To parameterize the oscillator, the crosspoint switch and the frequency synthesizer and to read out the temperature sensor a microcontroller with USB and I2C interface is placed on board (Cypress, CY7C68013A). For a stand-alone application there is the possibility to store the final boot values in an I2C-EEPROM. CLOSY2 can be powered over the USB port (power consumption ~400 mA at 5V), and also externally. All high-performance in- and outputs feature LVDS levels. In parallel the synchronized outputs and the SYNC signal can be monitored as LVTTL signals.

internal signal is generated and used as an input for a counter to get the required timing distance between

Results

Best results are obtained with an input clock frequency of 312.50 MHz (jitter measurement at CNTRL output: $\sigma_{TIE} \sim 2.7$ ps, $\sigma_{Period} \sim 3.7$ ps). In that case the outputs exceed the mentioned requirements by



Figure 3.58: Overview of the Clock system



Figure 3.59: Simplified scheme of the CLOSY card



Figure 3.60: Photo of the CLOSY2 board; the signal connectors are placed on the back side).

Current Simulation Time: 2.001e+06 ns		737310 737340 737370 737400	
olock1	1		٦
olock2	1		Π
Sync2	1		
Sync3	0		Т
Sync_int	1		l
Sync 🛛	0		

Figure 3.61: SYNC pattern; see Text.

far (see Fig. 3.62 and Tab. 3.9).



Figure 3.62: Jitter analysis of output signals of CLOSY2. The input frequency of the frequency synthesizer was 312.50 MHz

After cascading the clock tree over a distance of 20 m the RMS of the time jitter increases slightly, nonetheless it remains significantly below the requirements (see Fig. 3.63) After 25 epoch times (655.36 μ s), the SYNC signal occurs with a time jitter due to the 156.25 MHz clock signal with an RMS of less than 7 ps after the whole distance of about 20 m (see Fig. 3.64).

output freq.	method	@CLOSY2	$20 \mathrm{~m~distance}$
$156.25 \mathrm{~MHz}$	TIE	$3.2 \mathrm{\ ps}$	$4.2 \mathrm{\ ps}$
	Period	$2.3 \mathrm{\ ps}$	$3.1 \mathrm{\ ps}$
$250.00 \mathrm{~MHz}$	TIE	4.0 ps	$6.0 \mathrm{\ ps}$
	Period	$4.2 \mathrm{\ ps}$	$5.4 \mathrm{\ ps}$

Table 3.9: RMS values of timing jitter (TIE: time interval error, output signal at CLOSY2 and 2 times cascading over 20 m distance, XO frequency = 312.50 MHz).



Figure 3.63: Jitter analysis of the 156.25 MHz output signal after cascading and over a distance of about 20 m. The input frequency of the frequency synthesizer was 312.50 MHz.

Figure 3.64: Screen shot of the time jitter measurement between the SYNC pulse and the next leading edge of the 156.25 MHz output signal (both signals were casceded 2 times over a distance of about 20 m).

The on-board temperature sensor (TMP) placed next to the oscillator (XO) with good thermal coupling gives allows to observe the temperature dependence of the output frequency (see Fig. 3.65).





The measured temperature variation from 0° C to 75° C lies betwen +5 and -7 ppm related to the nominal frequency of 312.50 MHz. These values correspond to a maximum uncertainty in period time of about 50 fs and are negligible in comparison to the time jitter of the signal. If nonetheless there is a need

for correction, the oscillator allows to shift the frequency without interruption up to 3500 ppm from the center frequency with a frequency reprogramming resolution below 1 ppb. Fitting the data of Fig. 3.65 with a 3rd order polynomial and using these values for correction, the frequency stability is better than ± 0.3 ppm.

Conclusion and Outlook

The clock system is ready to be used in the CBM ToF system with parameters that exceed the requirements. The essential control parameters are easy to configurate via USB or over a boot sequence stored in an on-board EEPROM. The CPLD is also reprogrammable in the case of other frequency ratios or for a delay of the SYNC signal. Restrictions to direct output frequencies from the programmable oscillator (up to 1.4 GHz) are given by the bandwidth limitations of the crosspoint switch (750 MHz). A further constraint is the limited parameter-set of the frequency synthesizer, so not all output frequencies and division ratios are available. CLOSY could be deployed in other physics experiments and as well be used in the laboratory whenever precise phase-coupled clocks are needed.

3.3.9 Number of readout components

On the basis of the proposed TOF wall layouts (cf. section 2.3) one can evaluate the number of components needed for the full readout chain. The principles used for finding the number of readout controllers (ROC) are that up to 80 TDC can be connected to a single ROC and that ROCs are not shared between modules. For the case of the SIS300 configuration (setup C, chapter 2.4) these numbers are gathered in Table 3.10.

Maximal number of channels per module	5376
Maximal number of PADI chips per module	672
Maximal number of TDC chips per module	1344
Maximal number of ROCs per module	21
Total number of Channels (without spares)	106368
Total number of FEE-PADI8 (without spares)	13296
Total number of FEE-TDC (without spares)	26592
Minimal number of ROCs (without spares)	336

Table 3.10: Number of channels, needed FEE chips and ROCs for the full ToF wall when using GET4 as TDC.

With the given wall layout one can also estimate the average data rates per electronic channel, MRPC, module or module type. Minimum bias reactions of Au+Au as predicted by the event generator URQMD at an incident laboratory beam energy of 25A GeV at an interaction rate of 10 MHz have been analyzed within the CBM simulation framework for the SIS300 setup employing a realistic material budget. Fig. 3.66 shows the number of electronic channels with a given mean input rate for this case. These results demonstrate that all the channels stay below a mean rate of 500 kHz and are therefore well compatible with the GET4 TDC rate capabilities.

The maximal rate per channel for each MRPC type can be used to obtain an estimation of the necessary readout components with some safety margin, as only few channels reach these maximal rates for each type. In addition, the number of ROCs and GBTX can be optimized for later preprocessing and reconstruction tasks by keeping all channels from a single MRPC in the same ROC and when possible all channels from a single module in the same ROC(s) + GBTX unit. Table 3.11 presents the results of this estimation.

As many optical fibers as the number of GBTX will be needed before doing a further aggregation and eventually preprocessing in the DPB boards. The same simulation also allows to estimate the minimal number of optical links (4.8 Gb/s each) which are needed for transporting all raw data from the DPB to the FLES, see Table 3.12.

More details about the assumptions made for these simulations and estimations can be found in Appendix G.4.


Figure 3.66: Simulated hit rate per electronic channel in 10 MHz Au+Au collisions at SIS300 (25A GeV).

Type	Max. Rate	GET4/ROC	RPC/ROC	ROC/GBTX	GET4 Ch.	ROCs	GBTX
MRPC1	≤ 500	32	1	2	5120	40	20
MRPC2	≤ 400	64	2	1	31488	123	123
MRPC3a	≤ 300	80	5	1	37120	116	116
MRPC3b	≤ 100	80	5	4	12800	40	10
MRPC4	≤ 200	80	5	2	19840	62	31
Spares (arb.)					3632	12	10
Total					110000	393	310

Table 3.11: Number of ROCs and GBTX obtained from the channel rate simulation when optimizing the connections to keep RPC or module channels in the same readout unit (ROC+GBTX). The maximal rates are given in kHz.

Module Type	Links Number
M1	8
M2	41
M3	20
M4	14
M5	14
M6	30
Total	127

Table 3.12: Number of 4.8 Gb/s optical links needed for data transport of each module type (based on 10^6 minimum bias URQMD Au+Au simulations at an incident energy of 25A GeV and at an interaction rate of 10 MHz).

Chapter 4

T_0 - Reference

Each TOF - measurement needs a reference time called T_0 in this document. The Time-of-Flight is given by the difference $TOF = T_{MRPC} - T_0$. Since the range of possible physics runs and running scenarios for CBM is very wide (see chapter 1) there is no unique solution for determining the T_0 - reference time. However, there are different solutions for all the currently anticipated physics runs as detailed below.

4.1 Requirements

The future CBM experiment at FAIR will feature interaction rates of up to 10 MHz which are reached with heavy-ion beam intensities of 10^9 ions/s on targets of 1% of interaction probability [15, 16]. The physics program plans to run both light (minimum-ionizing particles i.e. protons, MIPs) and heavy-ion relativistic beams (e.g. Au) which require a separate treatment due to the different multiplicities of the interaction products. It is also possible that in experiments with light ions and protons the beam intensities will be even higher.

The time resolution for the full CBM ToF system is required to be better than 80 ps. If one assumes a time resolution of 60 ps of the ToF wall itself, the required resolution for the T_0 reference system should be better than 50 ps. Since the system is used as a reference it is also important to achieve a detection efficiency close to 100%.

Several methods are pursued targeted towards the different running conditions of CBM.

- For low beam rates and for calibrations a dedicated in-beam start detector (SD) appears most appropriate. Such a detector will be developed for common use by the CBM and HADES experiments in the CBM cave.
- For the study of central collisions the multiplicity of registered particles is sufficient to reconstruct the timing reference from the fastest hits in the TOF wall. This mode is available independent of the beam particle rate.
- For the study of high-rate semi-central to peripheral reactions an array of timing RPCs in the fragmentation region promises an adequate coverage to supply a high resolution T_0 -reference. Such beam fragmentation T_0 counter (BFTC) would overlap with the PSD acceptance.
- For the extraction of a time reference signal in high-rate proton-induced reactions, aiming e.g. at J/Ψ reconstruction, the development of a reaction detector measuring particles outside of the CBM spectrometer acceptance in the polar angular range of $35^{\circ} < \theta < 65^{\circ}$ is considered.

We describe all above mentioned cases apart from the reaction detector in the following; for a study case of the reaction detector please refer to [54]. Possible implementation of such detector is strictly limited to cases where aforementioned physics case would benefit from its use. It should be emphasized that the requirements may evolve with time.

4.2 Software Reference

The possibility to extract a timing reference from all hits registered by the TOF wall, i.e. to run the experiment without a direct beam particle measurement, was explored within the CBM Monte-Carlo environment using the event generator SHIELD that includes fragment production. The results are shown in Fig. 4.1 for the SIS100 incident energies of 4 AGeV and 10 AGeV as function of the impact parameter for the Au + Au reaction.



Figure 4.1: Mean ($\langle t0 \rangle$) and width (RMS) of time zero distributions calculated with the algorithm described in the text as function of the impact parameter for Au + Au reactions at 4 A GeV (left) and 10 A GeV (right). For the calculation only hits outside of the most central part of the TOF wall are used (|x| > 55 cm and |y| > 55 cm, magenta curves). Inspecting the BFTC region (see section 4.3) gives rise to the red values, adding BFTC hits yields the blue curves.

The t_0 - reference is calculated with the following preliminary algorithm:

- 1. Sort all hits in a region of interest according to the normalized arrival time $t_a = t_{meas} \frac{D}{c}$, with D being the straight line distance of the TOF hit to the nominal target position and c representing the velocity of light.
- 2. Calculate the mean arrival time of fast particles t_{NF} considering only the first 10 particles within the region of interest.
- 3. In order to minimize the impact of possible random hits, e.g. of those from δ -electrons, remove hits from the average that have the largest distance to the mean until the RMS of the remaining sample reaches a value below 1 ns (truncated mean).
- 4. Calculate the average time of all t_a values within an interval $t_{measured} < t_{NF} + 3 \times \sigma_{TOF}$.

The resulting average is called t_0 and the width of the t_0 -distribution is shown in Fig. 4.1. Over a wide range in centrality the method delivers a reference signal with a resolution of about 30 ps - 40 ps. While

this appears sufficient for the lower energies at the higher energies the performance becomes marginal for central collisions. As shown below this can be cured by the addition of additional timing counters in the forward region.

Thus a software solution is available for all physics cases presently being discussed for operating CBM at SIS100 even for the largest possible luminosities. It should be pointed out that the results of the simple algorithm described above can be refined by making in addition use of the tracking information available for matched and identified particles as shown e.g. in [55]. By comparison of measured (by ToF) and estimated (by tracking) times and by assuming a common offset one can obtain T_0 .

4.3 Beam Fragmentation T_0 - Counter (BFTC)

One option to deliver a timing reference is to make use of the beam fragmentation and to place timing counters at transverse distances between 25 cm and 50 cm to the beam. This concept was tested by software with the algorithm described in section 4.2.



Figure 4.2: Mean ($\langle t0 \rangle$) and width (RMS) of time zero distributions calculated with the algorithm described in the text as function of the impact parameter for Au + Au reactions at 4 A GeV (left) and 10 A GeV (right). For the calculation only hits in the BFTC region of the TOF wall are used (|x| < 55 cm and |y| < 55 cm, red curves). Inspecting the full TOF wall acceptance (see section 4.2) gives rise to the magenta values, averaging over all hits yields the blue curves.

Results are shown in Fig. 4.2 and demonstrate that a detector system in the forward region delivers a timing reference signal with a resolution of about 20 ps for the higher beam energies. At the same time even very peripheral reaction become measurable with a timing resolution of about 40 ps. For the lower beam energies the limited statistics of fast particles in the limited forward acceptance limits the achievable resolution. However, in this case the resolutions shown in Fig. 4.1 were already sufficient. A detector concept that could operate in this harsh environment where fluxes as high as 100 kHz/cm^2 are



Figure 4.3: Conceptual design of the BFTC consisting of single-cell MRPCs of dimension $2 \times 2 \text{ cm}^2$.

anticipated is based on the R&D described for RPCs with ceramic resistive plates (see section F.2.1). To fit the granularity requirements detectors with a single cell readout per counter are considered. A sketch of the system that covers the solid angle at distances from 20 cm to 60 cm from the beam axis is shown in Fig. 4.3. Single cell counters with the size of $2 \times 2 \text{ cm}^2$ seem to fulfill the double hit, maximum rate, and cross-talk requirements. A chamber with six gas gaps of 250 μ m thickness is foreseen to have a time resolution of about 60 ps and a detection efficiency of about 98%.

In order to cope with the high particle flux in the order of up to $100 \,\mathrm{kHz/cm^2}$ the BFTC counters are built from very radiation-hard materials and will be optimized for minimum gas aging characteristics.

4.4 In-Beam Start Detector

A high rate in-beam start detector (SD) could fulfill all CBM T_0 requirements, covering whole range of beams from proton to heavy-ions. Such detector is at the same time intended to be used for the on-line beam monitoring, giving the instantaneous information about the beam profile, the stability of the beam position on target, the amount of halo particles and time structure of the beam. In our opinion the best solution for such detector is an in-beam diamond Start detector.

SD will be installed inside the beam pipe in vacuum and it will measure the arrival time of every beam particle. In order to reduce the interactions in the SD itself its thickness has to be minimized. Fig. 4.4 shows the mounting of the planned SD system between the last focusing magnet in front of the cave and the focal point of the CBM detector.

At the last focusing magnet the beam may be as wide as 150 mm in diameter whereas at the focal point a spot of 1 mm diameter is required. So by moving the SD upstream the rate per mm² is reduced considerably; at 10⁹ ions/s we expect a spot rate of about 2.3×10^5 mm⁻²s⁻¹ at the last focusing magnet and 3.3×10^8 mm⁻²s⁻¹ at the focal point, hence the particle load can be reduced by up to three orders of magnitude - of course at the price of a considerably larger SD.

Experiments employing high-intensity HI beams require fast and radiation hard detection systems. For



Figure 4.4: Schematically drawn beam line in the HADES/CBM cave (not to scale) for the case of CBM running an experiment. The requested beam emittance is constrained by a long distance to the last magnet and the need of a small beam spot on the CBM target. The in-beam SD can be located at any place along the upstream beam line. In case that the same detector is used by HADES experiment, it will be places upstream from the HADES target.

these purposes pcCVD and scCVD diamond detectors (polycrystalline material and single crystals produced by Chemical Vapor Deposition, CVD) have been widely used [56, 57, 58, 59]. A high radiation hardness and excellent timing properties make the diamond material an almost ideal choice for our application. Based on our experience we plan to build the SD from the commercially available *electronic-grade*¹ CVD diamonds.

Experiments with light-ion and proton beams are posing additional challenges on the in-beam SD. Due to the large effective energy needed to create electron-hole pairs in diamonds (~13 eV), the total charge created by MIPs is marginal (14000 e-h pairs for a 300μ m thick diamond) [60]. Intrinsic defects in the widely used pcCVD diamonds lead to significant charge losses in this type in addition. Therefore they cannot be used for a ToF measurement with MIPs because the signal-to-noise ratio is not sufficient for the contemporary state-of-the-art electronics. Instead, the recently developed scCVD diamonds allow to build detectors for MIPs since they are almost free of structural defects and chemical impurities thus providing a charge collection efficiency close to 100%.

On the other side Au ions of 10A GeV suffer an energy loss of 4 MeV/ μ m in a diamond, protons of 10 GeV only about 0.6 keV/ μ m [61]. In any case, especially for MIPs, the low primary signals set high demands to the amplifying system.

While pcCVD diamonds are delivered in wafers of up to 8 inch diameter, the electronic-grade material is available only up to about 8 cm diameter. Readily available scCVD diamonds are much smaller, they are limited to sizes of about 4.5×4.5 mm². If the technology is driven further larger samples might be available in the future, but for the time being the necessary active areas can be reached only by placing several small scCVD diamonds close together on a board.

4.4.1 Diamond strip start detector

In tests and physics experiments with HIs it has been demonstrated that diamond SD prototypes reach the required time resolution and show the necessary radiation hardness [62, 63, 64]. The final detectors will feature a strip-electrode geometry in order to keep the particle rate per channel below 10^7 /s because this is at present the limit for the fast readout electronics. For heavy ions a single large-area pcCVD diamond plate will be used with a metallic electrode strip pattern on both sides. A large-area in-beam SD for protons and light ions, however, has to be put together by more scCVD plates in a mosaic-like structure; at this moment such a design is the only feasible solution. Furthermore required time resolution for MIPs has not been demonstrated with diamond SD.

A possible realization of such mosaic of scCVD detectors is shown in Fig. 4.5. Each diamond has the size $5 \times 5 \text{ mm}^2$, so the the active area of the whole setup is $15 \times 15 \text{ mm}^2$. The strip patterns on front and back sides are orthogonal, which allows to use the device also for the beam monitoring.

For an estimate of the rates on the electrodes (and in the corresponding electronics) it is assumed that

¹Element Six Ltd, Ascot, UK.



Figure 4.5: Left: Possible scenario of a start detector comprised of nine (three rows \times three columns) single scCVD diamonds; each plate has 16 electrode strips which are oriented in x and y on opposite sides. Right: The diamonds are mounted on two PCBs placed behind each other; in this case the strips can be bonded more easily onto PCB signal pads (not shown).



Figure 4.6: 2D Gaussian beam profile $(\pm 3\sigma)$ distributed over nine diamond plates in a 3×3 configuration. The inner plate is segmented into 32, all outer ones in 16 strips The color code of the Z-axis denotes the relative hit density in percent (see text).

the beam is distributed over the active area with a 2D-Gaussian profile as shown in Fig. 4.6. This yields a maximum hit density of less than 2% for the shown strip segmentation. As the maximum rate scales with surface as $\frac{1}{2\pi\sigma^2}$, this mosaic would have to sustain a maximum of about $2.5 \times 10^7 \text{ mm}^{-2}\text{s}^{-1}$ in a $\sigma = 2.5 \text{ mm}$ beam of 1 GHz. In case one could use $8 \times 8 \text{ mm}^2$ diamond plates this rate would drop to $10^7 \text{ mm}^{-2}\text{s}^{-1}$ if the beam was widened correspondingly.

We plan to use 300 μ m scCVD diamonds for protons and 50 μ m pcCVDs for Au, in both cases the interaction probability is about 0.4%. Compared to a nominal target interaction rate of 1% this can produce a significant load on the CBM detector that can be minimized by adjusting the distance between the SD and target.

When a mosaic SD as described is exposed to a proton beam of $10^9 s^{-1}$ the produced radiation dose is about 10 Gy per day which is well within the established radiation hardness of the diamond. In case of heavy ions the higher radiation damage is compensated by a larger surface; a detector with $4 \times 4 \text{ cm}^2$ exposed to 10A GeV Au ions would receive a dose of about 600 Gy per day which is still within limits established in previous tests [65]. In both cases one should be able to operate the detectors over a period of months.

4.4.2 Readout electronics for the start detector

The front-end electronics (FEE) requires broadband pre-amplifiers of proper bandwidth, depending on the signal-to-noise ratio of the detector. Due to a large difference between MIP and HI signals both the detector and the FEE need to be adjusted to the particular beam. In case of high rates it is also necessary to pay attention to the pulse-pair resolving power of the discriminators. Recently a dedicated chip (PADI8d - a version of PADI8, c.f. 3.3.4) for the readout of diamond detectors was designed and produced. This ASIC will be our first choice for the FEE of SD.

The digitizers (TDCs) used for SD need to be compatible to the readout of the TOF wall. Therefore the distributed-clock common-stop system described in 3.3 has to be implemented for SD readout even if different digitizers are used. A FPGA-based TDC implemented on a TRB3 board [66]) and optimized for readout with the CBM DAQ is going to be used in this development.

The amount of data produced by the in-beam SD is directly proportional to the beam intensity and therefore too large to be stored even temporary. Therefore a data reduction and feature extraction will be implemented on the FPGA readout boards. The feature extraction is directed by the beam monitoring requests, e.g. beam profile can be generated by averaging in certain time interval, while the data reduction is driven by the SD readout and the TOF wall reaction detection. In latter case the time frame defined by prompt particles detected by the TOF wall is used as a reference frame which in an ideal case reduces the amount of data acquired from the SD to only reaction related beam particles. The actual implementation will be developed in a due time as the development of readout chain progresses.

Chapter 5

System Integration and Services

5.1 Mechanical Integration

The mechanics of the TOF wall together with all connections (cables, gas pipes etc.) has to allow for a movement of at least 12 m along the beam axis. This is necessary since different experiments and campaigns, e.g. the runs at SIS100 and SIS300 plan to use rather different target distances; but also maintenance and repair might require a short move in order to gain access to the front of the wall. Detector movements will be possible by a system of 4 rails in the floor, which are used in common by the various CBM subdetectors as depicted in Fig. 5.1. Not shown in the figure is the base plate on which the TOF Wall is mounted. From there inclined support structures will stabilize the almost 10 m high wall. These mechanical details have still to be worked out.



