The CBM Time-of-Flight system

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ABSTRACT: The Compressed Baryonic Matter spectrometer (CBM) is a future fixed-target heavy-ion experiment located at the Facility for Anti-proton and Ion Research (FAIR) in Darmstadt, Germany. The key element in CBM providing hadron identification at incident beam energies between 2 and 11 AGeV (for Au-nuclei) will be a 120 m$^2$ large Time-of-Flight (ToF) wall composed of Multi-gap Resistive Plate Chambers (MRPC) with a time resolution of the system better than 80 ps. Aiming for an interaction rate of 10 MHz for Au+Au collisions the MRPCs have to cope with an incident particle flux between 0.1 kHz/cm$^2$ and 100 kHz/cm$^2$ depending on their location. Being the system characterized by wide ranges of both granularity and rate capability, the conceptual design of the ToF-wall foresees 6 different granularities and 4 different detector designs. In order to elaborate the final MRPC design of these counters several heavy-ion in-beam and cosmic-ray tests were performed. In this contribution we present the conceptual design of the TOF wall and discuss the performance results of full-size MRPC prototypes.

KEYWORDS: Gaseous detectors; Instrumentation and methods for time-of-flight (TOF) spectroscopy; Resistive-plate chambers; Timing detectors

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Introduction

The Compressed Baryonic Matter spectrometer (CBM) is a future fixed-target heavy-ion experiment located at the Facility for Anti-proton and Ion Research (FAIR) in Darmstadt, Germany. The CBM collaboration aims to explore the phase diagram of strongly interacting matter at high baryon densities in the energies range from 2 to 11 AGeV. This includes the study of the equation-of-state of nuclear matter at neutron star core densities and the search for phase transitions, chiral symmetry restoration and exotic forms of (strange) QCD matter [1]. The CBM detector is designed to measure the collective behavior of hadrons, together with rare diagnostic probes such as multi-strange hyperons, charmed particles and vector mesons decaying into lepton pairs with unprecedented precision and statistics. Most of these particles will be studied for the first time in the FAIR energy range. In order to increase both precision and statistics, the measurements will be performed at reaction rates up to 10 MHz. This requires very fast and radiation hard detectors, a novel data readout and analysis concept including free streaming front-end electronics, and a high performance computing cluster for online event selection [2].

2 The CBM Time-of-Flight (TOF) system

The CBM Time-of-Flight (TOF) system [3] will provide charged hadron identification (protons, kaons and pions) up to a particle momentum of about 4 GeV/c in the aperture range between 2.5° and 25°. In order to fulfill this requirement a time resolution of the system below 80 ps and an overall efficiency above 95% are mandatory. However, the most challenging requirement for the detector is the capability to cope with rates up to 30 kHz/cm² (cfr. figure 1). Below 2.5° no information on the momentum is available, nevertheless it is planed to install a so called “Beam Fragmentation T0 Counter” (BFTC), delivering the start time information, which has to cope with particle fluxes up to 100 kHz/cm². The current conceptual design foresees a 120 m² big TOF wall (including BFTC) composed of Multi-gap Resistive Plate Chambers (MRPC) which is movable between 6 m
and 10 m from the interaction point. An occupancy below 5% is desired. However, the limiting factor in terms of granularities of the counters is the readout bandwidth of the front-end electronics. Therefore MRPCs with granularities between 4 cm$^2$ (for the BFTC) and 50 cm$^2$ (low rate region), depending on the incident particle flux, are considered.

**Figure 1.** 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. The beam direction is considered to be in the Z direction. Left panel: flux as function of X coordinate (horizontal) at Y = 0 (i.e. left/right of the beam axis). Since the magnetic field lines of the dipole magnet run in vertical direction (Y direction) the X-axis also defines the deflection (bending) plane of the particles trajectories. Right panel: flux as function of Y coordinate (vertical) at X = 0 (i.e. above/below of the beam axis). The right-handed coordinate system is applied.

The BFTC is composed of 8 modules with 40 × 40 cm each containing 3200 single ceramic MRPCs channels in total. These modules are arranged chess board like around the beam axes at a distance between 12 and 15 m from the interaction point. Even though the BFTC is separated physically from the TOF wall it belongs to the TOF system. The active area of a MRPC is 2 × 2 cm$^2$ while it is composed of 3 stacked cells with 2 gaps each. The gap