Figure 5.1: The CBM subdetectors TRD, TOF and PSD can be moved along the beam axis on a system of 4 rails in the floor; shown are from left, behind the magnet with the STS inside: The RICH detector (it can be moved out sideways), the TRD, the TOF wall and the PSD, set here at arbitrary distances.

However, a shifting of the wall in beam direction leads to so-called dead zones (areas without acceptance). This is demonstrated in Fig. 5.2(a) where a fraction of the wall at 10 m is seen through a small hole in the target. The overlap in between modules and MRPCs is everywhere about 2 cm. Shifting the wall to

 $6~{\rm m}$ from the target without adjusting the vertical position of some modules leads to the mentioned dead zones shown in Fig. 5.2(b).



Figure 5.2: TOF wall seen through a small hole in the target. (a) The wall is positioned 10 m from the target; the overlap in between modules and MRPCs is everywhere about 2 cm. (b) Moving the wall to 6 m without vertically adjusting the modules will result in dead zones.

In order to avoid such dead zones the suspension of the modules should allow for a easy vertical shifting. This can be realized with commercial aluminum profiles with a groove as can be seen in Fig. 5.3



Figure 5.3: Detailed view of the mounting procedure of the modules. By releasing the screws the module can be shifted in vertical direction.

A further detail visible in Fig. 5.3 is the suspension technique of the modules. The modules are screwed on the frame without galvanic contact by using Teflon washers. Therefore the galvanic contact of the module is realized by thick ground cable screwed on the indicated place and the HV-cable.

The modules are mounted onto a frame also made of industrial aluminum profiles. The size of the frame is about $15 \times 10 \text{ m}^2$. A sketch showing the wall from the front and the back presented in Fig. 5.4 and Fig. 5.5.

Thick profiles with a radiation length of 30 % ($X_{0;Al} = 8:72$ cm) are used only for the outer frame and for only one vertical bar behind each column. These bars carry most of the load. The modules are screwed on vertical thin profiles of 80 × 16 mm² cross section with a typical radiation length of 6 %. The modules are mounted in a way that they can be easily removed or replaced without dismounting other modules. After unplugging the cables the modules can be pulled out from the side like caskets.

The pictures show the mounted modules without any infrastructure. However, no infrastructure will cover the front of the active detector material. The total amount of material (only aluminum bars for



Figure 5.4: Front view of the TOF wall.



Figure 5.5: Back view of the ToF wall.

mounting) in front of the active detector area was calculated to be about 250 kg. The total weight of the frame (without modules) is about 3.0 t, about 80 % of which is concentrated outside the acceptance. Fig. 5.6 gives a flavour of the flexibility in detector arrangements proposed for the various experimental setups.



Figure 5.6: Various detector arrangements of CBM: Upper figures, left: RICH, TRD and TOF at 6 m target distance; right: the same at 10 m target-wall distance. Lower figures: RICH and TOF, the latter at the shortest possible distance and at 10 m. Through the inner hole of the wall the modules of the PSD can be seen.

5.2 Gas System

Concept

The gas supply system for CBM TOF wall will be made as a closed loop (CL) system. It consists of following units: gas supplies (1), gas mixer (2), distribution manifold (3), active volume (counters), collection manifold (4), gas purifying (5), gas analysis/monitoring unit (5), and recycling exhaust¹ (6). The overall concept is presented in block diagram in Fig. 5.7. All the active elements in the system will be controlled via the CBM EPICS-based slow control system. This will allow for logging/monitoring of all parameters of the system, their comparison to other parts of the system e.g. detector currents, and implementation of global interlocks.



Figure 5.7: Block diagram showing subsystems within RPC gas system and their mutual relations. The gas is filled into the system and recirculated after purification, in case that is needed it can be extracted and recycled. The residual gas analysis is going to be implemented via small diameter capillary pipes connecting all points of interest to the gas spectrograph.

Stainless steel pipes will be used exclusively in the gas system apart from flexible connections between manifolds and MRPC modules that will be made from PTFE (Teflon®) pipes and quick connect sealed fittings on detector in/outlets. Only distribution/collection units will be placed next to the TOF wall inside of the cave; all other units will be placed on the above levels. The positioning of the gas system units above is marked with corresponding numbers in a cross-view of the CBM building in Fig. 5.8 On the ground level there is a dedicated storage space (1) where all necessary gases for the CBM detector are stored. We use three gases for RPC detectors: isobutane C_4H_{10} , sulfur hexafluoride SF_6 , and reclin-134a CH_2FCF_3 . The isobutane and reclin-134a are delivered in cylinders as liquids and they have to be kept at room temperature in order to insure enough vapor pressure in the cylinders to drive the mass-flow controllers. At room temperature SF_6 exhibits liquid to gas phase transition at approx. 20 bar. Therefore the monitoring of the rest quantity of all gases has to be implemented via appropriate scales and not by measuring the pressure. Weights are monitored by the slow control system. For each gas we foresee connection of two independent cylinders so that continuous supplying can be maintained.

One level below the storage there is a gas mixing room (2) where gas mixtures for diverse sub-detectors are prepared. We will use calibrated dual range mass flow controllers that will allow preparation of precisely defined mixture (long-term stability better than 0.1%) in both purging (high flow) and recirculating low flow mode. A multi channel controller connected to the slow control is used as a driver for mass flow controllers. This room also houses the purification unit and gas monitoring unit (5). Also an additional

 $^{^{1}}$ We denote the purified gas that is fed back into the detector as the *recovered gas*, under recycling we assume production of original components from the gas mixture



Figure 5.8: An intended gas system placement inside of the CBM building. Red, blue, and green lines show the fresh/recovered gas supply path, used gas collection, and recycling exhaust. See text for details.

supply of nitrogen will be available to be used for purging of the gas system if required. The fresh mixed gas is first led into expansion vessel (buffer) where it is mixed with recovered gas. From here the gas mixture is led into the CBM cave some 20 m downwards. Due to the mechanical requirements of a movable TOF wall the distribution system (3) comprises two parts. The first part consists of a buffer volume connected further to mass flow controllers each supplying different detector regions chosen by the expected load during operation. The second part is the supply manifold placed on the support structure; it uses capillary impedances for the local flow regulation and connection pipes to attach modules. In this way the flow of gas trough different regions of detector can be better controlled. In addition, manifolds are used to adjust flow and compensate differences due to static pressure. The mechanical construction of modules (see section 3.1) limits the maximum overpressure that can be exerted on them to about 15 mbar relative to the cave environment. The overpressure has to be monitored and regulated (by adjusting the exhaust under-pressure) in a range 3-8 mbar. The used gas is collected trough collection manifolds (4) into a buffer and pumped back to the mixing room where it can be recirculated after necessary purification (5). Here one can collect used gas for recycling (6) or exhaust it to atmosphere in case of an emergency. The purification of the used gas starts by flushing the gas trough a molecular sieve of $5 \text{ \AA}/3 \text{ \AA}$ that will remove water vapor from the gas mixture. In the next stage activated Cu is used to remove O_2 from the mixture by chemical adsorption. In the last stage aluminum(III)-oxide is additionally used to remove rest moisture. This combination of purifiers should allow for stable operation of MRPCs. Purifying agents should have the impurities removal capacity such that nominal flow trough the gas system can be maintained (approx. 750 cm³) and in addition a two parallel columns design to allow for their regeneration during operation. To monitor the gas mixture quality samples will be taken in regular intervals from all points of interest: fresh gas input, gas supply to detector (buffer), used gas collector (buffer), gas before and after purification. The samples will be supplied to the residual gas analyzer via capillary pipes. The quadruple mass spectrometer (enclosed ion source type) with range of up to 200 amu will be used for the gas analysis.

Due to the high global-warming potential of SF_6 and R-134a, those gases are not allowed to be exhausted into atmosphere. Instead the used gas will be periodically compressed into cylinders and returned to suppliers for recycling.

In periods where the CBM experiments will not be operated for more than 4 weeks the TOF wall could be completely purged with nitrogen and kept in a preserved state.

System parameters

Typical mixture used in our system consists of 85% CH_2FCF_3 , 5% C_4H_{10} , and 10% SF_6 . The full TOF wall has an active area of 120 m² with different detectors in inner and outer regions of the wall. Due to the different load on the inner region (factor of 20 compared to outer region) it is expected that flow in the

TOF wall: Gas-System Parameters				
detector surface	120 m^2			
gas volume in the whole system	$7.2 \mathrm{m}^3$			
gas volume in the detectors	6 m^3			
gas mixture $(CH_2FCF_3:C_4H_{10}:SF_6)$	$85{:}5{:}10$ vol. $\%$			
gas-exchange rate relative to full volume	$1/\mathrm{day}$			
maximum flow (purging)	$15 \ l/min$			
nominal flow (recirculating)	4 l/min			
overpressure in modules	3-8 mbar			
detector leakage-rate	$< 0.1 { m slm}$			
max. water vapor level	1000 ppm			
max. oxygen level	100 ppm			

inner region will have to be increased in comparison to the outer region of the detector. Estimated "gas volume per detector surface" is about 50 l/m^2 . Other parameters of the system are given in Table 5.1.

Table 5.1: Main parameters of the gas system.

We expect that more than 95% of the gas mixture could be recovered and reused so that the fresh gas supplement could be kept below 400 l/day. This will however depend on the rate of buildup of other (not removed) impurities in the gas system. Since the performance of detector will be closely monitored, any change in gas quality will trigger the gas replacement cycle. We expect this replacement to take place at the rate of once per week.

5.3 Power Distribution

High-voltage (HV) and low-voltage (LV) power supply (PS) systems for the ToF Wall operation will be placed within the CBM cave in region under the HADES apparatus, therefore protected from excessive radiation by concrete blocks. Based on FLUKA simulations B the area below the active detector area is exposed to the radiation levels that cannot be sustained by the commercial off-the-shelf components. However, the suppliers like CAEN and ISEG offer radiation hard power supplies that can be used in the CBM cave, albeit by heaving control placed outside of the hot area or additionally protected. The placement directly on the TOF wall space frame below the detector active area is especially interesting for LV PSs due to the removed voltage regulators. All power supplies will be remotely controlled via CBM EPICS system.

Based on the proposed TOF wall layout (see Chapter 3), HV will be supplied to each module, while an internal HV power divider will be used to supply each individual MRPC within module. Due to the differential operation both negative and positive HV supplies are needed. This results in 2×226 HV channels. It is not yet decided if an optimization of the HV power distribution layout by using additional passive power splitters will be implemented; in such a case the number of channels could be significantly reduced at the price that current could not be monitored per each SM without implementation of a custom control system. Possible suppliers that were contacted so far are CAEN and ISEG. Since power dissipation is localized in HV mainframes that are fan-cooled, the produced heat will be removed by the cave air-conditioning system.

The LV power requirements are estimated using data given in 3.1. The conservative estimate is 20 mW/ch for FEE and 30 mW/ch for digitizer. In addition readout electronics and clock distribution are considered. For all components the power is dissipated locally; since the density of the mounted components is rather low, passive cooling is estimated for most of them. It is possible that readout boards will have active (fan) cooling implemented. We estimate that the average power dissipation is less than 50 W/m2 therefore the produced head can be removed by the cave air-conditioning system.

According to the present layout of the TOF Wall, HV and LV will be distributed around the detector using the cable duct guides mounted on the space frame. Here care has to be taken that length of the LV cables and their cross-section do not cause a high voltage drop. The LV sensing will be installed to monitor voltage on passive splitters (power rails) that will distribute the LV power to nearby electronics. The care will be taken that the proper grounding is applied assuring the safe operation and minimizing electronic noise.

Chapter 6

Physics performance

The implementations of detector geometry, detector response and track reconstruction as described in the previous sections were subjected to simulation studies of the key physics observables of the CBM experiment. These studies use the UrQMD event generator as input for a realistic environment in terms of track multiplicities and phase space distributions.

The TOF - system response is modeled in an event based fashion down to the level of detector signals of the various electronic channels. To achieve this test beam results of the default detector components (MRPC1 - MRPC4) (see chapter 3.2) have been parameterized. The parametrization includes:

- a single gap efficiency of $\sim 70\%$,
- a gaussian response of the arrival time,
- a gaussian electronic response independent for both sides of a strip,
- the charge sharing between neighbouring hits and the parametrization of the corresponding Timeover-Threshold.

The multihit behaviour of the system is modeled in a realistic way. For the case when two signals are generated within the double hit resolution time (5 ns for the GET4 TDC), only the fastest rising edge is kept for any pair of signals. The Time-over-Threshold is calculated from the first rising edge to the last falling edge.

The digits corresponding to the TDC signals for each readout channel are then fed into a clusterisation method that has been used also to test beam data and that generates so called TOF - Hits. These hits are then merged with the information from the other CBM subsystem to entities called 'global tracks' that are used as the basic structure for the results shown below.

6.1 Acceptance

The acceptance of the STS tracking system is shown in terms of reconstruction efficiency in Fig. 6.1. Only particles that are found by the STS - tracking systems can be identified by the downstream detector systems like the TOF - system. In order to do so the STS - tracks have to be matched with the TOF - hits. This is done by extrapolating the STS - tracks by a Kalman - Filter method to the TOF - detectors and assigning the closest hit (in transverse direction). This method is called "nearest neighbor" - matching. Note that the efficiencies are calculated by normalizing the correctly found tracks verified by MC-truth information by the number of all particles of a given type (as shown in Fig. 2.1) into the specific (y,p_t) - bin. To assign a particle identification tag to the registered track additional information is necessary. At this level of analysis the actual geometry of the TOF wall that supplies a velocity measurement in addition to the momentum measurement by the STS enters. Three different TOF setups that have already been shown in Fig. 2.9 aiming to optimize the experiment for different physics cases are compared in the following. The projections of these setups are shown in Figs. 6.2, 6.3 and 6.4. The main difference is the distance of the TOF - wall to the target and the presence or non - presence of additional subsystems like the TRD and the RICH system.



Figure 6.1: Tracking efficiency of the STS system for Au + Au reactions calculated with the URQMD generator at beam energies of 4 (left), 10 (middle) and 25 A GeV for protons (top), pion (2. row), positively charge kaons (3. row) and antiprotons (bottom row). Red (blue) lines are locations of constant laboratory momentum (polar angle). Note that for the simulation at 4 A GeV the magnetic field was reduced to 40% of its nominal value.



Figure 6.2: Projection of experimental setup in xz - plane for hadron measurements at SIS100, optimized for charged kaons (setup A).



Figure 6.3: Projection of experimental setup in xz - plane for hadron measurements at SIS100, optimized for antiprotons (setup B).



Figure 6.4: Projection of experimental setup for in xz - plane for di-lepton measurements at SIS300 (setup C).

The probability that the matched pairs of track and hit reflect the true identity of the reconstructed particle is discussed in the next section.

6.2 Particle Identification

10⁶ Au+Au UrQMD events at 4, 10 AGeV and 25 AGeV for the setups A, B and C were simulated and reconstructed in the framework of the CBMROOT package. The overall system TOF resolution was chosen to $\sigma_{TOF}=80$ ps. For global track matching with TOF hits the "nearest hit" mode was selected. Figure 6.5 demonstrates as example the global track distributions in the plane (p, m^2) with $m^2 = p^2(t^2/l^2 - 1)$, where p, t and l being particle momentum, time-of-flight and track length for an incident energy of 10 A GeV employing setup B. $\pm 3\sigma_p(p), \pm 3\sigma_K(p)$ and $\pm 3\sigma_{\pi}(p)$ boundaries are shown by lines.

The performance of the TOF wall can be characterized by two quantities, the efficiency and the purity. The global PID efficiency (Fig. 6.6) is evaluated as the number of properly identified particles (by MC



Figure 6.6: Global PID efficiency for central URQMD Au + Au reactions at laboratory beam energies of 4 (left), 10 (middle) and 25 A GeV for protons (top), pion (2. row), positively charge kaons (3. row) and antiprotons (bottom row). Different setups A, B and C were used for the TOF detector from left to right, respectively. The colors are following a linear scale identical to the one in Fig. 6.1. Red (blue) lines are locations of constant laboratory momentum (polar angle).

information) normalized to the number of primary tracks emitted into the specific phase space cell. Hence it is the product of survival probability (weak decays and secondary interaction), tracking efficiency in the STS, hit finding efficiency in the TOF wall and track matching efficiency. For the SIS100 setups global efficiencies in excess of 80% (given by the orange colored bins) are found in the relevant parts of phase space for protons and anti-protons. For the latter the statistics at 4A GeV (left column) is too low to make any direct statement. The measurement of kaons clearly benefits from the shorter distance of setup A (left column) as compared to setup B (center column). The phase space coverage of pions looks least convincing mostly due to the small tracking efficiency of the STS system for small momenta (see Fig. 6.1). However, it should be stressed that pions are very abundant particles and spectra can be reconstructed to very small transverse momenta.



Figure 6.7: PID purity distributions for Au + Au reactions calculated for URQMD at beam energies of 4 (left), 10 (middle) and 25 A GeV for protons (top), pion (2. row), positively charge kaons (3. row) and antiprotons (bottom row). Different setups A, B and C were used for the TOF detector from left to right, respectively. The colors are following a linear scale identical to the one in Fig. 6.1. Red (blue) lines are locations of constant laboratory momentum (polar angle).

The purity of the particle sample is shown in Fig. 6.7 and is constructed as the ratio of properly identified particles (by MC information) normalized to all track candidates found with a $\pm 3\sigma$ - interval around the nominal TOF mass (as shown in Fig.6.5). Using this simple algorithm the purity is a function of the phase space cell. For the measurement of protons at a laboratory beam energy of 4 A GeV, a purity of better than 90% can be achieved over a large fraction of phase space, for kaons the clean identification is only possible in the vicinity of midrapidity. It should be noted that the purity can be improved by introducing asymmetric momentum dependent selection gates. For the purpose of the TDR there is, however, no specific signature to optimize for. In the real experiment, optimizations are certainly possible for a kaon multiplicity selection scheme.

For the case of antiproton detection discussed below, it is observed that antiproton efficiencies are similar to proton efficiencies and that a purity in the order of 40 - 50% can be reached almost independent of the phase space cell.

6.3 First Level Event Selection (FLES) capability

One of the prime features of CBM is the goal to measure rare probes and the plan to operate at an interaction rate of 10 MHz even for the heaviest collision system, i.e. Au + Au. To make use of this



Figure 6.8: Efficiency and purity of K^+ - measurements at an incident energy of 4 A GeV for minimum bias collisions, for primary particles.



Figure 6.9: Efficiency and purity of \bar{p} - measurements at an incident energy of 10 A GeV from central collisions, for primary particles.

rate capability efficient data reduction schemes must be available in order to reduce the data rate to a manageable level. Currently a data rate of 1 GByte/s is considered an upper limit for archiving CBM data. Since the raw data flow of CBM at an interaction rate of 10 MHz is estimated to amount to at least 100 GByte/s for SIS100 experiments without the TRD subsystem and 1 TByte/s at SIS300 with a complete TRD system, efficient event selection strategies are necessary to make use of the CBM rate capability.

Of special interest are therefore the efficiency and purity of rare particle. These are shown for the setups A, B and C in Fig. 6.8 for kaons at an incident energy of 4 A GeV and in Fig. 6.9 for antiprotons at an incident energy of 10 A GeV. These particles are interesting due to the fact that their multiplicity can be used as generic event selection criterion. Events with a large K^+ - multiplicity are tagging events that have a large strangeness fraction. Events with a large \bar{p} -multiplicity can be used to select rare events containing anti-baryons.

As can be seen in the Figs. 6.8 and 6.9 the efficiency and purity depends on the choice of setup. For example the efficiency of setup A (6 m distance of TOF wall to the target) for the detection of K^+ - mesons is almost a factor 2 larger compared to setup B (10 m distance). Clearly, for a strangeness measurement at low SIS100 energies the most upstream position of the TOF wall is advantageous.

In the following only one physics example making use of the PID capability of the CBM setup relevant for the operation at SIS100 is discussed: the anti-proton measurement is presented in order to demonstrate how the TOF subsystem can be used to reduce the CBM data archiving rate and at the same time to provide unique physics opportunities.

Antiproton event selection

The knowledge about \bar{p} -production in the the SIS100 energy range is rather limited, although they represent a very interesting probe for dense baryonic matter [67].

A prediction of the excitation function for antiproton production as obtained from statistical model calculation [68] is shown in Fig.6.10. The production probability per event ($P_{\bar{p}}$) is converted into a the \bar{p} - production rate ($R_{\bar{p}}$) assuming the maximum interaction rate that CBM is designed for (10⁷ MHz). The numbers presented in Fig. 6.10 can be used to estimate the necessary run-time to measure phase



Figure 6.10: Antiproton production probability (left axis) and yield per day (right axis) at an interaction rate of 10 MHz for Au + Au collisions as function of incident beam engergy (bottom axis) and available energy in the CMS (top axis).

space distributions of antiprotons. The minimum number of particle tracks, necessary for a statement about phase space population and flow characteristics is assumed to be $N_{\bar{p}} = 10^5$. Ignoring the duty cycle of the machine the necessary run time T is then given by

$$T = N_{\bar{p}}/R_{\bar{p}} \cdot \epsilon_{\bar{p}}$$

Events containing anti-protons can be easily selected combining information from the STS and TOF subsystems of CBM. The efficiency for measuring anti-protons depends on the setup and on the incident energy and is shown differentially in Fig. 6.9 for an incident energy of 10 A GeV. Integrating over the populated phase space yields an integral efficiency for anti-proton detection in central Au + Au collisions at 10 A GeV of $\epsilon_{\bar{p}} = 36\%$, resulting in a necessary beam-on-target time of T = 40 s to archive 10⁵ antiprotons for the 10% most central collisions.

It is obvious that the physics goal of measuring 10^5 antiprotons at an incident energy of $10 \,\mathrm{A \, GeV}$ does not require the high rate capability of the CBM experiment. The goal can easily be reached by running with an interaction rate of $100 \,\mathrm{kHz}$ for $4000 \,\mathrm{s}$.

However, the beam time demands grow very large for the lower SIS100 energies since the run time scales with the cross section. Going from 10 A GeV to 4 A GeV reduces the cross section by a factor of 470, so that for a measurement with an interaction rate of 100 kHz, 22 days beam on target would be needed for a single data point. Even lower incident energies would push the demand even higher and are clearly not possible without the high rate capability of CBM and a fast event selection scheme.

That a measurement at 4 A GeV is feasible can be demonstrated by estimating the event selection rate of the FLES system based on the performance described above. The following numbers are based on the assumption that the FLES functions according to the specifications and is able to inspect all events at a 10 MHz input rate up to the particle identification - level. It is further assumed that a timing performance of $\sigma_t^{system} = 80 \text{ ps}$ can be realized in the FLES system during data taking.

The output rate is then given by

$$R_{sel} = R_{event} \cdot f_{cen} \cdot P_{\bar{p}} \cdot \epsilon_{\bar{p}} \cdot \frac{1}{\Pi}$$

with f_{cen} representing the fraction of the cross section for the event sample and Π describing the purity. The relevant numbers for the two incident beam energies are collected in Table 6.1.

incident energy (A GeV)	10	4
\bar{p} production probability	$7 \cdot 10^{-3}$	$1.5 \cdot 10^{-5}$
\bar{p} detection efficiency	36%	55%
\bar{p} purity	0.2	10^{-3}
\bar{p} selection rate @ 10 MHz	$12.6\mathrm{kHz}$	8.2 m kHz

Table 6.1: FLES selection performance (see text for details)

Since the simulation framework does not allow to generate a sufficient number of antiprotons at 4 A GeV, the performance needs to be scaled from the analysis of the situation at 10 A GeV. This is done by assuming that the background in the antiproton mass gates scales with the total multiplicity of the events. With such a selection scenario the time needed for the measurement of 10^5 antiprotons reduces by a factor of 100 with respect to running at an untriggered 100 kHz event rate, i.e. instead of 22 days, the measurement can be done in 6 hours, enabling a very interesting physics program at the lower SIS100 energies.

It should be noted that (once working) an anti-proton selection by the FLES system also selects all other anti-baryons that ultimately decay into anti-protons. Therefore the scheme described here represents a general method towards anti-matter physics with CBM at FAIR.

Similar arguments also hold for the selection of high multiplicity K^+ - events that are instrumental to archive event samples with an increased probability to discover rare clusters with large strangeness number. Details will be given in the CBM physics performance report.

Chapter 7

Prototype Developments

7.1 Rate capability studies

In high-rate experiments like CBM the rate capability of the detectors is a key issue. However, a MRPC by construction is limited in rate capability due to the resistivity of the plates. The time interval needed for a localized discharge to recharge from the glass plate is given by

$$\tau = RC = \rho \varepsilon_0 \varepsilon_r. \tag{7.1}$$

 $R = \frac{\rho d}{A}$ is the resistivity, $C = \varepsilon_0 \varepsilon_r \frac{A}{d}$ is the capacitance, ρ is the volume resistivity, d is the thickness, A is the surface, ε_r is the relative permittivity of the resistive plate, and ε_0 is the dielectric constant. Typical values for float glass are $\rho \simeq 10^{12} \Omega$ cm and $\varepsilon_r = 8$ leading to $\tau \simeq 1$ s. Assuming a charge spot on the glass surface of few hundred μ m in diameter, float glass RPCs are limited to rates about 1 kHz/cm². An analytical description of rate effects is based on the so-called DC model [69]. The average ohmic drop

An analytical description of rate effects is based on the so-called DC model [69]. The average ohmic drop \overline{IR} in the plate is related to the average voltage drop \overline{V}_{drop} in the gap by [69]:

$$\overline{V}_{drop} = V - \overline{V}_{gap} = \overline{I}R = \overline{q}\phi\rho d.$$
(7.2)

V is the applied external voltage, \overline{q} is the average charge of an avalanche and ϕ denotes the incident particle flux. Since V is a constant value the real voltage across the gap is $\overline{V}_{gap} = \overline{V}_{gap}(\phi\rho d)$. If the performance of the RPC is ruled by the average effective field \overline{V}_{gap} , then any RPC observable O is just a function of $f(\phi\rho d)$ [70]. This is the case for the efficiency. The time resolution, however, is related to the fluctuations of the field and therefore a second moment observable. Nevertheless, in first approximation the following relations for the time resolution and the efficiency hold [71]:

$$\sigma_T = \sigma_0 + K_T \overline{q} \phi \rho d \tag{7.3}$$

$$\epsilon = \epsilon_0 - K_{\epsilon} \overline{q} \phi \rho d. \tag{7.4}$$

 K_T , K_{ϵ} are positive constants depending on the RPC multi-gap structure. The second term in equations (7.3) and (7.4) determines how much the time resolution and the efficiency and thus the performance are deteriorated with the incident particle flux ϕ . One way to define the rate capability is by setting a limit at the deterioration of the resolution or the efficiency. In practice often a deterioration in time resolution of 20 ps or a drop in efficiency of 5 % is used. According to the definition given above the rate capability can be improved by minimizing the slope $K_i \bar{q} \rho d$ of the functions given in (7.3) and (7.4).

The average charge of an avalanche \overline{q} can be decreased by lowering the gap size of the RPC while keeping the same field strength. However, this leads to smaller induced signals and, hence, to a reduced signal to noise ratio. Modern MRPCs are already optimized in terms of gap size.

Another attempt to increase the rate capability is to reduce the thickness d of the resistive plate to 0.1 mm. This is a reasonable approach for small area RPCs (few cm²). However, large area RPCs suffer from the fragility of the material. Furthermore, these materials are often not produced in an industrial way which makes them more expensive. The minimal thickness for industrially produced float glass is about 0.3 - 0.5 mm.

Another possibility is to decrease the resistivity ρ by increasing the plate temperature. Float glass generally follow the Arrhenius law [72] which for narrow temperature intervals is approximately given by:

$$\rho \cong \rho_{T_0} 10^{(T_0 - T)/\Delta T},\tag{7.5}$$

where T is the temperature, ρ_{T_0} the resistivity at the reference temperature T_0 and ΔT the temperature increase required for a resistivity decrease by one order of magnitude. By increasing the temperature by 25 °C the resistivity of the float glass changes by one order of magnitude [73].

The most promising way to improve the rate capability is selecting materials with lower resistivity than float glass. During the last years two classes of materials were considered for high-rate RPCs: low resistive glass also called semi-conductive glass or chinese glass and ceramics. For ceramics the resistivity is even tunable in a certain range [74] by adjusting its composition.

Fig. 7.1 shows the rate capability as a function of $1/\rho d$ for various CBM prototypes, normalized to the typical value of float glass RPCs ($\rho_0 d_0 = 300 \text{G}\Omega/\text{cm}2$). The plot illustrates the broad spectrum of possibilities to cope with high particle rates even exceeding the CBM requirements. In the following some



Figure 7.1: Measured rate capability (maximum operating flux) for various counter types as function of $1/\rho d$ (normalized to the value of float glass) [75]

mentioned methods to increase the rate capability are elaborated in more detail. units in figure

7.1.1 Low-resistive glas

The counters MRPC1, MRPC2 and MRPC3a are exposed to a flux between 1 kHz/cm² and 25 kHz/cm². The optimal way to increase the rate capability of this counters is to use electrode materials with lower resistivity as float glass. At Tsinghua University, a stable production line of a promising new type of doped glass has been developed especially for high rate MRPCs. It is characterized by an ohmic behavior and stability under charge transport, properties that rely on a balanced admixture of oxides of transition elements. The glass is black and opaque to visible light which is commonly attributed to glass exhibiting a form of electron conductivity. Its final conductivity turns out to be very sensitive to both the initial chemical composition of the raw material and to the glass melting procedure. Different compositions and related production processes have been studied, yielding a tunable bulk resistivity in the range of 10^{10} - 10^{11} Ω cm. Fig. 7.2 shows the measured bulk resistivity of a randomly selected, 30 cm long plate as function of the position. The measurements were performed at constant-temperature in a dry box in which the temperature and the humidity could be controlled. At room temperature $(25 \ ^{o}C)$ and at a relative humidity of about 30 % the resistivity shows a mild 30 % variation around an average value of $\rho = 1.5 \times 10^{10} \Omega$ cm. The material exhibits a highly ohmic behavior up to 1 kV and follows an Arrhenius law as function of temperature according (7.5). Strikingly, it shows a (potentially usable) decrease in resistance of one order of magnitude every 28 degrees i.e. $\Delta T = 28^{\circ}C$. Its dielectric constant in the GHz-range, measured both with capacitive and transmission line techniques, shows a value of $\epsilon_r(1 \text{GHz}) = 7.5 \cdot 9.5$, just moderately higher than the one measured for float glass ($\epsilon_r(1 \text{GHz}) = 6 \pm 0.5$). Its loss-tangent of $tan\delta(1 \text{GHz}) = 0.035$ is also comparable to the one of float glass $tan\delta(1 \text{GHz}) = 0.025 \pm 0.05$ [76]. Neither we expected nor we observed any limitation for the CBM counters caused by these modest deviations with respect to float glass, neither from the point of view of signal induction, nor transmission or cross-talk.

More importantly, this new low-resistive glass shows a large stability against electrical stress: under static conditions its breakdown field is above 1 kV/1 mm (a comfortable lower bound) and its resistivity increases within an acceptable factor 2 for a density of transported charge as large as $1C/cm^2$ (34 days),

7.1. RATE CAPABILITY STUDIES



Figure 7.2: Bulk resistivity of the lowresistive doped glass as function of the position along a randomly selected sample (plate dimensions $20 \text{ cm} \times 30 \text{ cm} \times 0.11 \text{ cm},$ measured at about 25° C).

a value close to the expected CBM live-time [71], cf. Fig. 7.3. Recently we have started aging tests under dynamic conditions, i.e. directly on a (externally irradiated) RPC, and observed no discernible aging effects up to 0.05C/cm^2 (300h). This figure, still much lower than the anticipated CBM live time, does already exceed the operating live times of existing timing MRPC walls.



Figure 7.3: Longterm stability test (34 days) of the low-resistive glass, showing current (in blue, left ordinate)) and bulk resistivity (in red, right ordinate) as function of time at 28° C, for an applied voltage of 1 kV. The total integrated charge across the material was 1 C/cm².

As compared to the well-established float glass technology, low-resistive glass production is in a less mature stage of development. Similar to the former, the technique of melting and annealing is very important in order to produce glasses of high quality. But in contrast to float glass, the required surface quality of the low-resistive glass can only be achieved after a post-production polishing procedure. The roughness of the electrode introduces local field variations which may deteriorate both efficiency and time resolution [77],[78]. Since a high surface quality is required, surface measurements might be a key issue in quality control during the mass production. Here we report on the surface roughness of the glass plates, determined with a MicroXAM 3D surface profiler that can measure the surface profile and the roughness of highly-polished optical elements and rough surfaces, such as steel, paper, plastics or ceramics. A 3-D scanning image is shown in Fig. 7.4. The surface roughness can be expressed by a number of parameters which are subject to different definitions [79]. Three of the most commonly used values, evaluated over 857 μ m×638 μ m are: Average roughness 1.06 nm, peak-peak roughness 10.6 nm and ten-point height roughness 9.42 nm. For reference, the numbers for a float glass sample analyzed with the same procedure are 0.608, 8.17 and 6.22 nm, respectively.

A summary of the parameters of the low-resistance glass is shown in Table 7.1.

7.1.2 Thin glass

The counter MRPC3b and MRPC4 are supposed to have electrodes made of float glass. However, some modules are exposed to fluxes at about 1 kHz/cm^2 and slightly above (1.5 kHz/cm²) which is already



Figure 7.4: Scanned 2-D image of a glass plate.

Table 7.1: Specific parameters of the low-resistive glass.

stable up to 1 C/cm^2

critical for counters with electrodes of 0.5 mm thick float glass. Lowering the thickness of the glass plates is a possibility to increase the rate capability of this MRPCs.

In order to study the rate capability as function of the glass thickness three MRPCs with float glass electrodes (resistivity of about $3 \times 10^{12} \ \Omega cm$) with thicknesses of 0.35 mm, 0.5 mm and 0.7 mm where build. The structure of this counters is depicted in Fig. 7.5. The counters are designed in a double stack configuration with 10 gas gaps. The gas gaps are defined by nylon monofilaments and have a size of 0.25 mm. The read-out electrodes have 8 strips of $12.5 \text{ cm} \times 2.2 \text{ cm}^2$ with inter-strip gaps of 3 mm. The high voltage electrodes are covered with colloidal graphite spray, yielding a typical surface resistivity of about 2 M Ω /cm². With this prototypes beam tests were carried out at the Nuclotron of JINR at Dubna in March 2013 in a deuterium beam. The MRPCs were conditioned under high voltage for a few hours in order to attain a stable, low dark current and a low-noise working status. The preamplifiers (NINO) used in this test were set at thresholds of 1.6 V. In order to find the optimum working voltage of the three MRPCs, efficiency and time resolution were scanned as a function of the HV under a low flux of about 100 Hz/cm^2 . The results are summarized in Fig. 7.6. From this result the working voltages of the 0.7 mm MRPC, the 0.5 mm MRPC and the 0.35 mm MRPC were set to 6.8 kV, 6.7 kV and 6.6 kV, respectively. Results on the efficiency and time resolution as function of the incident particle flux up to 3.2 kHz/cm^2 With increasing rate the time resolution worsens moderately from 55 ps are summarized in Fig. 7.7. to about 75 ps up to about 3 kHz/cm^2 . The efficiencies, however, decrease linearly in all counters. For a comparison we just note the flux at which the efficiency drops below 90 % in the three modules: this happens at 0.5 kHz/cm², 1 kHz/cm² and 3 kHz/cm² for the glass thickness of 0.7 mm, 0.5 mm and 0.35 mm RPC, respectively. According this measurements and the definition of the rate capability one can assume that the counter with 0.35 mm thick float glass electrodes can handle a rate of 3 kHz/cm^2 which would fully meet the demands of the ToF wall in the region of MRPC3b and MRPC4. However, the counter was exposed only on a spot and not fully illumination which leads to an overestimation of the rate capability.

The current flowing through such an MRPC stack (5 \times 2 gaps a 0.22 mm gap size) with 0.35 mm thick float glass, however, was measured in a different beam time with heavy ions collisions where the counter was illuminated on the full surface. The exact structure of the stack is composed of 2 outer glass plates of



Figure 7.5: Strip MRPC, featuring a 10-gap 8-strip structure with float-glass electrodes of 0.35 mm, 0.5 mm and 0.7 mm thickness.



Figure 7.6: Efficiency and time resolutions of the 3 modules with different electrode thickness as function of the HV.



Figure 7.7: Efficiency and time resolutions of the 3 modules with different electrode thickness as function of the flux.

0.4 mm thickness where the HV is applied and 4 inner glass plates with 0.35 mm thickness corresponding to a total glass width of 0.22 cm. The current per unit area for different incident particle fluxes is shown in Fig. 7.8. The flux was measured with plastic scintillator in front and behind the MRPC. The flux in



Figure 7.8: Current per unit area as function of the incident particle flux.

the MRPC was determined by taking the mean of the measured fluxes. The error comes mainly due to spill fluctuations. At about 3 kHz/cm^2 the current in the chamber (across 2 stacks) per cm² is about 5

nA i.e. 2.5 nA/cm^2 . From this value one can calculate with (7.2) the voltage drop in the MRPC.

$$\overline{V}_{drop} = \frac{\overline{I}}{A}\rho d = 2.5 \cdot 10^{-9} \frac{A}{cm^2} \cdot 2.6 \cdot 10^{12} \Omega cm \cdot 0.22 cm = 1430 V.$$
(7.6)

As glass resistivity ρ we used the value quoted in [80]. The voltage drop in the MRPC is about 1500 V at about 3 kHz/cm². The average charge \bar{q} generated by a through-going particle can be calculated via:

$$\overline{q} = \frac{\overline{I}}{A} \cdot \frac{1}{\phi} = \frac{5 \cdot 10^{-9}}{3 \cdot 10^3} As = 1.7 pC.$$
(7.7)

It is about 1.7 pC which is to small for 10 Gaps. We assume that the effective voltage and thus the electric field was to low in order generate enough charge.

However, we measured the current of the MRPC also at 1.1 kHz/cm² (see Fig. 7.8). The current per area is 3.12 nA/cm^2 leading to a voltage drop of:

$$\overline{V}_{drop} = 1.56 \cdot 10^{-9} \frac{A}{cm^2} \cdot 2.6 \cdot 10^{12} \Omega cm \cdot 0.22 cm = 890V.$$
(7.8)

The charge per through-going particle is about 2.8 pC and corresponds to a value quoted in [80]. The applied voltage during this measurements across the single stack was 11 kV. Assuming a maximal rate of about 1 kHz/cm² for the counters MRPC3b and MRPC4 a voltage drop in the order of 1000 V has to be considered which should be well in the efficiency plateau of the counter. With this current measurements we conclude

7.1.3 Warming

According to Arrhenius law (7.5) the resistivity of float glass and thus the rate capability of MRPCs is highly temperature dependent. It was shown [73] that for float glass the resistivity was decreased by one order of magnitude for an temperature increase of 25° . Moreover the dependence is linear. This offer us another possibility to tune the rate capability of the counters equipped with float glass electrodes (MRPC3b and MRPC4).

In order to study the rate capability as function of the gas temperature a beam time at COSY with protons of momenta of 3.35 GeV/c was carried out. To warm up the gas the back plane of the gas box was flushed by heated water. Inside the box an MRPC3b prototype called HDMRPC-P2 (see subsection 7.2.2.2) was surrounded by 18 PT100 temperature sensors. Therefore, a full temperature control was guaranteed. In order to estimate the incident particle flux the beam profile was measured with the hodoscope. The beam had an oval 2-dimensional Gaussian shape with the RMS values of $RMS_x = 2.60$ mm in x-direction and $RMS_y = 5.87$ mm in y-direction. From these RMS values a beam cross section of about 0.4 cm² was calculated. The beam hit mainly one strip generating a so-called spot response. The incident particle rate was estimated using the scalers of the vertically positioned PMTs averaged over 200 triggers. The flux is calculated by the ratio of particle rate and beam cross section. Since the beam profile is not uniform over the full surface the calculated flux is rather an average.

Figure 7.9 illustrates the efficiency as function of the flux measured at four different gas temperatures (high voltage HV = 11.5 kV, PADI preamplifier threshold Thr. = 30 mV). The statistical error is below 10^{-6} . The systematic error is due to the temperature uncertainty 0.3 % at 27°. It rises linearly to 1.7 % at 48°. At 27 °C the efficiency starts to decrease already at 1 kHz/cm². Warming up the gas by 15 degrees seems to be sufficient to obtain a fully efficient counter. By warming up to 50 °C an efficiency of 90% is achievable for a particle flux of 15 kHz/cm².

Figure 7.10 illustrates the RPC time resolution as function of the incident proton flux for different temperatures. The systematic error is calculated from the uncertainty of the temperature. All timing signals involved are corrected for walk and for integral non-linearities of the TDC. The time resolution deteriorates as already indicated in the previous section with the flux in a logarithmic way but can be improved drastically by warming. This can be seen best from the data points between 15 kHz/cm² and 20 kHz/cm² (see also Fig. 7.11).

These results demonstrate that warming offers the possibility to improvement in rate capability of the counters equipped with float glass. Increasing the temperature to about 40° allow to operate MRPCs up to 3 kHz/cm² which is fully sufficient for MRPC3b and MRPC4.



Figure 7.9: Efficiency as function of the incident particle flux measured for the gas temperatures $\vartheta = 27 \,^{\circ}C \,(dots), 32 \,^{\circ}C \,(squares), 41 \,^{\circ}C \,(diamonds), 48 \,^{\circ}C \,(triangles)$. The errors of the efficiency are not visible since they are smaller than the symbols. The applied high voltage was set to $\pm 11.3 \, kV$ and the preamplifier threshold to 30 mV.



Figure 7.10: RPC time resolution as function of the incident particle flux measured for the gas temperatures $\vartheta = 27 \circ C$ (dots), $32 \circ C$ (squares), $41 \circ C$ (diamonds), $48 \circ C$ (triangles). The vertical error bars represent the sum of the statistical and the systematic error. The applied high voltage was set to $\pm 11.3 \text{ kV}$ and the preamplifier threshold to 30 mV.

7.2 Area coverage

7.2.1 High granularity, high counting rate MRPC prototypes

7.2.1.1 High granularity BMRPCs with fully symmetrical structure

The short BMRPC prototypes were designed and built in a completely symmetric architecture relative to the middle plane i.e. also the center anode features an isolated strip pattern for high voltage and separate readout strips. Hence, with negative HV set on the cathodes and the same value of positive HV on the anode, one needs just half of the absolute voltage for the same HV per gap, a definite advantage of such an architecture. Details of the design can be seen in the zoomed zone of Fig. 7.12.

The high-voltage and read-out electrodes have exactly the same strip structure, i.e. a 2.54 mm pitch with 1.1 mm strip and 1.44 mm gap width; the strip length is 46 mm. Three such prototypes were built,



Figure 7.11: Efficiency and RPC time resolution as function of the gas temperature. The incident particle flux is between 15 Hz/cm^2 and 22 Hz/cm^2 . The vertical error bars represent the statistical and the systematic errors. The applied high voltage was set to ± 11.3 kV and the preamplifier threshold to 30 mV.



Figure 7.12: Schematically drawing of a complete symmetrical, strip readout BMRPC counter.

each with 72 strips and an active area of 46 x 180 mm². The three counters differ as in the following description. In BMRPC1 the HV strip electrodes are in direct contact with a resistive layer deposited on the last float-glass electrode. In BMRPC2 both are in direct contact without this layer. Both BMRPC1 and BMRPC2 use float-glass resistive electrodes of 0.55 mm thickness and have 2 x 7 gas gaps of 140 μ m. BMRPC3, on the other hand, features low-resistive glass electrodes (~2.5x10¹⁰ Ω cm) [81] of 0.7 mm thickness and 2 x 5 gaps of 140 μ m; the HV strips are in direct contact with the last glass electrode. Each of these BMRPCs is housed in a separate gas-tight aluminum box.

The first in-beam tests of these prototypes BMRPC1, BMRPC2 and BMRPC3 were performed at the T10 beam line of the CERN-PS in a pion beam of 6 GeV/c where the counters have been placed behind each other. The dark counting rate of each detector was measured before the start of the measurements, as is shown in Fig.7.13. The lowest counting rate has BMRPC2, which has the high voltage electrode in direct contact with the last float glass electrode. The BMRPC3, based on low resistivity glass, has the highest dark rate but its values are still very low. The very low dark rate observed for all the three measured prototypes was reached using very good sealing between the edges of the glass electrodes and the Cu traces which distribute the high voltage trough a 12 k Ω resistor to each high voltage strip. The good quality of the resistive glass electrodes (float glass as well as low resistivity glass) plays also an



Figure 7.13: Left side: dark counting rate as a function of the HV. Right side: efficiency as a function of the HV.

important role. In some runs one of the counters was oriented orthogonal to the others in order to determine the position resolution along the strips. In this geometry we were able to tag the position along the horizontal strips by requiring a coincidence with hits in the rotated BMRPC. Signals from both counter ends were amplified and discriminated by our NINO-based differential FEE (ALICE-type) [41, 42]. Time and Time-over-Threshold (ToT) signals from 15 strips of each counter were recorded. Two pairs of plastic scintillators with 1 x 1 cm² overlap were used as active collimators; two other scintillators with 2 x 2 cm² overlap, readout at both ends, provided the time reference. Two channels of each TDC were used for the signals of both ends of a reference plastic scintillator.

The efficiency of each BMRPC is calculated as number of events with a valid time and ToT information from both ends divided by the number of triggers. The results are presented in Fig 7.13.

At lower voltages the low-resistive glass counter BMRPC3 displays higher efficiencies than the two others with float glass. Among them BMRPC1 (HV strips separated by a resistive layer from the last glass electrode) performs better than BMRPC2, where the HV strips are in direct contact with the glass electrode. However, above 2.1 kV/gap these differences have vanished, all prototypes are \sim 97% efficient. The cluster size as function of the voltage per gap is shown in Fig. 7.14. Here BMRPC2, shows a systematically lower values. At \sim 2.1 kV/gap where an efficiency larger than 95% is reached, the cluster size is \sim 3 strips, i.e. 7.5 mm.



Figure 7.14: Cluster size for the three 2.54 mm strip pitch BMRPCs as a function of the HV.

Fig. 7.15 presents the time resolution of BMRPC1 for three gas mixtures as function of the applied voltage (scintillator as reference). Adding isobutane improves the time resolution by $\sim 15\%$, at 2.1 kV/gap it is better than 50 psec. This effect could be due to the average number of clusters per mm for isobutane which is larger than that for the standard gas mixtures used for operation of the BMRPCs [82]. In the


Figure 7.15: Time resolution of BMRPC1 as function of the HV for the 3 gas mixtures mentioned in the figure; time reference are plastic scintillators.

same time the quenching effect of the UV photons in isobutane avoids producing secondary avalanches which spoil the time resolution.



Figure 7.16: Time resolution as time difference between BMRPC3 and BMRPC2, assuming that both counters contribute equally.

Fig. 7.16 shows the time resolution in different runs; plotted is the time difference between BMRPC3 and BMRPC2 under the assumption that both contribute equally. Considering that the five runs were measured over a time period of 6 hours this result confirms the stability of the system.



Figure 7.17: Position resolution along two strips; the position itself is given by a coincidence with single strips in a rotated BMRPC.

The position along the strips is derived from the time difference at both ends. In order to extract the

position resolution, we selected the tracks in coincidence with strips (pitch 2.54 mm) of the rotated BMRPC. The resulting resolution is presented in Fig. 7.17 for two strips in coincidence with 5 orthogonal strips. The resolution of ~ 4.5 mm does not depend on the position itself.



Figure 7.18: Position resolution across the strips in BMRPC3 using residual distributions relative to the track determined by all three counters, i.e. BMRPC1, BMRPC2 and BMRPC3.

The position information across the strips was analyzed in runs where all three prototypes had the same orientation. The position in one counter was determined by the tracks reconstructed by means of the two others. The hit position itself was obtained by a Gauss fit over ToT of the most significant strip and the two adjacent strips. The position resolution depends on the type of glass and the way in which the high voltage is applied (all counters were operated at 2.1 kV/gap), i.e. directly on the glass electrodes or via a resistive layer. All measured values vary between 220 μ m and 450 μ m. As an example Fig. 7.18 shows a resolution of about 400 μ m in BMRPC3 (low-resistive glass type).

7.2.1.2 High count rate test of short / increased pitch BMRPCs

The results obtained with the decribed prototypes BMRPC1, BMRPC2 and BMRPC3 in terms of time resolution and position resolution along and across the strips are very good. However, the number of channels required to equip the most forward polar angles with BMRPCs of this type is quite high, \sim 140,000 electronic channels. In order to reduce the costs, a further prototype (BMRPC4) with 5 gas gaps, 7.112 mm pitch (5.588 mm strip, 1.524 mm gap width) and 96 mm length was designed and built. The active area of 96 x 280 mm² is covered by 40 strips.

The two identical counters, BMRPC4a and BMRPC4b, feature low-resistive glass electrodes [81] of 0.7 mm thickness and 2 x 5 gaps of 140 μ m. They are mounted in a common gas box in a staggered way with an overlap of 6 mm along the strips as shown in Fig. 7.19.

High count rate tests were performed at COSY/Jülich with a proton beam of 2.5 GeV/c. The beam intensity varied between 10^4 and 10^6 protons/s. A new mother board version with an 8 channel NINO chip was used as FEE for signal processing, everything mounted on the outer side of box back plane. Altogether 64 strips were readout at both ends. Beside these new BMRPC4 prototypes the counter BMRPC3 was mounted in the beam as reference. The gas mixture was $85\%C_2F_4H_2 + 10\%SF_6 + 5\%$ iso- C_4H_{10} .

The LVDS-NINO outputs were sent to 32-channel TDCs (CAEN V1290A). The NINO ToT information was used for slewing correction and the position information across the strips. The count-rate performance of these 7.112 mm pitch prototypes is depicted in Fig. 7.20. The time resolution (full triangles) is derived from the overlap regions of BMRPC4a and 4b. The full dots denote the efficiency, i.e. the number of events with a valid time and ToT information at both ends divided by the number of triggers. Even at 100 kHz/cm² the time resolution remains better than 70 ps and the efficiency higher than 90%. These



Figure 7.19: Schematic view into the gas box with two BMRPC4 prototypes mounted in a staggered way.



Figure 7.20: Efficiency and time resolution as measured between two overlapping BMRPC4 counters) as function of count rate.

results [83] show that differential strip BMRPCs equipped with low-resistive glass electrodes are good candidates to meet for high count rate and the granularity demands of the inner ToF wall.

7.2.1.3 High counting rate test of a prototype with module architecture

A continuous coverage of the active area of the TOF wall requires a staggered arrangement of BMRPCs inside the modules. A protoptye of a module containing four identical counters inside a gas tight-box was built and tested; the active areas of the BMRPCs overlap 16.5 mm along the strips and 17.5 mm in perpendicular direction.

The arrangement of the BMRPCs inside the box and the cable routing towards the connectors is shown on the left side of Fig. 7.21. The right side shows a photo of the four counters mounted on the back flange of the box. The BMRPCs are of type BMRPC4 described in the previous section 7.2.1.2.

The lateral and the front walls of the gas box are made of 10 mm thick honeycomb sheets; these are sandwiched between two stesalit layers of 0.4 mm which are covered on the inner side by a 0.13 mm PCB. The back plate is aluminum of 12 mm thickness, it carries the support structure of the counters. All signals are led through this plate; the connectors on PCBs are glued into rectangular openings milled into the plate.

A high counting rate test of the protoptye of a module was performed in October 2012 at the SIS18 accelerator of GSI Darmstadt. The whole prototype surface was exposed to charged particles produced by Ni beam of 1.7 A·GeV on a 1 mm thick Pb target up to the highest intensity per spill delivered by SIS18. The detector was operated in a standard gas mixture of 85% C₂H₂F₄+ 5% iso-C₄H₁₀+10% SF₆



Figure 7.21: Staggered setup of four BMRPCs. Left side: schematic arrangement inside the gas box, right side: the counters mounted on the back flange of the box.

and at an electric field stenght of 157 kV/cm. Signals of 16 strips of each counter were processed by NINO fast amplifiers, their differential outputs being converted by FPGA TDCs (see section G.2). The cluster size as a function of the counting rate is shown in Fig. 7.22 - left side. A decrease of about 7% is observed. The time resolution was obtained using the time difference between two BMRPC counters



Figure 7.22: Left side - cluster size as a function of counting rate. Right side - time resolution as a function of particle rate.

overlapped along the strips, i.e. BMRPCa-BMRPCb or between two BMRPCs overlapped across the strips, i.e. BMRPCa-BMRPCc. For the first case, where the overlap is at the edge of the strip, some influence of edge effects is not excluded. After walk correction, a time resolution of ≈ 70 ps was obtained, including electronic resolution and considering an equal contribution of the two BMRPC counters. For the overlap across the strips a time resolution of ≈ 60 ps was obtained. The time resolution as a function of counting rate is shown in Fig. 7.22 - right side. A slight deterioration of the time resolution of about 5% is observed up to $3 \cdot 10^3$ particles/(cm²·s) counting rate followed by a levelling off, within the error bars, up to 10^4 particles/(cm²·s), the highest average counting rate, on the whole area of the counter, accessed in the experiment.

7.2.1.4 High counting rate test of a real size counter prototype

Based on the results obtained with the prototypes described above in section 7.2.1, a BMRPC5 prototype, close to the real sizes of the MRPC2 counter, planed to be used in M1 - M3 modules (see subsection 3.2.1), was designed and built. The prototype is based on low resistivity glass and has the same inner structure as the previous described ones, i.e. 2 x 5 gas gaps symmetric architecture. The 64 readout strips define an active area of 266 mm x 200 mm. The strip pitch is of 4.19 mm with a 2.16 mm strip width and 2.03 mm gap. The pitch configuration was chosen based on APLAC simulations such to obtain an impedance close to 100 Ω for a transmission line corresponding to the architecture mentioned above, therefore, a good matching with the input impedance of the front-end electronics. The tight gas box was built similar with that described in subsection 7.2.1.3.



Figure 7.23: Left side: Schematic 3D view of the prototype architecture inside the gas box. Right side: Photo of the prototype mounted on the back flange of the tight gas box

The measured dark counting rate of this prototype reproduced the values measured with BMRPC3 prototype described in subsection 7.2.1.1. After 2 days of conditioning under high voltage, the dark current decrease to a few nAs. The detector was operated in a gas mixture of 85% C₂H₂F₄ + 5% iso- C_4H_{10} +10% SF₆ and at an electric field strength of 157 kV/cm (2.2 kV/gap). A CAEN A1526 high voltage power supply was used. It provides both negative and positive polarities in a range of 1 - 15 kV and has 10 nA current resolution. The prototype was tested in high counting rate at the SIS18 accelerator in GSI-Darmstadt. The whole detector surface was exposed to charged particles produced by a Ni beam of 1.5 A.GeV on a 1 mm thick Pb target. The counting rate was varied by changing the spill length at the highest intensity per spill delivered by SIS18.

During the measurements, the time evolution of current and high voltage were recorded. In the off-line analysis the RPC current data has been combined with the DAQ scalers for rate estimation. The scalers were two plastic scintillators, each one readout at both ends by photomultipliers. The first scintillator was positioned in front of the BMRPC5 and the second one behind it. The mean value of the two scalers was considered in estimating the counting rate. The measured current as a function of counting rate is presented in Fig. 7.24. The largest measured current value was of about 0.037 μ A/cm² at the highest



Figure 7.24: BMRPC current as a function of counting rate.

counting rate of 105 kHz/cm^2 . The calculated voltage drop per gas gap corresponding to this current is of 33 V/gap, taking into consideration the resistivity of the glass given in subsection 7.1.1. The total voltage drop on the all five gaps is 165 V, (a voltage drop of 83 V for each polarity). However, this values would correspond to the maximum counting rate anticipated for the CBM-TOF wall (see chapter 2.2). For a counting rate of 25 kHz/cm², the calculated voltage drop per gap is only of 10 V/gap, with a total voltage drop on all five gaps of 50 V (\sim 25 V for each polarity). As the detector is supposed to be operated within the efficiency plateau, this voltage drop has no consequences on the detector performances.

resistivity for operated BMRPC were not performed. Therefore, our estimate on the potential variation is a conservative one, based on the measured current and separate measurement of the glass plate resistivity.

7.2.2 Wide strip differential demonstrator

In the current design the peripheral area of the ToF wall (cf. Fig. 3.3) i.e. all modules M4 - M6 are equipped with wide strip differential MRPCs called MRPC3a, MRPC3b and MRPC4 featuring long and wide electrode strips. In order to approach to a working design three prototypes called HDMRPC-P1, HDMRPC-P2 and HDMRPC-P3 were developed. Alternative counter designs are presented in the appendix F.2.4.

7.2.2.1 The HDMRPC-P1 prototype

In order to study possible configurations of long and wide strip MRPCs a prototype called HDMRPC-P1 with fully differential readout was developed (see Fig. 7.25). Fully differential means a configuration where the central electrode is removed i.e. the active volume is only filled with a stack of glass plates between two outer HV electrodes. The differential readout has two advantages:



Figure 7.25: A pictorial view of the cross section of this fully symmetric differential HDMRPC-P1. For more information see text.

- 1. The charge of the signal is accumulated in both electrodes (anode, cathode) and hence twice as big as for a single ended readout.
- 2. The common pickup noise on both electrodes has typically the opposite polarity and cancels out in a differential preamplifier i.e. the counter is more stable with respect to DC offset variations.

The active area of the prototype is 28 x 16.5 cm². Its active volume is subdivided by nine 0.55 mm thick float glass plates. The space between the glass plates is ensured by 220 μ m thick fishing lines. The bottom and top glass plates are coated by an industrial spray called Licron[®] [84] forming a conductive layer (surface resistivity 100 $M\Omega/\Box$). To this conductive layer the high voltage (HV) is applied via a copper strip running across the electrode (see Fig. 7.27). The end of the copper strip is bent to the back side of the signal pickup electrode. The resistivity of the electrode is high enough to be transparent for fast signals (GHz) like the ones generated in an RPC. The two outermost layers are made of 4 mm thick PCBs which act as support for the MRPC and simultaneously as pickup electrode. They contain 16 readout strips with a width of 7 mm. The distance between the strips is 3 mm. The relatively large gap leads to reduced cross talk. With a pitch of 1 cm the electrode strips have a similar size like a typical cluster pattern created in the FOPI MMRPC [53]. Between the readout strips and the HV electrode 2 Kapton[®] foils of 75 μ m thickness serve as isolation.

The counter is embedded in a gas tight aluminum box with feed through for signals, HV and gas (see Fig. 7.28). Twisted pair cables of 110 Ω impedance are soldered to the signal pickup electrode. The other end of the cables is soldered to a 34 pin connector which is plugged to the feed through of the box.

The strip configuration together with the total number of glass plates and gas gaps was simulated with APLAC [85] in order to obtain an impedance of 100 Ω . A good impedance matching with the Front



Figure 7.26: Photograph of the signal pickup electrode. The width of the strips is 7 mm. The gap in between is 3 mm.



Figure 7.27: Illustration of the high voltage electrode. A conducting layer is sprayed on a glass substrate. The HV is applied by the copper strip running across the counter.



Figure 7.28: Photograph of the HDMRPC-P1 prototype embedded in a gas tight aluminum box.

End Electronics (FEE) is necessary in order to reduce signal reflections in the counter. Measurements with a time-domain-reflectometer show on average an impedance of about 80 Ω in the active area of the MMRPC (cf. Fig. 7.29). The reflectometer measurements show additionally the impedance of the signal path starting with a 50 Ω cable. The first jump in the impedance appears at the connector to the feed through. A second spike happens inside the box. At the soldering points the impedance reaches values of up to 140 Ω . At both ends of the twisted pair cable impedance spikes happen on the soldering points. These measurements demonstrate that the signal transmission lines from the detector to the preamplifier have to be treated in terms of impedance matching equally careful as the detector itself. In the middle of the active RPC area the impedance has a dip generated by the copper strip in the HV electrode. The effect of this copper strip will be discussed in more detail later on.

Figure 7.30 shows an oscilloscope snap shot from a typical signal generated in the MRPC. The units in the graph are: x-axis \rightarrow time in 2.0 ns/dev and y-axis \rightarrow voltage in 10.0 mV/dev. The signal has an amplitude of 32 mV. The FWHM is about 500 ps and the rise time about 250 ps. After the signal reflections are visible with an amplitude below 10 mV. The reason is the impedance discontinuity between counter, cables and connections. The oscilloscope used for this measurement is a LeCroy Wavepro 7300A with 3 GHz bandwidth and 20 GS/s [86].



Figure 7.29: Impedance measurements with a time domain reflectometer. For more information see text.



Figure 7.32: Experimental setup used at

COSY in November 2010

The HDMRPC-P1 prototype was tested in two different beam times. The first beam time was carried out in August 2009 at the SchwerIonenSynchrotron (SIS18) at GSI Helmholtzzentrum für Schwerionenforschung GmbH in Darmstadt. In this beam time a proton beam with a kinetic energy of 3.5 GeV was hitting a lead target producing a secondary particles which were used for the measurement. The setup was installed below the nominal beam height under a polar angle of 5°. The flux at this angle was approximately 100 Hz/cm². The second beam test took place at the COoler SYnchrotron (COSY) at Forschungszentrum Jülich in November 2010. During this beam time protons of 3 GeV/c momentum were used. The beam was defocussed having a diameter of about 4 - 5 cm at the detector position.

Between the two beam times the RPC was slightly modified. The copper strip on the HV electrode (see Fig. 7.27) generated a deficiency in the RPC at this position. Therefore, the strip was shortened in order to protrude only 1 cm inside the coated area. A second modification was exchanging the twisted pair cables connecting the RPC strips to the feed through inside the box. The new cables had a 100 Ω impedance and on the feed through side a non-soldered connector. New PADI III preamplifier boards with individual channel threshold setting were implemented in the setup. In both beam tests a gas mixture of 85 % Tetrafluorethan ($C_2H_2F_4$), 10 % Sulfurhexafluoride (SF_6) and 5 % Isobutane (C_4H_{10}) was used. A sketch of the experimental setup is shown in the Fig. 7.31 and Fig. 7.32.



Figure 7.31: xperimental setup used at GSI in August 2009

Some test results are presented in the following.

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Efficiency

The Efficiency ε is defined as the number of detected events in the RPC N_{RPC} divided by the number of detected events in a reference counter N_{Ref} on a restricted common active area:

$$\varepsilon = \frac{N_{RPC}}{N_{Ref}} \tag{7.9}$$

The reference is in most cases the coincidence of the trigger counters since the trigger area (in our case $4 \times 2 \text{ cm}^2$) is mostly covering the active area of the RPC under investigation. A coincidence of two scintillators placed in front and behind the RPC ensures that the particle crosses the active area of the RPC. It is always possible to cut on the reference without affecting the result.

Figure 7.33 shows the trend of the efficiency as function of applied high voltage for three different preamplifier threshold settings. The threshold of PADI III is applied after the amplification of the signal. The amplification has a gain of approximately 8 i.e. a set threshold of 70 mV corresponds to a discrimination value of 8.75 mV on the input signal. At a threshold of 70 mV only one data point was taken since the efficiency value was only 64 %. For the thresholds of 30 and 50 mV a voltage scan was performed. The rise of the efficiency as function of applied high voltage in this manner is typical for MRPCs. In our case the plateau starts at 11.5 kV and defines the nominal working voltage. These measurements were performed at an incident particle flux of about 150 Hz/cm^2 . These results demonstrate that a lower threshold setting is particularly important in order to fulfill the CBM ToF efficiency requirements. The attempt to lower the threshold even further failed due to the noise level. It was found out that the noise was mainly induced in the cables between gas box and preamplifier which allow for improvements as will be discussed later in subsection 7.2.2.2. The projection of the efficiency across the strip is shown in Fig.



Figure 7.33: Efficiency of the RPC as function of the applied HV for three different preamplifier threshold settings.

7.34. The black data points correspond to the condition that strip 1 or strip 2 or strip 3 had a signal on both ends (total efficiency). The average value indicated by the arrow is about 95 %. From the blue data points (strip 3) it is possible to estimate the cross talk of the counter by evaluating the efficiency after the drop in strip 1 and strip 2. It is in the order of 3 %. The measurement of the efficiency across the readout strips was performed at an incident particle flux below 100 Hz/cm². The applied high voltage on the counter electrodes was ± 11.5 kV corresponding to a field of 130 kV/cm.

Time resolution

First results of the time resolution from the test at COSY are displayed in Fig. 7.35. It shows (left side) the TDC channel distribution of the reference system after walk correction; the resolution of 6.1 channels corresponds to $\sigma_T \approx 152$ ps. The right side shows the time difference between RPC and the reference system after walk correction with a sigma of 3.75 channels.



Figure 7.35: (a) TDC channel distribution of the reference system, (b) TDC channel distribution of the time difference between RPC and reference system; both have been corrected for walk.

The time resolution of the RPC is calculated with the formula

$$\sigma_{RPC} = \sqrt{\sigma_{ToF}^2 - (\frac{\sigma_{ref}}{2})^2} \tag{7.10}$$

resulting in $\sigma_{RPC} \approx 55$ ps.

7.2.2.2 The HDMRPC-P2 prototype

In the previous subsection it was demonstrated that the performance of the newly designed prototype (HDMRPC-P1) fulfills the CBM ToF requirements up to an incident particle flux of 100 Hz/cm^2 . However, this prototype consists of components which could still be improved. One example is the HV electrode. At the prototype HDMRPC-P1 the HV was applied by a copper strip which was glued by a conductive glue to the coated surface of the HV-electrode (cf. Fig. 7.27) It turned out that this glue subjects aging effects. This glue losses its conductivity within half a year. A further weak point of RPC-P1

was the signal connection between the counter and the preamplifier.

In order to approach a real size demonstrator (MRPC3a and MRPC3b) a fully symmetric MRPC prototype (HDMRPC-P2) with an active area of $32 \times 27 \text{ cm}^2$ and 32 read-out strips was developed. The inner structure of the counter (gap size, number of gaps, strip width, glass thickness and glass type) is identical to prototype HDMRPC-P1. Modifications were done to the signal pickup electrodes, to the high voltage electrode and in particular to the signal transmission between strip and FEE. The pickup electrode is made of a 1.6 mm thick PCB containing strips of 27 cm length. Transmission lines with 50 Ω impedance with respect to ground starting from both ends of the strips guide the signals to the connectors (see Fig. 7.36). At the end of the transmission lines 200 k Ω resistors connected to ground prevent the pickup electrode to charge up i.e. every strip has a 100 k Ω connection to ground. The connector consists of 17 L-shaped pins where the even pins have contact to the transmission lines and the odd pins are connected to ground. Therefore, the cross talk is minimized. Alternatively, it is possible to connect either a twisted pair cable of 100 Ω impedance or the preamplifier card directly to the pickup electrode. The design of the high voltage electrode was changed completely (cf. Fig. 7.36). The Licron[®] layer is now coated on the Kapton[®] foil facing the glass. The coating is done by spraying the Lycron[®] through a mask onto the Kapton[®] surface allowing for all possible geometrical shapes. On the side of the electrode a strip is coated where the HV is applied. This strip is bent to the backside of the counter and fixed with screws. A spring on which the HV cable is soldered presses on the coated surface. A photograph of the described electrodes is depicted in Fig. 7.36. On top, the HV electrode is visible and underneath the pickup electrode. In order to improve the mechanical stiffness two 6 mm thick honeycomb structured



Figure 7.36: Photograph of the coated HV electrode. The pickup electrode is visible underneath the HV electrode.

plates are placed on top of the pickup PCBs. All pieces of the RPC, beside the pickup electrode, were manufactured in the institute. The RPC was built in the clean room of GSI.

A photograph of the counter embedded in the gas tight aluminum box as it was used for in-beam tests is shown in Fig. 7.37. One preamplifier board on each side was connected directly to the pickup electrode (8 readout strips). The threshold of the preamplifier was set from outside via Inter-Integrated Circuit interface (I²C-interface). The threshold setting is common for all channels of the board. The signals from the remaining strips were routed outside the box via 100 Ω impedance matched twisted pair cables. Measurements with a time domain reflectometer (see Fig. 7.38) on strips connected via cables showed that the slightly changed geometry of the counter increased the impedance from 80 Ω to 93 Ω . In addition the spikes in the impedance (cf. Fig. 7.29) created by the soldering vanished mostly. Impedance peaks of 120 Ω are observed only at the non-twisted part of the cables. Measurements of the distribution of the signal rise time are shown in Fig. 7.39. The rise time of the signal is defined as the time which the signal needs to rise from 10 % to 90 % of its total height. The maximum of the distribution is at 200 ps. After performing two in-beam tests the normal float glass was replaced by low resistive glass described in section 7.1.1 in order to improve the rate capability. Figure 7.40 depicts the opened counter during the



Figure 7.37: Photograph of the MRPC embedded in the gas tight aluminum box. The MRPC has connectors on the pickup electrode which allow to connect either a twisted pair cable or the preamplifier card.



Figure 7.38: Impedance measurements with a time domain reflectometer. The impedance of the counter is 93 Ω . For more information see text.



Figure 7.39: Signal rise time measurements with the oscilloscope. The distribution shows a maximum at about 200 ps.

assembling of the low resistive glass. Based on results obtained during the in-beam tests (see below) it was decided to implement the preamplifier cards inside the box connecting them directly to the readout electrode of the MRPC. The preamplifier cards carrying the PADI VII discriminator are connected to a common base board. The base board distributes the power to the preamplifier cards and collects the signals. Additionally, it transmits the threshold settings via Serial Peripheral Interface (SPI). The MRPC together with the FEE mounted in the box is depicted in Fig. 7.41. HDMRPC-P2 is a full size prototype for the MRPC3a and MRPC3B counter (see section 3.2.2).

The HDMRPC-P2 prototype was tested in June 2011 at SIS 18 with low rates (about 50 Hz/cm²). The structure of the setup was similar to the one used at COSY in November 2010 (see Fig. 7.32). This time, a narrow strip MRPC prototype (see F.2.2.3) was used as a reference counter being positioned behind HDMRPC-P2. Results are presented in the following. In particular, the difference between the results obtained with the preamplifier mounted inside and outside the box are discussed in detail. The second beam test was performed in November 2011 at COSY with protons of momenta of 3.35 GeV/c. The goal



Figure 7.40: Photograph of the MRPC during the assembling of the low resistive glass. The vertical lines across the glass are the fishing line keeping the gap size of $220 \ \mu m$ fixed.



Figure 7.41: Photograph of the RPC-P2 prototype embedded in the gas tight aluminum box. The active area is 32×27 cm².

of this test was to measure the performance of the MRPC at different gas temperatures and at different rates. Results of this in-beam test are presented in section 7.1.3.

Efficiency

As reference, the coincidence of the plastic scintillators forming the trigger was used. The efficiency as function of the applied high voltage is shown in Fig. 7.42. The red data points (diamonds) represent the efficiency achieved with the preamplifier card connected directly to the readout electrode. The threshold was set remotely to 27 mV. The black data points (squares) represent the efficiency having the preamplifiers mounted outside the box. For these preamplifiers a threshold of 30 mV was used. The statistical and systematic errors are not visible since they are smaller than the symbols representing the data. The black data points can be compared to the results obtained for the prototype HDMRPC-P1 described in section 7.2.2.1 (cf. Fig. 7.33 red diamonds). HDMRPC-P2 reaches the 90 % level already at

10.8 kV in comparison to HDMRPC-P1 where the 90 % level was reached at 11.2 kV. This can be explained by the improved signal transmission. An efficiency of 95 % was reached at 11.3 kV being the nominal working voltage. Efficiency measurements done with the electronics mounted inside show slightly better



Figure 7.42: Efficiency of the RPC as function of the applied high voltage. The red (black) data points represent the efficiency obtained with the preamplifier mounted inside (outside) the box. The errors are smaller than the data symbols and therefore not visible. For more information see text.

results even if one scales them to the same threshold. A threshold scan for the preamplifiers mounted inside is depicted in Fig. 7.43 (red symbols). The two black data points stem from the preamplifiers



Figure 7.43: Efficiency as function of the preamplifier threshold.

located outside. The preamplifiers mounted inside were much more stable in terms of pick-up noise from the environment. Therefore, it was possible to lower the threshold by almost 10 mV which is actually the bigger advantage. At a threshold of 23 mV an efficiency above 97 % was achieved. The applied high voltage during the threshold scan was 11.3 kV. These results triggered the decision to mount the front end electronics as close as possible to the readout electrode of the MRPC.

Using the high granular prototype as reference edge effects can be investigated. Especially the efficiency on the border of the electric field region i.e. on the edge of the HV-electrodes is worthwhile to explore. The active area of the reference counter covered the end of the strips and beyond (cf Fig. 7.44). The efficiency was calculated by comparing the number of hits in every reference counter strip with the number

of hits in the HDMRPC-P2. The result is shown in Fig. 7.45. The efficiency on top of the HV electrode is about 95 % indicated by the dashed arrow. 2 mm from where the HV electrodes end the efficiency starts to diminish. Within 5 mm corresponding to 2 strips of the reference counter the efficiency drops from 90 to 10 %.



Figure 7.44: Pictorial view of the detector alignment used to study age effects. The active area of the reference counter covered the end of the strips and beyond. The trigger area fully covered the active area of the reference counter.

Figure 7.45: Efficiency of the test counter at the strip end. For more information see text.

Time resolution

First time resolution measurements of HDMRPC-P2 were performed at SIS 18 at low particle fluxes ($\approx 50 \text{ Hz/cm}^2$). At these particle fluxes a system time resolution of (72.3 ± 1.2) ps was measured taking only one strip of the reference MRPC and only one strip of the test MRPC into account. The preamplifiers used for these measurements were placed outside the box and the threshold was set to 30 mV. It was assumed that both detectors have the same resolution leading to a counter time resolution of $(51.2 \pm 0.9) ps$. All times were corrected for walk and TDC nonlinearities. The time distribution dt is depicted in Fig. 7.46.



Figure 7.46: Time distribution between reference RPC and Heidelberg RPC. The system time resolution σ_{sys} is 72.3 ps. Assuming both detectors have the same time resolution the system time resolution can be divided by $\sqrt{2}$ leading to a counter time resolution σ_{RPC} of about 51.2 ps.

Mean cluster size

The mean cluster size as function of the applied high voltage is shown in Fig. 7.47 for the preamplifier mounted outside the box (black squares) and for the preamplifier connected directly to the read out electrode (red diamonds). The rise of the mean cluster size as function of the applied voltage is very similar for both preamplifier locations. However, the data sample with the preamplifier mounted inside the box is offset about 0.1. At the nominal working voltage (HV = ± 11.3 kV), for example, the mean cluster size measured with the preamplifier outside the box is about 1.28 and for the preamplifier inside the box about 1.38. The effect caused by the different threshold settings is only about 40 % of the discrepancy. The main contribution (60 %) comes from the fact that the signal discriminated inside the



box does not suffer from losses in the cable and on the connectors. This effect can be seen better in Fig.

Figure 7.47: Mean cluster size as function of the applied high voltage. The red (black) data points represent the efficiency obtained with the preamplifier mounted inside (outside) the box. The errors are smaller than the data symbols and therefore not visible. For more information see text.



Figure 7.48: Mean cluster size as function of the preamplifier threshold measured with preamplifier connected directly to the readout electrode (red data points) and preamplifiers mounted outside the gas box. The trend line follows the function $f(x) = ax^b$.

7.48 where the mean cluster size is plotted as function of different threshold settings for the preamplifier mounted inside and outside the box. The trend line in Fig. 7.48 follows the function $f(x) = ax^b$. A lower threshold, which is favored in terms of efficiency, causes a bigger mean cluster size which can improve also the timing performance since the time of a single avalanche is measured on several strips. However, a bigger mean cluster size decreases the effective granularity of the counter.

7.2.2.3 The HDMRPC-P3 prototype

In order to approach to a full size prototype of MRPC4 but also for maximal size feasibility study reason a MRPC called HDMRPC-P3 with an active area of $53 \text{ cm} \times 52 \text{ cm}$ was developed. The design of the

MRPC did not change with respect to HDMPRC-P2 described in section 7.2.2.2. Changes occur only due to the bigger size. The number of readout strips increased to 56 in order to maintain a multiple of 8 preamplifier channels. Therefore, the strip width changed to 7.6 mm and the gap between the strips to 1.8 mm. The impedance of this prototype was not measured. The signal pickup electrode is depicted in Fig. 7.49. On top of the signal pickup electrode the coated HV electrode is visible. Due to the large size the HV electrode has two redundant HV connectors. In order to minimize bending and barreling honeycomb





Figure 7.49: Signal pickup electrode and on top the HV electrode of the full size prototype for the low rate region.

Figure 7.50: Photograph of the HDMRPC-P3 prototype for the low rate region.

plates of 1 cm thickness were placed on top of the pickup electrodes. In addition, the whole structure was pre-stressed uniformly before screwing. After mounting the detector in the gas tight chamber the electronics are connected to the pickup electrode. Twisted pair cables of 100 Ω impedance transmit the discriminated signals to the feed through. A photograph of the counter mounted in the gas box is presented in Fig. 7.50.

The time resolution of the reference system is (54.8 ± 0.4) ps. The time resolution of the RPC and its efficiency are derived from clusterized hits and thus from the full counter response with corrections for all known and measured dependencies. The applied corrections are: timing corrections due to different signal path length, walk, integral nonlinearities of the TDC, corrections due to the incident angle of the particles, corrections due to the velocity spread of the particles. The time-of-flight distribution derived from the RPC is shown in Fig. 7.52. The system time resolution is about (67.2 ± 0.5) ps. This results in a MRPC time resolution of (39.0 ± 1.0) ps. Note that this value contains the jitter of the whole electronics chain. These measurements were performed at an applied high voltage of ± 11 kV.

The efficiency is determined by dividing the number of clusters contributing to the time resolution (12151 events) by the number of coincidences within the 3σ cut of the reference system time-of-flight distribution (12333 events). One finds an efficiency of (98.5 \pm 0.1) %.

The distribution of the clusters on the RPC surface is shown in Fig. 7.53. The majority of the hits is located within the area which is covered by the plastic scintillators (on the RPC surface about $9.5 \times 3 \text{ cm}^2$). The outliers accounting for of about 3 % of the hits stem from particles which are either scattered in the RPC or from a shower where the particle which triggered the system was not detected by the RPC. The mean cluster size at ± 11 kV is about 1.39. The distribution of the cluster size is shown in Fig. 7.54. The cluster building algorithm does not only check if two neighboring strips have a signal. It also checks if the signals are correlated in space. The matching radius was set to 2.5 cm. The cluster multiplicity is depicted in Fig. 7.55. The mean of the cluster multiplicity distribution is about 1.26. In most cases (> 90 %) only one cluster is created per event. However, a few events show cluster multiplicities of 10 or more clusters. The reason is that sometimes the system is triggered by a particle shower.

During the cosmic ray tests a second data point at ± 10.2 kV was analyzed. The results are summarized together with the data point taken at a high voltage of ± 11.0 kV in Tab. 7.2



Figure 7.51: Time-of-flight distribution measured for the reference system. The Gaussian fit is represented by the red line. The range of the fit is 3 sigma. It amounts to (109.6 ± 0.8) ps.



Figure 7.52: Time-of-flight distribution measured for the RPC system. The Gaussian fit is represented by the red line. Sigma amounts to (67.2 ± 0.5) ps.



Figure 7.53: Spatial cluster distribution on the RPC surface. The plastic scintillator cover a surface of about $9.5 \times 3 \text{ cm}^2$. The binning of the y-axis is given in units of the strip width.



Figure 7.54: Cluster size distribution of the prototype HDMRPC-P3. The applied high voltage is ± 11.0 kV.



Applied high voltage	± 10.2 kV	± 11.0 kV
Efficiency	(94.4 ± 0.2) %	(98.5 ± 0.1) %
RPC time resolution	(43.5 ± 1.2) ps	(39.0 ± 1.0) ps
Mean cluster size	1.24	1.39
Mean cluster multiplicity	1.26	1.26

Table 7.2: Results obtained in the cosmic ray test for HDMRPC-P3.

Chapter 8

TOF Project Organization

8.1 Participating institutes

The institutes participating in the TOF project are located in China, Germany, Romania and Russia.

Beijing, China, Department of Engineering Physics, Tsinghua University (THU)
Bucharest, Romania, Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH)
Darmstadt, Germany, GSI Helmholtz Center for Heavy Ion Research GmbH (GSI)
Darmstadt, Germany, Institut fÃijr Kernphysik, Technische Universität Darmstadt (TUD)
Dresden, Germany, Institut für Strahlenphysik, Helmholtz-Zentrum Dresden-Rossendorf (HZDR)
Frankfurt am Main, Germany, Institute for Computer Science, Goethe University (IRI)
Hefei, China, Department of Modern Physics, University of Science & Technology of China (USTC)
Heidelberg, Germany, Physikalisches Institut, Ruprecht - Karls - University (UHEI-PI)
Wuhan, China, Institute for Theoretical and Experimental Physics (ITEP)

8.2 Objective of the TOF project

The aim of the project is to build the full TOF detector to be used as the main hadron identification tool in the CBM experiment starting in 2020 at SIS100 and later at SIS300.

8.3 Organization and project structure

The TOF project, led by Norbert Herrmann, Heidelberg, with the deputy leadership of NN, is structured into the following subprojects:

- Counter production (Yi Wang, THU; Y. Sun, USTC; M. Petrovici, IFIN-HH; A. Akindinov, ITEP)
- Front End Electronics (J. Frühauf, GSI; Deng Zhi, (THU); Yonjie Sun USTC)
- Readout Electronics (J. Frühauf, GSI; Ping Cao, USTC)
- Online Data Processing (Dong Wang, CCNU; S. Manz, IRI)
- ROC Production (Chiangzhou Xiang, CCNU)
- Module Assembly (I. Deppner, UHEI-PI;)
- Mechanics (W. Niebur, GSI)

- Services: Gas, LV, HV (NN, (UHEI-PI,GSI))
- Calibration/Alignment (Xianglei Zhu, THU)
- System Integration, (M. Kis, GSI;)

The project steering group, consisting of the project leader, the deputy project leader and the subproject leaders, is the decision body which discusses and decides all issues of the project in consultation with the participating institutes.

8.4 Responsibilities

8.4.1 Sharing of tasks in the construction phase

The member institutes of the TOF workgroup contribute with their individual expertise to various work packages of the TOF project. The engagement of the TOF member institutes in the construction phase is coordinated by the steering group. In the following the assignment for the various tasks is described in more detail:

- The production of the resistive glas is coordinated by the Tsinghua group. The group will also provide the quality assurance of the glass production
- MRPC counters will be produced in Beijing, Bucharest, Hefei and Moscow. The forward small angle counters are made from ceramics and will be assembled in ITEP. The MRPC1 and MRPC2 counters and the modules of type M1 M3 are manufactured in Bucharest. The Beijing group produces the MRPC3a and MRPC3b with and without low resistivity glass for modules M4 and M5. MRPC4 counters with thin window glass electrodes are fabricated at USTC in Hefei.
- The frontend chips are produced under the supervision of GSI. Quality control measurements are carried out in USTC and CCNU.
- Frontend electronics boards are designed at GSI. Production, quality control and functional tests are carried out in USTC and THU.
- Modules are assembled in Bucharest and Heidelberg, integrating the readout electronics and testing the full functionality. The work in Heidelberg will be carried out with the help of Chinese colleagues.
- The interface to the Diamond start counter (HADES) is developped and build by TUD in Darm-stadt.
- TOF specific readout controllers are developped in collaboration of IRI and GSI.
- System integration is coordinated by GSI and carried out by personal from China and Heidelberg.

The rough time lines of the various working packages are presented in Appendix D.

8.4.2 Sharing of tasks in the engineering design and prototyping phase

The activities already concluded before the submission of this document comprises all conceptual issues, which are relevant in order to assure a valid detector concept. Those are:

- 1. production and testing of counter prototypes,
- 2. production and testing of electronics prototype,
- 3. verification of streaming data readout scheme,
- 4. aging tests of semiconductive glas.

After the submission of the TDR further tests relevant for the system performance will still have to be performed. The following work packages will be addressed:

- 1. evaluation high rate load test in heavy-ion environment,
- 2. evaluation of full area response of full size prototypes with final electronics.

Depending on the results of these tests the final choices for the following components will be made:

- 1. Choice between Strip and Pad MRPCs for modules M1 M3,
- 2. Choice between single or mirrored HV stack configurations for MRPC3 and MRPC4,
- 3. Choice between GET4 or FPGA based TDCs.

The decision is to be based on a comparative study in a harsh heavy-ion reaction environment. Several test beams have already been executed (April 2014 (GSI), Oct. 2014 (GSI) or are planned Feb.2015 (SPS), Dec.2015 (SPS).

The decision of the MRPC counter design will be reached and the results will be reported in an annex to the TDR before the construction phase of those components currently planned for the beginning of 2016.

8.5 Sharing of TOF construction costs

The construction costs for the complete TOF detector system has been estimated and amounts (in 2009 prices) to approximately 6.7 Million Euro. The sharing of responsibilities for the construction of the different components and the intended taking over of costs is agreed on in the signed CBM preconstruction Memorandum of Understanding (IMoU).

The largest contribution to the TOF detector system is coming from China. The sharing of the costs includes FAIR project funds from Romania (0.8 MEuro), from Germany (0.8 MEuro) and from Russia (0.5 MEuro). Additionally funding of 1.6 MEuro will be applied by the Universities of Darmstadt, Frankfurt and Heidelberg, Germany, from the German university funding program.

The cost and funding matrix with the sharing of costs and responsibilities is presented in Appendix C in Table C.1. Note that with respect to the IMoU the contribution from Croatia and Korea have been cancelled. In total 6.7 MEuro are available for the TOF detector.

8.6 TOF project time lines and work breakdown structure

The project time line comprises three distinct phases:

- I 2007 2015 Development, prototyping and engineering design;
- II 2015 2018 Production phase: Pre-production prototypes and production of all system components;
- III 2018 2020 Installation, commissioning and begin of operation.

The breakdown and sequence of work packages during the prototype and production phases is further detailed in Appendix D.

The TOF system shall be delivered to the CBM cave and mounted starting in the last quarter of 2018. A detailed and resource loaded planning for the production, integration and installation of all required work packages is under preparation. The preliminary work breakdown structure for the construction phase shows the present planning of the time lines and dependences of the work packages. This work breakdown structure also contains the prototyping and engineering design phase and is shown in Appendix D.

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References

- [1] S. Borsanyi et al. J. High Energy Phys., 1009:73, 2010.
- [2] A. Basavov et al. arXiv:1111.1710v1, 2011.
- [3] Y. Aoki et al. Nature, 443:675, 2006.
- [4] Z. Fodor and S. D. Katz. JHEP, 0404:50, 2004.
- [5] A. Andronic et al. Nucl. Phys. A, 837:65, 2010.
- [6] K. Fukushima and T. Hatsuda. Rept. Prog. Phys., 74:014001, 2011.
- [7] T. Galatyuk, 2014. QM2014 proceedings.
- [8] A. Schmach et al. arXiv:1202.2389v1, 2011.
- [9] A. Aduszkiewicz et al. Acta Physica Polonica B, 43:635, 2012.
- [10] Nica white paper, 2011. http://nica.jinr.ru/files/WhitePaper.pdf.
- [11] W. Ehehalt and W. Cassing. Nucl. Phys. A, 602:449, 1996.
- [12] S.A. Bass et al. Prog. Part. Nucl. Phys., 41:225, 1998.
- [13] W. Cassing, E.L. Bratkovskaya, and A. Sibirtsev. Nucl. Phys. A, 691:753, 2001. E.L. Bratkovskaya, priv. comm.
- [14] A. Andronic, P. Braun-Munzinger, and J. Stachel. Nucl. Phys. A, 772:167, 2006.
- [15] P. Senger and V. Friese (Eds.). Cbm report 2012-01, 2012. http://www.gsi.de/documents/DOC-2011-Aug-29-1.pdf.
- [16] B. Friman et al., editors. The CBM Physics Book, volume 814. Springer-Verlag, Berlin Heidelberg, 2011.
- [17] Fair baseline technical report, 2006. http://www.fair-center.de/fileadmin/fair/publications_FAIR/FAIR_BTR_3a.pdf.
- [18] A. Senger, 2011. 18th CBM Collaboration Meeting.
- [19] D. Fabula and H. Lesea. MAPLD Conference, 2008.
- [20] W.F.J. Müller, 2014. 23th CBM Collaboration Meeting.
- [21] V.V. Parkhomchuck, Yu.N. Pestov, and N.V. Petrovykh. Nucl. Instr. and Meth. A, 93:269, 1971.
- [22] Yu.N. Pestov. In Proceedings of the Fourth San Miniato Topical Seminar, page 156, Singapore, 1991. World Scientific.
- [23] Ch. Neyer. In Proceedings of the Workshop on Electronics for LHC Experiments, page 383, Lisbon, 1995.
- [24] H.R. Schmidt. Nucl. Phys. B (Proc. Suppl.), 78:372, 1999.

- [25] A. Devismes et al. Nucl. Instr. and Meth. A, 482:179, 2002. and GSI Scientific Report 1998. p. 178.
- [26] Alice tdr of the tof, 2000.
- [27] E. Cerron Zeballos et al. Nucl. Instr. and Meth. A, 374:132, 1996.
- [28] P. Fonte et al. Nucl. Instr. and Meth. A, 449:295, 2000.
- [29] M. Petrovici et al. Nucl. Instr. and Meth. A, 487:337, 2002. and NIPNE Scientific Report 1999, p. 59.
- [30] P. Moreira et al. J. Inst., 5:C11022, 2010.
- [31] GBTX specifications.
- [32] http://dabc.gsi.de.
- [33] http://go4.gsi.de.
- [34] http://fairroot.gsi.de/.
- [35] http://root.cern.ch.
- [36] N. Abel et al. Internal report, 2012. https://subversion.gsi.de/cbm/rocv3spec/trunk/.
- [37] E. Bayer and M. Traxler. IEEE Trans. Nucl. Sci., 58:1547, 2010.
- [38] C. Ugur et al. *IEEE NoMe TDC Workshop*, pages 1 5, 2013.
- [39] A. Schüttauf et al. Nucl. Instr. and Meth. A, 602:679, 2009.
- [40] M. Ciobanu et al. IEEE Trans. Nucl. Sci., 54:1201, 2007.
- [41] F. Anghinolfi et al. Nucl. Instr. and Meth. A, 533:183, 2004.
- [42] F. Anghinolfi et al. IEEE Trans. Nucl. Sci., 51:1974, 2004.
- [43] K. Koch et al. IEEE Trans. Nucl. Sci., 52:745, 2005.
- [44] M. Ciobanu et al. IEEE NSS Conference Record, 978-1-4244-2714-7:2018, 2008.
- [45] M. Ciobanu et al. IEEE NSS Conference Record, N13-44:401, 209.
- [46] M. Ciobanu et al. IEEE Trans. Nuc. Sci., 61:1015, 2014.
- [47] P.-A. Loizeau. PhD thesis, University of Heidelberg, 2014.
- [48] S. Löchner, 2008. CBM Progress Report 2008, p. 52.
- [49] S. Löchner and H. Deppe. RADECS 2009 Conference Record, page 614, 2009.
- [50] S. Löchner, 2013. https://wiki.gsi.de/foswiki/pub/EE/EEMeetVortragArch/EE-2013.pdf.
- [51] 2005. CBM Technical Status Report.
- [52] H. Flemming and H. Deppe. IEEE NSS Conference Record, N15-25:322, 2007.
- [53] M. Kiš et al. Nucl. Instr. and Meth. A, 646:27, 2011. GSI Scientific Report 2007, p.226.
- [54] P. Koczoń, 2013. CBM Progress Report 2012, p. 82.
- [55] A. Akindinov et al. Eur. Phys. J. Plus, 128:44, 2013.
- [56] M. Ciobanu et al. IEEE Trans. Nucl. Sci., 58:2073, 2011.
- [57] G. Agakichiev et al. Eur. Phys. J. A, 41:243, 2009.
- [58] Kiš et al., 2006. GSI Scientific Report 2005, p. 269.
- [59] Kiš et al., 2009. GSI Scientific Report 2008, p. 245.
- [60] M. Pomorski. PhD thesis, University of Frankfurt, 2008.
- [61] O.B. Tarasov and D. Bazin. Nucl. Instr. and Meth. B, 266:4657, 2008.
- [62] W. Adam et al. Nucl. Instr. and Meth. A, 447:244, 2000.
- [63] W. Adam et al. Nucl. Instr. and Meth. A, 565:278, 2006.
- [64] W. de Boer et al. Phys. Stat. Sol. A, 204:3004, 2007.
- [65] J. Pietraszko, 2012. http://www-adamas.gsi.de/ADAMAS01/talks/pietraszko.ppt.
- [66] M. Traxler, 2006. GSI Scientific Report 2005, p. 281.
- [67] S. Teis et al. Phys. Rev. C, 50:388, 1994.
- [68] A. Andronic et al. Phys. Lett. B, 673:42, 2009.
- [69] D. González-Díaz et al. Nucl. Phys. B (Proc. Suppl.), 158:111 117, 2006.
- [70] D. González-Díaz. PhD thesis, Universidad de Santiago de Compostella, 2006.
- [71] I. Deppner et al. Nucl. Instr. and Meth. A, 661:121, 2012.
- [72] D. González-Díaz et al. Nucl. Instr. and Meth. A, 555:72, 2005.
- [73] C. Gustavino et al. Nucl. Inst. and Meth. A, 527:471, 2004.
- [74] L. Naumann et al. Nucl. Inst. and Meth. A, 635:113 116, 2011.
- [75] I. Deppner et al., 2008. CBM Progress Report 2008, p. 43.
- [76] D. González-Díaz, H. Chen, and Y. Wang. Nucl. Instr. and Meth. A, 648:52, 2011.
- [77] D. González-Díaz et al. Nucl. Phys. B, 158:111, 2006.
- [78] C. Lu. Nucl. Instr. and Meth. A, 602:761, 2009.
- [79] http://www.misumiusa.com/CategoryImages/Metric_2009_pdf/p2839.pdf.
- [80] A. Akindinov et al. Nucl. Instr. and Meth. A, 490:58, 2002.
- [81] Y. Wang, 2012. XI Workshop on Resistive Plate Chambers and Related Detectors, Frascati.
- [82] W. Riegler et al. Nucl. Instr. and Meth. A, 500:144, 2003.
- [83] M. Petrovici et al. J. Instr., 7:P11003, 2012.
- [84] https://www.techspray.com/d-5-licron-crystal.aspx.
- [85] http://www.awrcorp.com/products/innovative-technologies/aplac.
- [86] Mod. 1182.
- [87] E. Bayer and M. Traxler. 17th IEEE-NPSS Real Time Conference, page 1, 2010. and C. Ugur et al., GSI Scientific Report 2009, PHN-IS-EE-09.
- [88] A. Senger. CBM Progress Report 2011, p. 5.
- [89] The radiation source elbe. http://www.fzd.de/db/Cms?pNid=145.
- [90] R. Kotte et al. Nucl. Instr. and Meth. A, 564:155, 2006.

- [91] V. Ammosov et al. Nucl. Instr. and Meth. A, 576:331, 2007.
- [92] A. Schüttauf et al. Nucl. Instr. and Meth. A, 533:65, 2004.
- [93] H.G. Essel and N. Kurz. *IEEE Trans. Nucl. Sci.*, 47:337, 2000. http://www-w2k.gsi.de/daq/.
- [94] M. Petrovici et al. Nucl. Instr. and Meth. A, 487:337, 2002.
- [95] M. Petrovici et al. Nucl. Instr. and Meth. A, 508:71, 2003.
- [96] A. Schüttauf et al. Nucl. Phys. B, 158:52, 2006.
- [97] A. R. Forlov et al. Nucl. Instr. and Meth. A, 307:497, 1991.
- [98] F. Anghinolfi et al. Nucl. Instr. and Meth. A, 533:183, 2004.
- [99] D. Bartoş et al. IEEE NSS Conference Record, 978-1-4244-2715-4:1933, 2009.
- [100] M. Petriş et al. Nucl. Instr. and Meth. A, 661:S129, 2012.
- [101] J. Wang et al. Nucl. Instr. and Meth. A, 661:S125, 212.
- [102] J. Wang et al. J. Inst., 7:P10004, 2012.
- [103] J. Wang et al. Nucl. Instr. and Meth. A, 621:151, 2010.
- [104] F. Geurts et al. Nucl. Instr. and Meth. A, 533:60, 2004.
- [105] W.J. Llope et al. Nucl. Instr. and Meth. A, 596:430, 2008.
- [106] F. Lemke. PhD thesis, University of Mannheim, 2012.
- [107] J. De Cuveland and V. Lindenstruth. J. Phys. Conf. Ser., 331/2:22006, 2011.
- [108] S. Manz et al. J. Instr., 5:C11017, 2010.
- [109] S. Manz et al. FPL Conf. Proc., 2013. Doi:10.1109/FPL.2013.6645532.
- [110] E. Bayer and M. Traxler. *IEEE NSS Conference Record*, page 876, 2011.
- [111] C. Xiang et al. J. Instr., 8:P02002, 2013.

Appendix A

The CBM Collaboration

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Appendix B

Dose and flux distributions



Figure B.1: FLUKA calculation of for 4 AGeV Au+Au collisions at SIS-100 and the CBM experiment in electron-hadron setup.

The fluences are given per cm². The 1 month of running corresponds to 10^9 Au ions/s on a 250 μ m Au target yielding 2.6×10^{13} interactions in its 1% nuclear interaction length. 99% of the ions do not interact there but produce delta electrons.

Au+Au @ 4 AGeV, 10⁷ interactions/s, 1 month run 44.5 % magnet field



Figure B.2: FLUKA calculation of for 4 AGeV Au + Au collisions at SIS-100 and the CBM experiment in electron-hadron setup.



Figure B.3: FLUKA calculation of for 10 AGeVAu+Au collisions at SIS-100 and the CBM experiment in electron-hadron setup with reduced magnetic field.



Figure B.4: FLUKA calculation of for 10 AGeVAu+Au collisions at SIS-100 and the CBM experiment in electron-hadron setup with full magnetic field.



Figure B.5: FLUKA calculation of for 25 AGeV Au + Au collisions at SIS-300 and the CBM experiment in electron-hadron setup (full magnetic field).

Appendix C

Construction costs

	THU	GSI	TUD	UHEI-PI	IRI	IFIN-HH	ITEP	cost [kEuro]
	USTC							in 2009
	CCNU							prices
low resistivity glass plates	1210					450		1660
counters	400					250	100	750
modules				130		50		180
space frame		150					150	300
services (HV,LV,cooling)	220			220	10			450
gas system incl. controls				200				200
preamplifier/discriminator		50		300				350
digitizer and clock	100	500						600
FEE - PCBs	100			50				150
readout controler (ROC)				100	300			400
data processing board (DPB)	300			50				350
crates & cables	180			30			20	230
prototypes and tests	160							200
commissioning	20			10			20	50
spare parts	180			60			20	260
safety elements		50						50
installation		80						80
transport	30					20		50
tools, infrastructure	100			20		30		150
T_0 - system (Start, BFTC)			90				190	230
cosmics ray stand				50				50
sum	3000	830	90	1220	310	800	500	6750
		2330						
	China	Germany			Romania	Russia	total	

Table C.1: Breakdown of TOF construction costs in 2009 prices and intended sharing of construction costs between the project participants.

Appendix D

Work Breakdown Structure



Figure D.1: TOF work breakdown and milestones.

Appendix E

Alternative Solutions for Modules M1, M2 and M3

E.1 Layout of the inner part of the wall

In contrast to the modules M1, M2 and M3 this design comprises 30 modules equipped with pad MRPCs. The modules come in two versions: 24 modules called M1P and 6 modules called M2P. All modules contain the same type of MRPC, however they different in the number of MRPCs and therefore in the total active area. Their arrangement is depicted in Fig. E.1. A 2-dimensional drawing highlighting the active area and showing some dimensions is presented in Fig. E.2.

M5	M5	M4	M5	M5
M5	M5	M4	M5	M5
M5	M5	M4	M5	M5
M5	M1P	M1P	M1P	M5
M5	M1P	M1P	M1P	M5
M5	M1P	M1P	M1P	M5
M5	M1P	M1P	M1P	M5
M5	M2P		M2P	M5
M5	M2P		M2P	M5
M5	M2P		M2P	M5
M5	M1P	M1P	M1P	M5
M5	M1P	M1P	M1P	M5
M5	M1P	M1P	M1P	M5
M5	M1P	M1P	M1P	M5
M5	M5	M4	M5	M5
M5	M5	M4	M5	M5
MAE			MAE	A 45

Figure E.1: Arrangement of the modules M1P and M2P in the backup solution for the inner part of the wall.



Figure E.2: Layout of inner part of the wall equipped with pad RPCs. Red (M1P) and yellow (M2P) colored area represent the active area of the MRPCs. All modules have the same size, but do contain a different number of MRPCs.

Key numbers about the pad solution are shown in Tab. E.1 The total number of cells and due to the pad readout the total number of electronic channels is 27792. The total glass area is about 211m^2 .

E.2 Module description

Both module version (M1P and M2P) have the same gas box with the dimension $1802 \times 370 \times 110 \text{ mm}^3$. They are adapted to the design and the size of the modules M4 to M6. M1P contains 38 MRPCs with a total active area of $1524 \times 264 \text{ mm}^2$ and M2P contains 41 MRPCs with a total active area of

Module	Number	Module size	Number of	Number of	Number of	Number
notation	of		MRPCs	MRPCs	cells per	of cells
	$\operatorname{modules}$	mm^3	per module	in total	module	in total
M1P	24	$1802\times370\times110$	38	912	912	21888
M2P	6	$1802\times370\times110$	41	246	984	5904
Sum	30			1158		27792

Table E.1: Numbers and dimensions of the modules.

 $1684 \times 264 \text{ mm}^2$. The internal structure of the modules and the staggering of th MRPCs can be seen in Fig. E.3-E.5: The MRPCs are staggered in 2 rows leading to an overlap in the active area of 20 %.



Figure E.3: View into an opened supermodule containing 38 or 41 RPCs in 2 rows, each with 24 individual pads. HV connectors and gas pipes are placed at one short side of the module box



Figure E.4: Backplane of the module including the feed through for the MRPC signals. The preamplifiers are plugged outside the module box directly to the connector.



Figure E.5: Side view of pad MRPCs inside the module, explaining the overlap in an upper and lower plane. The thin lines denote the signal readout through the back flange.

The preamplifiers will be located outside the gas box. They are plugged directly on the box. The staggering of the modules and the space constrains for the electronic card is depicted in Fig. E.6. HV plugs and gas pipes lead through are placed at the short side wall of the box (Fig. E.4).

The SMs contain either 41 or 38 cells, denoted in red and yellow in Fig. E.2, respectively. In total there are 1240 modules with 24 pads, altogether 29760 electronic channels.



Figure E.6: Overlap of the modules showing the space for the preamplifier cards.

E.3 Pad MRPC description

Based on prototype (see appendix F.2.3) studies with proton and electron beams, a 24-pad MRPC has been designed with a geometry shown in Fig. E.7. It has a double stack configuration with 10 gas gaps of 0.22 mm thickness. It has an active area of $26.4 \times 4.2 \text{ cm}^2$, subdivided in 24 pads of $2 \times 2 \text{ cm}^2$ pads with 2 mm spacing in between. The MRPC consist of 4 outer and 8 inner glass plates with the dimensions $283 \times 58 \times 1 \text{ mm}^3 283 \times 48 \times 0.7 \text{ mm}^3$, respectively. The total weight of the MRPC is about 1 kg.



Figure E.7: Cut-away and side view of a pad RPC module; 38 and 41 of them, respectively, form a supermodule as shown in Fig. E.3.

Appendix F

Prototype Developments

F.1 Ceramic composites

Different ceramics have been manufactured and tested. Among those the Si_3N_4/SiC composite appeared to be a promising material for low-resistive RPC electrodes. Its bulk resistivity is tunable in a wide range from $10^7 \ \Omega cm$ to $10^{12} \ \Omega cm$, cf. Fig. F.1. This is a very important and interesting feature in view of various applications.



Figure F.1: Bulk resistivity of the Si_3N_4/SiC ceramic composite vs. the its SiC content (percentage by weight). The measurement has been performed with small samples of 3 cm diameter after a full technological manufacturing cycle.

For tests ceramic plates of $10 \times 10 \text{ cm}^2$ and $20 \times 20 \text{ cm}^2$ size and 2.0 mm thickness have been produced. The bulk resistivity of the smaller sheets, measured in their center, varies by a factor five which is considered to be tolerable. The bulk resistivity of a single sample, measured at ten equally distributed positions varies by a factor of two. The sample surfaces were polished with a resulting surface roughness of 400 nm; the tolerated thickness variation of the sheets is 10 μ m.

The bulk resistivity of 30 large plates has been measured at four different surface positions, the variation of the mean value is a factor ten, see Fig. F.2. For a number of samples the bulk resistivity has been measured at nine equally-spaced positions, it varies by a factor ten, cf. Fig. F.3.



The relative permitivity of the material has been determined by transmission-line techniques to $\epsilon_r = 12.2 \pm 0.03$ (frequency range 0.1-5 GHz). In the same frequency range the loss-tangent is tan $\delta = 0.030$. Two small probes of 5×5 cm² have been exposed at the Munic Research Reactor FRM II to non-ionizing radiation doses of the order of $10^{13}n_{eq}/\text{cm}^2$. This NIEL is compatible to the dose accumulated in the region of CBM's Silicon Tracking System in one year of operation, but two orders of magnitude higher than the one calculated for the ToF region [88]. The measurement of the bulk resistivity of both probes before and after irradiation has shown a decrease by a factor two.

In Table F.1 the main properties of Si_3N_4/SiC composites are summarized.

Maximal dimension	$[\mathrm{cm}^2]$	20×20
Bulk resistivity	$[\Omega{ m cm}]$	$10^8 - 10^{10}$
Standard thickness	[mm]	2
Thickness uniformity	$[\mu m]$	10
Surface roughness	[nm]	~ 100
Dielectric constant		$12.2{\pm}0.3$
DC measurement		Non-Ohmic bebavior
		${ m stable} > 1 { m C/cm^2}$

Table F.1: Main parameters of the Si_3N_4/SiC ceramic plates.

F.2 Area coverage

F.2.1 Strip counters with ceramic electrodes

Two identical prototypes were build containing a stack of six 2 mm thick ceramic electrodes of 10×10 cm², separated by 300 μ m mylar spacers, see Fig. F.4. The central anode is a 0.4 mm thick double-sided PCB with 8 strips of 10 mm pitch, the cathodes are formed by conductive paint on mylar foils. The ceramic plates are electrically floating. The stack is housed in a gas-tight aluminum box. With the very same layput two larger detectors with electrodes of 20×20 cm² were assembled. The gas gap is 250 or 300 μ m wide. The central anode has 16 strips of 11.25 mm pitch. The counting gas was a mixture of 85 % C₂H₂F₄ + 10 % SF₆ + 5 % C₄H₁₀ at normal pressure. The detector box was flushed with a flow exchanging the gas volume a few times per hour



F.2.1.1 High- flux detector tests

Electron beam tests at ELBE

The electron linac ELBE [89] at HZDR is able to deliver intense picosecond pulses of high brilliance and low emittance at beam energies up to 40 MeV. The beam current can be attenuated down to attoamperes which allows to form single-electron bunches of 5 ps length (see Fig. F.5), ideal for detector development and calibration. This ps pulse structure of the beam allows to use the machine RF signal as time reference for time-of-flight measurements. With the standard DAQ the accuracy of the accelerator time stamp is about 35 ps. During the accelerator commissioning and the beam setting a higher intensity in the region of a few microamps is needed. During this time the beam is guided into a shielded beam dump, afterwards the intensity is reduced by a few orders of magnitude and the beam is sent in direction to the experiment by switching off the last dipole magnet. The beam leaves the vacuum pipe through a 200 μ m beryllium window behind which the spectrometer is placed in a distance of 1 m behind the magnet.

The bunch charge is varied by changing the amplitude of the pulsed gate-potential of the electron gun. This allows for a variation of the electron rate in a wide range from 1 s^{-1} up to 10^7 s^{-1} , see Fig. F.6. The single-electron beam modus at ELBE offers the possibility to test RPCs under varying rates with single relativistic electrons which exhibit a very similar specific energy loss as minimum ionizing hadrons.



Figure F.5: QDC spectrum of a scintillation counter placed in front of the test RPC; it demonstrates that most of the 5 ps beam bunches contain one electron only. The tail at higher amplitudes is due to twoelectrons bunches.

Properties of the $10 \times 10 \text{ cm}^2$ ceramic prototype

The efficiency of the ceramics prototype with 4 gaps of 300 μ m is shown in Fig. F.7; it remains at 95 % up to a flux of $2.7 \cdot 10^5$ cm⁻²s⁻¹. This result is compared to the efficiencies of a float glass [90] and a semi-



Figure F.6: Electron beam flux vs. gate potential of the electron source of ELBE. The dependence is linear over a wide dynamic range. The flux was measured with a scintillator in front of the RPC test setup.

conductive glass RPC [91], both tested with the same setup. The efficiency of the former is surpassed by the ceramics RPC by at least two, the one of the latter still by at least one order of magnitude.



Figure F.7: Efficiency RPCscomparison ofwith different electrodematerials (ceramics, *low-resistive* andhighresistivefloat glass) in dependence of the electron flux.

The efficiency of the ceramics prototype in dependence of the gap field is depicted in Fig. F.8 for various fluxes up to $1.2 \cdot 10^5 \, \text{s}^{-1} \text{cm}^{-2}$.

The measured times have been walk-corrected by means of time vs. amplitude correlations; in order to get the pure detector+FEE resolution of a single strip also the TDC contribution has been folded out. It was determined by a self-coincidence of an R.F. start signal split into two TDC channels. The time resolution as function of the flux is shown in Fig. F.9. It is remarkably constant with about 80 ps up to $7 \cdot 10^4 \, \mathrm{s^{-1} cm^{-2}}$ and does not depend on the applied electric field within errors.

The typical cluster size in these measurements f was 3 strips, cf. Fig. F.10. The strip-wise efficiency is shown in Fig. F.11. It decreases somewhat in the outer strips; this could be due to cross talk, since here also the typical cluster size decreases to 2. This effect can probabely be improved by an optimization of the strip architecture.

The RPC signals were amplified in a 4-channel FEE card [92]. The 3-stage charge-sensitive preamplifier (gain 200 in our runs, bandwidth 1 GHz) is followed by a leading-edge discriminator with a common threshold of 100 mV at all channels. This setting allows to register primary RPC signals above 0.5 mV. Analog signals are registered for walk correction in a QDC (CAEN V965) with 25 fC/channel and 60 ns gate length. The FEE-card delivers also a fast OR for trigger purposes. The data acquisition (DAQ) runs on a small Multi-Branch System (MBS) [93]. The essential component of the DAQ is a CAEN 21-bit multihit TDC type (V1290N, NIM input) with a least significant bit (LSB) bin size of about 25 ps. The RPC is placed between 3 scintillators; one smaller (5 mm diameter) with one PMT in front of the RPC, two of $2 \times 2 \text{ cm}^2$ area with two-side readout behind the detector. A coincidence of all PMTs was used as trigger signal. The time resolution between the two last scintillators was 80 ps. The RPC and the small



Figure F.8: Efficiency of the ceramics RPC vs. gap field for the electron fluxes given in the insert.

Figure F.9: Time resolution of the ceramics RPC in dependence on the electron beam flux. The exposed detector area amounts to 10 cm^2 , covering 3 or 4 anode strips.

scintillator could be moved in common in two dimensions by means of a step motor. This allowed to scan the beam spot size; the slightly elliptical spot varied between 5 and 25 cm^2 .

Proton beam tests at COSY

Irradiation tests with 2.6 Gev/c protons have been performed at COSY/Jülich. The beam spot as measured with a fiber hodoscope had less than 1 cm diameter, the fluxes went up to $10^6 \text{ cm}^{-2} \text{ s}^{-1}$. For time reference we used two crossed plastic scintillators which were both read out on two ends. They provided a start signal with $\sigma_{START} \approx 50$ ps for low fluxes. For triggering one scintillator, also read from both sides, was placed after the RPC setup. The trigger was a coincidence between this scintillator and any of the front PMT pairs.

Properties of the 20×20 cm² ceramic prototype

Out of the prototypes with an active area of $20 \times 20 \text{ cm}^2$ a four-gap version with $250 \,\mu\text{m}$ has been tested in both electron and proton beams. A comparison of the performance in these beams is shown in Figs. F.12 and F.13. Due to the smaller gap size the detector exhibits a lower efficiency than its 100 cm² colleague with 300 μm gaps. With the higher gap voltage of 110 kV/cm the electron efficiency is still above 80 % for fluxes up to $4 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1}$ (Fig. F.12) which will certainly improve with more gaps. The proton efficiency is lower. This could be due to to the positioning of the RPC: The beam had its small focus in between two strips. The increased rate capability in case of the protons is not understood at present. Nevertheless, the comparison between the two beam tests demonstates that ceramics RPCs are able to stand rates of the order of $10^5 \text{ cm}^{-2} \text{ s}^{-1}$ without degradation in efficiency.

The time resolutions are shown in Fig. F.13. For electrons a resolution of of 70 ps (RPC and FEE together) is achieved. For the protons the result is slightly worse. After considering the different start contributions which are still contained in the values of the figure ($\sigma_{START,ELBE} \approx 30 \text{ ps}, \sigma_{START,COSY} \approx 50 \text{ ps}$) the



Figure F.10: Cluster size in a small ceramic RPC prototype. The typical cluster size is 3.

Figure F.11: Efficiency of every anode strip of the small RPC. Marked with red is the position of one of the outermost strips.

difference reduces to about 10 ps.



Figure F.12: Dependence of efficiency on the flux of electrons and protons, measured with different voltage settings.

Conclusion

Several four-gap RPC with low-resistive ceramic electrodes have been constructed and tested, featuring a size of $10 \times 10 \text{ cm}^2$ and $20 \times 20 \text{ cm}^2$, respectively. The bulk resistivity of the Si₃N₄/SiC composite can principally be tuned over five orders of magnitude from $10^7 \Omega \text{cm}$ to $10^{12} \Omega \text{cm}$. In our case material with a bulk resistivity of a few $10^9 \Omega \text{cm}$ has been chosen.

These RPCs have been exposed to electrons of 32 MeV from the ELBE accelerator at HZDR and to 2.6 GeV/c protons at COSY/FZ-Jülich. The flux has been varied over a wide range from $5 \cdot 10^0 \text{ s}^{-1} \text{ cm}^{-2}$ up to $1 \cdot 10^6 \text{ s}^{-1} \text{ cm}^{-2}$. For the smaller $10 \times 10 \text{ cm}^2$ prototypes the time resolution was about 80 ps for fluxes up to $5 \cdot 10^5 \text{ s}^{-1} \text{ cm}^{-2}$, while efficiencies above 90%. The larger $20 \times 20 \text{ cm}^2$ prototypes have reached in our tests an efficiency above 80% and time resolutions of 70 ps up to fluxes of $1 \cdot 10^5 \text{ s}^{-1} \text{ cm}^{-2}$.



Figure F.13: Dependence of time resolution on the flux of electrons and protons, measured with different voltage settings.

F.2.2 Narrow strip counters

The development of glass resistive-plate chambers with narrow-strip electrode structures started more than one decade ago [94, 92]. All prototypes at that time featured a symmetric multi-gap structure with a central electrode subdivided in long strips of 2.54 mm pitch; both strip ends were read out in single-ended mode. Promising test results with time resolutions as low as 60 ps and efficiencies above 95% came along with high position resolutions both parallel and perpendicular to the strips. The following R&D activities on detectors [95, 96] and front-end electronics [43, 40] lead to the construction of the FOPI ToF barrel [53]. With about 2500 strip electrodes (i.e. 5000 electronic channels) it covered in cylindrical geometry of almost 6 m² and was operated succesfully until 2012. Because these RPCs have commercial float-glass electrodes with a bulk resistivity of ~ 10^{12} - 10^{13} Ω cm their upper limit in rate capability is in the region of 1 kHz/cm².

In the planned CBM ToF wall one has to cope with count rates above 25 kHz/cm² at the lowest polar angles, cf. chapter 2.2. This requires timing detectors which combine high resolution and high granularity at affordable costs. Therefore the R&D activity was concentrated on the development of multi-gap RPCs with narrow electrode strips; some of the prototypes feature low-resistivity glass electrodes with a resistivity of the order of $10^{10} \Omega$ cm.

F.2.2.1 Long RPCs w. low-resistive electrodes (single-ended readout)

The first built prototype is described in [94]; it features non-commercial glass with a resistivity of the order of $10^{10} \ \Omega \text{cm}$ [97] (so-called "Pestov" glass) and was read out in single-ended mode. It was tested with a 60 Co source in the laboratory and later on with the 30 MeV electron beam at the ELBE facility at FZ Dresden-Rossendorf [90]. A cross section through the counter is shown in Fig. F.14.

Two plates of Pestov glass of 2 mm thickness and $40.6 \times 300 \text{ mm}^2$ total area are stacked on each side of the central readout electrode. This anode is a 0.5 mm thick printed circuit board (PCB) which has on each side 14 strips of 2.54 mm pitch (gap width 1.4 mm). The glass plates are separated by 0.3 mm fishing line which defines the gap size. The outermost HV electrodes are highly polished aluminium plates of 2 mm thickness. The detector was housed in a gas-tight aluminum box of 40 x 80 x 330 mm³.

Time spectra have been obtained in the laboratory from $\gamma - \gamma$ coincidences between the RPC and an NE102 plastic scintillator (1 cm diameter, 1 cm height) coupled to an XP2972 photomultiplier. The detector was operated at a HV of 2.9 kV per gas gap. The counter volume was flushed with a gas mixture of 85% C₂H₂F₄+ 5% iso-C₄H₁₀+10% SF₆ at atmospheric pressure. As electronics we used the first generation of a four-channel amplifier/discriminator card (FEE1) developed for the FOPI experiment; it provides the time and charge information for each channel [40]. The mean time (t_{left} + t_{right})/2 of each strip measures the time of flight relative to the scintillator time; the time difference between the two ends delivers the position along the strip. An intrinsic RPC time resolution of 93 ps ± 10 ps is obtained after subtracting the contribution of the reference scintillator .

Further detailed tests were performed at the ELBE facility with an electron beam of 30 MeV. Electronics, gas composition and HV settings were the same as in the laboratory tests, as well as the analysis methods; as time reference the R.F. signal of the accelerator was used which delivers micro-pulses of ~ 5 ps duration.



The dependence of the time of flight on the integrated charge before slewing correction is presented for one strip in the upper left panel, the corrected data in the upper right panel of Fig. F.15. The TOF spectrum after correction is shown in the lower left panel, the fit delivers a resolution of 58 ps. By selecting events with the highest charges the time resolution improves to 52 ps (the electronics resolution always included). The time resolutions of the four measured strips are shown in the left part of Fig. F.16. The difference in the time resolutions of the strips is attributed to the difference in time resolution between the electronic channels. It should be stressed that these results have been obtained under an uniform illumination of the whole counter with a particle flux of 975 Hz/cm² in contrast with tests with minimum ionizing hadrons where only a small part of the active area is exposed.

The right panel of Fig. F.16 displays the RPC count rate versus electron beam current. The linear curve shows that the electric field inside the gas gaps is not significantly reduced by a possible perturbation of the electrical potential of the electrodes at count rates up to 9 kHz/cm². Thus any saturation effect, if present, should show up at higher intensities only.

F.2.2.2 Long RPCs w. low-resistive electrodes (differential readout)

A second prototype with Pestov glass was built in an architecture designed for differential readout. This kind of readout delivers two-times higher amplitudes and is potentially less sensitive to pick-up of external noise. A cross section through the counter structure is shown in Fig. F.17.

The prototype has two gaps of 300 μ m on each side of the central readout electrode. All six electrodes are made of Pestov glass. The central double-sided readout electrode, the anode, is a 0.6 mm PCB with 16 strips on each side. A 200 μ m mylar foil is used as insulator between the high-voltage plane and the cathode read-out strips in order to prevent leakage currents due to imperfections in the printed circuit



Figure F.16: Left: The time resolutions of the four measured strips. Right: Dependence of the RPC rate on the electron beam current.



Figure F.17: Crosssection through a symmetric double-gap RPC with Pestov glass plates, designed for differential readout

layer. The HV electrodes have the same strip structure as the readout electrodes; the HV strips are in contact with the last glass plate. The outermost readout electrodes, the cathodes, are made out of a 1.2 mm thick PCB with the same strip structure on their inner side as the anode. The corresponding strips on the two sides of the central anode and the corresponding strips of the two outer cathodes are connected together. The two signals, induced on the central and outer corresponding strips are transported from each strip end via twisted cables through flanges in the gas box to the differential amplifiers.

Again the prototype was tested first with a 60 Co source in the laboratory with 3.2 kV/gap and the standard gas mixture (85% $C_2F_4H_2 + 10\%$ SF₆ + 5% C₄ H_{10}). The signals have been amplified by fast differential amplifiers/discriminators with the NINO chip, developed within the ALICE Collaboration [98]. After this they were fed through a home-made LVDS-NIM convertor into LeCroy 2228A TDCs. The resulting time resolution was 99 ps (after subtraction of the contribution of the plastic scintillator). The in-beam test of the prototype was performed at ELBE together with that of the single-ended strip type. The electron energy was 28 MeV, the RPC was operated at 2.7 kV per gap. Only two strips could be read out on both sides since the number of electronics channels was limited. The correlation between the time of flight t=1/2(t_{left} + t_{right})-T_{ref} and TOT (time-over-threshold) delivered by the NINO amplifier is shown for one strip in Fig. F.18 together with the time spectra, both before and after correction. The rate was ~1900 electrons \cdot cm⁻² \cdot s⁻¹ over the whole area of the counter. The Gaussian fit of the corrected time distribution delivers a time resolution of 39 ps which has been measured separately has been subtracted.

The time resolution as function of the count rate can be followed in Fig. F.19. No degradation of the time resolution was observed up to rates of about $16 \cdot 10^3$ electrons $\cdot \text{ cm}^{-2} \cdot \text{s}^{-1}$. Since only two strips of the counter were operated, it was not possible to assess the counter efficiency as function of the count rate.

This new differential architecture of a strip RPC with low-resistive glass electrodes maintains a 80 ps time resolution up to a uniform illumination of 16000 particles $\cdot \text{ cm}^{-2} \cdot \text{s}^{-1}$ [99] over the whole surface of 4 x 30 cm².



F.2.2.3 Short RPCs w. float glass (differential readout)

The low polar-angle region of the TOF wall has to cope with high count rates (up to 25 kHz/cm²) and high multiplicities (up to 1000 tracks/event at 25A·GeV Au+Au collisions). This requires highly-granular detectors able to stand these rates. Based on the results bescribed above, another MRPC version with a high-granularity strip structure and thin float glass electrodes has been built and tested.

Fig. F.20 shows a cross section through this counter which features 2 x 5 gaps of 140 μ m [100].

On each side of the anode there are 6 electrodes of commercial float glass, 0.5 mm thick, with a resistivity of the order of $\sim 10^{12} \ \Omega \cdot cm$. The HV electrodes are PCBs which have on their inner side the same strip pattern as the readout electrodes. Their metallic strips are in contact with the last glass plate. An extra layer of mylar of 100 μ m is used between the high voltage and the cathode read-out layers. All readout electrodes (the cathodes and the central, double-sided anode) feature a 2.54 mm pitch with 1.1 mm width and 46 mm strip length.

The cathodes are PCBs of 1.5 mm thickness, the anode and the HV electrodes are 0.6 mm thick. The active area of the prototype comprises 72 readout strips, covering 46 x 180 mm². The corresponding strips on the two sides of the central anode and of the outer cathodes are connected together as shown in Fig. F.20. The signals from the anode and the connected outer strips are led via twisted cables and connectors through the walls of the gas-tight aluminum box to differential amplifiers.



Figure F.20: Schematical structure of the differential RPC with 2 x 5 gaps.



Figure F.21: Left: time spectrum, RPC vs. plastic. Right: time spectrum, plastic vs. plastic.

Preliminary tests performed in the detector laboratory with a 60 Co source showed a 96 ps time resolution after subtracting the contribution of the reference scintillator.

Further tests were performed at GSI with protons of 3.1 GeV/c on a Pb target. Two identical RPCs were mounted on a movable platform below the primary beam i.e. the counters were exposed to reaction products. RPC1 had its strips horizontally, RPC2 was rotated by 90° . Two plastic scintillators (Pl1 and Pl2) of 1 x 2 cm² cross section and 100 mm length, readout by R9800 Hamamatsu photomultipliers, served as beam triggers. Each was positioned in front of one RPC; mounted cross-wise they defined by their overlap a beam spot of 2 x 3 cm² on the center of 15 strips on each RPC.





The differential front-end electronics was based on the NINO chip which delivers time and time over threshold (ToT) used for the walk correction. The discriminated signals were fed through a home-made LVDS-NIM converter into a 32-channel CAEN V1290A. The front-end electronics was identical to the one used in the source measurement. Both ends of 15 strips were recorded for each counter. The scintillator times were digitized as reference in the same TDC as the channels from the corresponding RPC. Both counters were operated with the same gas mixture and high voltages between 1.9 kV/gap and 2.02 kV/gap. The distribution of the fired strips (RPC1) in one run is shown in Fig. F.22. The 3 cm overlap of the scintillators covers 12 strips of RPC1 almost uniformly; only the first two and the last strip exhibit a lower number of counts as a result of the cluster size or scattered particles.



Figure F.24: Left: Time resolution for a HV of 9.5 kV (1.9 kV/gap) in 5 strips of RPC1. Right: Time resolution for 10.1 kV (2.02 kV/gap) in 3 strips of RPC2.

The dependence of the time of flight on time over treshold before and after slewing correction is presented for one strip in Fig. F.23 together with the corresponding time spectra. Reference is the mean time $t_s = (t_{Pl1}+t_{Pl2})/2$ of the two plastic scintillators with a time resolution of 50-60 ps, determined under a narrow cut on one RPC strip. Typical time resolutions (after subtracting the reference contribution) of various strips are shown in Fig. F.24 for the two RPCs operated under different high voltages.

F.2.3 A pad RPC with low-resistive electrodes

F.2.3.1 Structure of the pad RPC

With fluxes up to 25 kHz/cm² in central Au+Au collisions at 25A GeV the particle density reaches values of about $0.01/cm^2$ in the innermost ToF wall regions. An alternative to the proposed strip designs could



Figure F.25: Pad RPC, featuring a 10-gap structure with 2 x 6 electrodes.

be small-pad RPCs as cells in the future super modules. A corresponding prototype has been developed, cf. Fig. F.25.

The counter has 10 gas gaps and consists of two symmetric stacks of plates made of 0.7 mm-thick lowresistive glass with a resistivity of about $2 \times 10^{10} \Omega$ cm. It has 6×2 pads of $2 \ge 2 \text{ cm}^2$ with gaps of 2 mm in between (occupancy < 5%). The gas gaps are 0.22 mm, defined by nylon monofilaments. The HV electrodes are covered with colloidal graphite spray, yielding a typical surface resistivity of about $2 \text{ M}\Omega/\text{cm}^2$. As in case of a strip counter, it can be considered as a super-imposed structure of two 5-gap MRPCs mirrored with respect to the inner electrodes, which allows to easily provide the same (negative here) HV to 'both' chambers. The positive HV is applied to the outer electrodes.

F.2.3.2 Performance

Electron beam test

The electron beam test was performed at ELBE. The test setup was similar as for the strip counter and we follow the same analysis procedure (cf. section F.2.1.1). The dark rate of the test module (RPC#1) was around 1 Hz/cm² at 110 kV/cm. The dark current was below 0.1 nA/cm². Efficiency and time resolution were scanned as function of the HV at a low particle flux. Since the counter area did not fully cover the beam spot in vertical direction, an auxiliary thin scintillator (S6) was used to reduce the trigger area in order to obtain the scaling factor for the efficiency (×1/0.85). The result is shown in Fig. F.26. The typical slewing correction in the time vs. charge plane which have been applied in the analyses and resulting time distributions are shown in Fig. F.27. The average particle flux was 28 kHz/cm² as measured with the S5 scintillator and 17 kHz/cm² in the RPC. The mean cluster size at a typical working voltage is 1.2, which we believe could be reduced by improving the connections between the counter and the electronics.

Although a precise position scan is hardly feasible in a low-energy electron beam, we have studied the dependence of the RPC performance on the position within our (limited) trigger conditions, obtaining a statistical spread of 71.5 ± 3.5 ps at 25 kHz/cm²; for this we have combined the performance of all 12 pads as measured in separate runs (Fig. F.28). The pad efficiency is more sensitive to a beam-detector misalignment and geometrical inefficiency, however the counter efficiency was observed to be well within a 2 % variation when the trigger was centered with respect to any of the 4 central pads. We note that the effective area A^* over which the rate is spread (eq.2), extends well beyond the pad boundaries (pad area =2.2 cm x 2.2 cm =4.84 cm², $A^*=4\pi$ (1.1 cm x 1.5 cm)=20 cm²). Therefore the present conditions represent, for low rates, a reasonable first-order approximation of the counter performance under the final uniform use-case, as far as the effect of signal loss at the pad boundaries is concerned. Counter non-uniformities, beyond this intrinsic limitation of multi-cell readouts that stems from the shape of the induction profile, can be shown to be small through the afore-mentioned pad scan and results admit a direct extrapolation to the strip counter due to the similar architecture.

The high-flux behavior i.e. efficiency and time resolution as function of the particle flux of two pad counters is shown in Fig. F.29. RPC#1 has a gas gap of 0.22 mm. It has electrodes with a bulk resis-



Figure F.26: Efficiency and time resolution of the pad RPC as function of HV.



Figure F.27: Correlations of time vs. charge and projected time spectra of the pad counter RPC#1. Upper row: Before, lower row after slewing correction.



Figure F.28: Time resolution for each pad at 2 typical particle fluxes (5 and 25 kHz/cm²). The beam profile, denoted by the shadowed oval has been chosen in all these measurements to be centered with respect to the pad under study (by remotely moving the counter platform). The AOI used to estimate the quoted average flux $\overline{\phi}$, is illustrated by dashed lines. Except for the pad scan whose numerical results are shown in the figure, the actual relative alignment between beam and RPC for all measurements of the pad response presented in this work is the one sketched in the figure (and similarly for the strip counter). The AOI for the flux determination in the efficiency study is taken to be the full active size of the detector itself.

tivity of the order of $10^{10} \Omega$ cm, designed for the usage in high-flux regions of the wall. RPC#2 has a similar structure as RPC#1 but gas gaps of 0.25 mm. Its electrodes have a bulk resistivity on the order of $10^{11} \Omega$ cm, it is shown here for comparison. It can be seen in the figure that the maximum tolerable particle flux is around 75 kHz/cm² for the pad counters made of low-resistive glass; here the resolution surpasses a 40 ps and the efficiency falls short of 90 %. Concerning the the beam profile uncertainty $(A_{RPC}/A_{S5} \sim 1.2), 55$ - 65 kHz/cm² is a pertinent estimate of the rate capability.

Deuteron beam test

The pad counters were also tested with a 1 GeV deuteron beam at JINR in Dubna. The test setup is shown in Fig. F.30. A common trigger condition (7 cm x 7 cm) is determined by the coincidence $S2 \land SFFD \land S3 \land S4$. An even smaller trigger area (3 x 3 cm^2) can be obtained by selecting particles on one FFD (FFD1 and FFD2) cell. The reference time is defined by the average time of FFD1 and FFD2, featuring a resolution of 30 ps. The time-of-flight is given through the time difference between the RPC and the reference time. The beam profile was measured by means of the drift chambers, showing a 2-D gaussian shape of $\sigma_x = \sigma_y = 3.6$ cm. Without multiple scattering effect, the beam profile is assumed to be identical everywhere.

The efficiency and time resolution were scanned as a function of the high voltage, see Fig. F.31. The optimized working voltage of 6.0 kV. In order to study the rate capability, the performances were scanned as function of the flux. Fig. F.32 shows the results.

Summary

The requirements of the inner-most region of the ToF wall, namely, 80 ps time-of-flight resolution at 90 % efficiency for fluxes up to 20 kHz/cm², have been fulfilled by the presented pad RPCs equipped with the newly developed Chinese doped glass. Using the flux as determined by external reference scintillators, these counters can run with tolerable performance degradation up to 80 kHz/cm². The requirements of the outer-most regions of the wall can be achieved by RPCs with standard thin float-glass electrodes. The performances of pad- and wide-strip counters are summarized in Table F.2.

As a summary, the developed real-size prototypes are able to operate at the required 90 % efficiency and 80 ps time of flight resolution under fluxes at least two times higher than the ones expected in the future ToF wall of CBM, thus providing a comfortable safety margin for operation.



Figure F.29: Measured efficiencies and time resolutions for two 12-pad counters as a function of the flux of 30 MeV electrons. RPC#1 has low-resistive electrodes (bulk resistivity $10^{10} \Omega cm$), the electrodes of RPC#2 have a resistivity of $10^{11} \Omega cm$.



Figure F.30: Schematic view of the deuteron-beam test setup. The beam trigger was defined by the coincidence $S2 \land SFFD \land S3 \land S4$. The drift chambers were used to measure the beam profile.

F.2.4 Long wide-strip counters

F.2.4.1 RPCs with low-resistive electrodes

A real-size module:

In order to develop an backup solution for MRPC3a a 3-strip prototype of such a strip RPC with lowresistive glass electrodes was developed at Tsinghua and has already been tested with both proton (2009 at GSI) and electron beams (2011 at HZDR). The results indicate a rate cdcapability up to 25 kHz/cm² [101, 102]. At the moment we are working on scaling the 3-strip module to larger sizes; as an example a full-size 8-strip module is depicted in Fig. F.33. The counter has 10 gas gaps and consists of two stacks


Figure F.31: Efficiency and time resolution as function of the high voltage.



Figure F.32: Efficiency and time resolution as function of the average flux of 1 GeV deuterons.

of 0.7 mm thick low-resistive glass plates with a resistivity of about 2 ×10 10 Ωcm. It features 8 strips of 12.5 cm×2.2 cm with inter-strip gaps of 3 mm. The gas gaps are 0.25 mm wide, defined by nylon monofilaments. The high voltage electrodes are covered with colloidal graphite spray, yielding a typical surface resistivity of about 2 MΩ/cm².

	Strip RPC	Pad RPC $\#1$	Pad RPC $\#2$	Strip RPC
Electrodes	8 strips	12 pads	12 pads	8 strips
Resistive material	Low-resistive	Low-resistive	Low-resistive	thin Float
$ ho[\Omega cm]$	10^{10}	10^{10}	10^{11}	$10^{12} - 10^{13}$
Glass thickness [mm]	0.7	0.7	0.7	0.35
N _{gaps}	10	10	10	10
Gap size [mm]	0.25	0.22	0.25	0.25
Cell size $[cm \times cm]$	12.5×2.5	2.2×2.2	2.2×2.2	12.5×2.5
Electron beam $@$ 30 MeV				
Field [kV/cm]	109	110	110	-
Dark rate $[Hz/cm^2]$	< 3.5	<2	<3	-
Dark current $[nA/cm^2]$	< 0.05	$<\!0.05$	< 0.1	-
σ_T [ps]	42	45	50	-
ϵ	> 0.95	> 0.97	> 0.97	-
$\phi_{max}~(\sigma_T{<}80{ m ps})~[{ m kHz/cm^2}]$	30	70	25	-
$\phi_{max}(\epsilon{>}0.9)~[m kHz/cm^2]$	100	100	15	-
Deuteron beam @ 1 GeV				
Field $[kV/cm]$	107	110	-	106
Dark rate $[Hz/cm^2]$	< 1.5	< 1.5	-	< 1.5
Dark current $[nA/cm^2]$	< 0.05	$<\!0.05$	-	< 0.03
σ_T [ps]	42	42	-	45
ϵ	> 0.97	> 0.97	-	> 0.97
$\phi_{max}~(\sigma_T{<}80{ m ps})~[{ m kHz/cm^2}]$	80	80	-	3.5
$\phi_{max}~(\epsilon{>}0.9)~[m kHz/cm^2]$	100	100	-	3.0

Table F.2: Summary of Tsinghua counters

In a similar way as in the 10-gap counter [103] induced signals of both polarities are sent differentially to the front-end electronics (FEE) used for the STAR TOF prototype 'TOFr' [104] in RHIC Run 3. This FEE is described in [105]. The working gas is a mixture of 85% $C_2H_2F_4$, 5% iso- C_4H_{10} and 10% SF₆ at atmospheric pressure.



Figure F.33: Strip-readout MRPC, featuring a 10-gap 8-strip structure.

Beam test at ELBE:

Test of the rate capability of this 8-strip module have been performed at the Electron Linac with high Brilliance and low Emittance (ELBE) facility at HZDR in June 2012. The experimental setup was already used in previous studies for ceramic counters, a simplified scheme is shown in Fig. F.34. The MRPC and scintillator S5 were both placed on a moving platform, which allows a movement of 50 cm both in vertical and horizontal direction. Via remote control a two-dimensional position scan was possible during the run. A trigger condition was required in the form of $S1 \land S2 \land S3 \land S4 \land RF$ (3 of the used scintillators have



a double-end readout denoted by even and odd numbers, respectively, see Fig. F.34).

Figure F.34: Schematic view of the RPC test setup at HZDR. Beam trigger was a coincidence $S1 \land S2 \land S3 \land S4 \land RF$. Together with the MRPC, a small scintillation counter S5 (finger) was mounted at a step-motor to measure the beam profile. The counters S24, S25 are large scintillators with a diameter of 4 cm to monitor the count rate. Counter S9/S10 is a 4 cm-thick scintillator used to monitor the single-electron distribution of the bunches.

The time of flight is defined as the time difference between the MRPC signals and RF signal of the accelerator. These discriminated signals are fed into a TDC (CAEN V1290N) with a least-significant bit (LSB) of 24.5 ps. It provided an overall resolution of 35 ps per channel, measured via the time difference between two channels which were fed by a split signal. The charge signal was pre-amplified by a factor 80 in the front-end electronics and by a further factor 10 in an auxiliary amplifier. The amplified signal was then fed into a QDC (CAEN V965, 25 fC/channel) and integrated over a 50 ns gate. The data acquisition was running on a GSI multi-branch system (MBS).

Performance of the 8-strip prototype:

The 8-strip MRPC was conditioned under high voltage for a few hours in order to reach a stable, low darkrate working regime. The electronics threshold was set to 30 mV (for δ -impulse excitation it translates to q=30 fC). The dark rate of the module was about 3.5 Hz/cm² at 109 kV/cm, the dark current below 0.13 nA/cm². Despite this rate is approximately a factor 10 higher than in float-glass RPCs (~1 Hz/cm²) it remains a factor 1000 below the typical working flux in future high-rate applications. One has to remark that the origin of the dark rate in all kind of glasses (extremely higher than the natural background radiation) is poorly understood at present.

In order to find the optimum working voltage of the counter, efficiency and time resolution were scanned as a function of the HV under a 'low' flux of 5.4 kHz/cm^2 . The results are summarized in Fig. F.35. The counter exhibits a comfortable efficiency plateau above 95 % and simultaneously time resolutions below 50 ps.

For a study of the rate capability the counter was tested with varying fluxes of electrons at a working voltage of 6.75 kV, corresponding to a field of 108 kV/cm. For efficiency estimates we take as AOI the whole active region of the counters, while for the time and charge distributions we restrict AOI to the cell which is best centered with respect to the beam profile. The high-flux behavior of efficiency and time resolution are shown in Figs. F.36 and F.37. At fluxes up to 150 kHz/cm^2 the 8-strip counter shows an efficiency above 90%. However, its time resolution deteriorates fast once the flux exceeds 60 kHz/cm².

Regarding these high-flux measurements, it has to be noted that the electron beam did not operate in a clean single-electron mode. From the charge distribution of the scintillators, we observed clear double-hits in the 5 ps electron bunch. Therefore, the efficiency of the counter (black symbols in Fig. F.36) might be overestimated at high fluxes, because the counter had chance to detect a second electron, Moreover, as compared to the pad cell (2cm*2cm), the strip cell (12.5cm*2.5cm) has a higher probability of detecting a





Figure F.36: Measured efficiencies for different runs as function of the average particle flux determined with reference scintillators. Open symbols are obtained through an indirect analysis.



Counter flux[kHz/cm²]

Figure F.37: Measured time resolutions for the cell with highest statistics (centered with respect to the beam) as a function of the average particle flux determined with reference scintillators.

double-hit simultaneously. The double-hit on the strip gives a wrong timing which could worsen the time resolution of the strip-counter. For estimating the efficiency, we show in Fig. F.36 the efficiency of the 3-strip counter measured with the same setup in single-electron mode. The 8-strip counter is expected

to have similar performance as the 3-strip module. Limited by the beam time, we could not take data at high fluxes with the optimum field of 108 kV/cm (6.75 kV in Fig. F.35) but only at 103 kV/cm (6.45 kV in Fig. F.35). The open symbols in the figure do not refer to measured data; they are just estimates based on recorded currents and rates in combination with a simple DC model which may yield reasonable values.

As a summary, the low-granular 8-strip RPC shows a rate capability up to $25-30 \text{ kHz/cm}^2$, sufficient for the coverage of the region for which it has been envisaged. The uncertainty in the quoted flux-ranges is related to the uncertainty in the beam profile due to the observed broadening of the electron beam caused by multiple scattering in the RPC itself.

F.2.4.2 Standard float-glass RPCs

In order to develop a backup solution for the MRPC3b and MRPC4 a float glass MRPC prototype called LMRPC was build. The readout-electrode structure of the prototype is schematically shown in Fig. F.38, a counter cross section in Fig. F.39. The readout strips are 50 cm long, 2.5 cm wide with 0.6 cm gaps in between. The signals are read out on both ends of each strip. The module has ten gas gaps of 250 μ m, arranged in two stacks. The resistive electrodes are of normal float glass with a volume resistivity of ~ 10¹³ Ω -cm. The HV electrodes on the outer surface of each glass stack are produced by means of Licron spray yielding layers of of ~ 40 $M\Omega/cm^2$ surface resistivity. The module is enclosed in a gas-tight aluminum box. The working gas is a mixture of 95% Freon R-134a, 3% iso $-C_4H_{10}$ and 2% SF_6 .





FigureF.39:Schematicside-viewof the LMRPC module.

Beam test setup

In such long-strip MRPCs cross-talk is a critical issue since the electromagnetic interference between strips increases with the strip length. To study this in detail, an LMRPC prototype was designed and constructed at USTC and tested in beam at GSI in August 2009. The test was performed with secondary particles produced with a 3.5 GeV/c proton beam on a lead target; the set-up is shown schemetically in Fig. F.40. Two scintillators, placed on movable platforms, defined the trigger area of 4 cm \times 2 cm along and across the LMRPC strips, respectively. The scintillators were read out from both ends by four PMTs. They provided the time reference T_0 with a resolution of \sim 67 ps σ .

Test results

Fig. F.41 shows the detection efficiency and time resolution versus the high voltage (HV). The efficiency, requiring valid signals on both ends of any strip, reaches above $6.9 \,$ kV a plateau above $98 \,$ %. After



Figure F.40: Setup of the LMRPC beam test at GSI.

correcting the time jitter of T_0 , the time resolution of the LMRPC is about 60-70 ps. Since the test beam contained various secondary particles, this resolution includes contributions from their momentum dispersion.



Figure F.41: Detection efficiency and time resolution as function of the HV.

With leading-edge discrimination used for timing, a slewing correction is necessary to get rid of the time dependence on the signal amplitude. Since the strips are read out at both ends, we can take the advantage of the mean value of the measured time $(T_{end1} + T_{end2})/2$ which is independent of the hit position along the strip. The variation of this mean time as a function of the mean charge (the corresponding QDC value) is shown in Fig. F.42 with the fit function

$$f(A) = p_0 + p_1/\sqrt{A} + p_2/A + p_3/A^{3/2} + p_4/A^2$$

where A stands for the charge and p_0 , p_1 , p_2 , p_3 , p_4 are fit parameters. A typical time spectrum after slewing correction is shown in Fig. F.43; the σ of the Gaussian fit is 2.57 TDC channels opr 90 ps. Removing the contribution from T_0 of 67 ps one obtains an LMRPC time resolution of about 60 ps. The position of the LMRPC (cf. Fig. F.40) can be changed both horizontally and vertically. In order to understand better especially the level of the inter-strip cross-talk, a scan perpendicular to the strip direction was performed. In Fig. F.44 the efficiency of all the six strips is plotted. The positions are measured in relative units to the platform. Since the trigger area is 2 cm wide i.e. only 0.5 cm narrower than the strip width, the efficiencies of adjacent strips change slowly near the strip edge. Only when the trigger area is in the center of one strip, few particles could really hit the adjacent strips. In this case, their efficiencies are mainly related to cross-talk. When the trigger area is in the center of strip 4 (see Fig. F.44), the efficiency of both strip 3 and strip 5 is about 3%. This value can be regarded as the upper cross-talk limit.



Figure F.42: Correlation between mean time and signal charge. The fit parameters are used for the slewing correction.

Figure F.43: Mean time distribution after slewing correction. The unit is 35 ps/TDC channel.

Figure F.44: The efficiency of all six strips versus the relative position.

To better understand the cross-talk level of the LMRPC, precise hit positions on the strips are needed. During the later period of the beam test, two pairs of Silicon Strip Detectors (SSDs) were installed in

front of the two scintillators shown in Fig. F.40. With the position information from these SSDs the hit position in the LMRPC plane can be precisely determined. Fig. F.45 shows a scatter plot of the reconstructed hit positions.





With this information the position scan can be analyzed in more detail. Fig. F.46 shows the efficiency of each strip which the trigger sitting in the center of strip 5. Going from the edge to the center of strip 5, the efficiencies of the neighbours strip 4 and strip 6 decrease slowly, related to the decrease of the "charge sharing". The efficiencies of other three strips remain very low, their efficiencies are mainly due to cross-talk. Fig. F.47 shows the case where the trigger covers the edge between strip 4 and 5. The "or efficiency" of strip 4 and 5 is also plotted. Even at the center of the strip gap, this "or efficiency" is still above 85%. From these results we can conclude that the cross-talk ratio of this LMRPC is less than 2%.

The time difference from the two strip ends delivers the hit position along the strip. Fig. F.48 shows the linear correlation between the so-determined position and the position from the SSDs, indicating that this method delivers reasonable results. The slope of the linear fit corresponds to the signal propagation velocity along the strip, ~ 16.7 cm/ns in our case. The variance around the shown correlation is assumed to be exclusively due to the LMRPC since the spatial resolution of the SSDs is as low as 20 μ m. It is depicted in Fig. F.49 and exhibits a position resolution of 0.36 cm.

Summary

In beam tests the LMRPC prototype has demonstrated a time resolution of 60-70 ps and an efficiency above 98 %. The cross talk which is an importantly figure for such a long-strip design is less than 2 %. The spatial resolution along the strips is 0.36 cm. These results show that the presented LMRPC design is a very good opportunity to replace baseline counters developed for the outer part of the CBM ToF wall. The required granularity can be adjusted by varying the strip length.



Figure F.46: Position dependence of the efficiencies of each strip when the trigger area is just in the center of strip 5. The position is reconstructed using SSDs.

Figure F.47: Position dependence of the efficiencies of each strip when the trigger area is set over the gap between strip 4 and 5. The position is reconstructed using SSDs.

Figure F.48: Correlation between the measured time difference from both strip ends and the reconstructed position from the SSDs. The slope of the linear fit corresponds to the signal propagation velocity along the strip.





Appendix G

RPC Electronics Development

In this appendix, some additional details from the development of the CBM TOF wall electronics are provided.

The section G.1 merely list some references where one can find information about the ReadOut Controller (ROC) prototype used to achieve the results presented in this document.

The section G.2 provides some description and test results of the FPGA TDC prototypes. These convinced us to select these components as backup solution and possible alternative for the GET4 TDC.

Section G.3 describes the currently planned preprocessing tasks and the already tested functionalities. Section G.4 presents the assumption made to evaluate the data rates one can expect in the readout chain and the corresponding number of required components from simulations of heavy ion collision.

G.1 Readout Controller for the GET4-TDC

For details on the hardware of the board, please refer to the SysCore V3 specification document [36]. The protocol used for transmitting data from the ROC (CBMnet) is described in [106]. The CBM computer farms and its software are described in [107].

Details on the firmware implementation can be found in [108].

One important topic fo the CBM TOF wall is the radiation hardness of the readout controller, as placing it not too far away from the digitizers allow to replace many copper cables by single optical fibers. Improvements were obtained by using techniques like scrubbing and were tested using real beam. These techniques and the beam tests results are described in [109].

G.2 FPGA -TDC

FPGA TDC: VFTX

For highly-accurate time measurements the VME-Module VFTX (VME-FPGA-TDC 10ps) has been developed at the GSI Experiment-Elektronik Department cf. the photo of Fig. G.1. Its FPGA TDC Core employs the tapped delay-line method which is described in [110]. At present it can handle 28 LVDS input channels, 56 internal channels (28 leading-edge / 28 trailing-edge chs) with 10 ps resolution. There are also different program versions available e.g. 16 channels with about 7 ps and 32 channels with about 10 ps time resolution (both leading edge only). An external clock input allows to have more than one module running on the same clock. Hence there is no need of a reference signal in each TDC. Pulser tests in the laboratory show a channel-to-channel resolution of about 10 ps in one module and about 12 ps between different modules. The readout of the module is trigger-based, the used data acquisition is MBS (Multi Branch System).

Laboratory test of VFTX

For a pulser test in the laboratory one pulse is splitted into ten identical pulses with the CLOCKDIS-TRIBUTION2 (chapter 3.3.8). These pulses are injected into the VFTX modules. The master clock



Figure G.1: VFTX-Prototype (VME-FPGA-TDC-Module)

of 200 MHz is generated by a modified version of CLOSY2 (see chapter 3.3.8) and distributed to the modules.

The following Fig. G.2 shows the time difference between two input signals in the same VFTX module; the time resolution is 9.55 ps.



Figure G.2: Time resolution between two VFTX TDC channels.

Pulser Test of PADI and VFTX

To measure the system resolution of PADI-6 in conjunction with VFTX an analog pulse was split and fed into two PADI-6 inputs, its discriminated output pulses are plugged into the VFTX TDC.

The time resolution was measured for different input-signal heights in PADI and different thresholds. The results are plotted in Fig. G.3.



Input single ended signal (mV)

Figure G.3: Time resolutions with PADI6 and VFTX for various input amplitudes and thresholds.

Irrespective of the threshold the resolution is better than 30 ps once the input signals exceed 10 mV (the typical input amplitude is about 30 mV).

G.2.1 Outlook: FPGA TDC Hardware

Since there is an increasing interest in FPGA TDCs and the results are promising the tests of these TDCs will continue. As in the case of GET4 new PCBs have been designed which can place FPGAs directly on the RPC box.

The new FPGA TDC board is shown in Fig. G.4. The 32-channel TDC is implemented on a Lattice FPGA and can be readout via SFP. An in-beam test is planned 2014.



Figure G.4: Time digitization card featuring a 32-channel FPGA TDC.

We also have to test a free-streaming readout with an FPGA TDC. Such tests will start with an FPGA TDC which is implemented on the TRB3 Module from HADES ([87]).



Figure G.5: TRB3 ([87]) of HADES, an FPGA TDC with 126 channels.

TRB3 features 256 channels for leading edge discrimination with time resolutions below 20 ps. With a small change of the FPGA code one can change to 128 channels with time-over-threshold information. The HADES DAQ can be used as a non-triggered system by reading out the TRB3 continuously by means of an internal pulser trigger.

G.3 Outlook: Hardware Preprocessing

An option to reduce the amount of data in the CBM-network is to implement part of the operations which are handled now in software into the hardware chain as an intermediate layer. Depending on the amount of needed resources, it could happen either in the ROC between the Readout and communication layers, or in a dedicated FPGA on a preprocessor board placed between the ROCs and the CBM-network. An investigation of the transfer of the following (GET4 specific) hardware operations has started:

- Time ordering of all messages inside the same epoch (chip-wise).
- Hit building (association of two opposite-edge messages in the same channel, including some mismatch checks) => Available as optional readout mode in GET4 (version 1.0 and higher).
- Time ordering of all hits inside a same epoch/synch block (ROC-wise).
- Synch block validation (25 epochs count between synchronizations).

This was tested in a prototype using the GET4 and the Syscore v2 board both in-beam and with cosmic data. A description of these tests and their results can be found in [111]

Additionally, the following functionalities are planned to be investigated as part of the preprocessing:

- Monitoring the data rate per channel.
- Noisy/oscillating-channel alert.
- Automatic threshold adjustment in case of high rates in order to maintain system stability.
- Automatic disabling of channels in case of oscillations or ringing.
- Automatic bin-to-time calibration + update + database history.
- Time-slices building (Data block used for the CBM time-based Online Event Building), data messages formatting for transport.
- Fired strips and clusters detection/building.
- Local rejection of unphysical signals at the RPCs (e.g. single-end firing on a strip).

The place where each of these options could be implemented is not fixed yet.

G.4 Readout Chain Simulations

The simulations were performed using the parameters described in section 3.3.9. Assumptions were made to take into account currently existing/planned hardware and the proposed preprocessing tasks. In the simulations the following assumptions about the various components were made:

- Left and right channels of an RPC are always connected to the same ROC and all channels of a single MRPC are connected to the same ROC. This is meant to simplify eventual preprocessing tasks.
- Different modules do not share ROCs.
- There are at most 80 GET4 per ROC, with 32-64-80 chips connected by means of 3 types of motherboards (same FPGA firmware).
- A hit on an electronic channel is encoded in 2x32 bits.
- CERN GBTX chips/boards are used as data concentrators and as converters to optical data transport.
- Each GBTX has one optical fiber as output link.
- Nominal Bandwidth of optical links is 4.8 Gb/s.
- Optical links have 80% of their nominal bandwidth available for data transport (control, epochs, hits, errors, ...)
- If possible the data from a module are not split on different GBTX (e.g. data volume smaller than a single GBTX capacity). This is meant to simplify eventual preprocessing tasks.
- The minimal number of optical links before preprocessing is determined by the number of CERN GBTX chip (aggregation layer) for each MRPC type, which is optimized using the simulated data rates and the setup description.
- The minimal number of optical links after preprocessing is determined only by the simulated data rates (implies at least one further stage, e.g. the DPB boards).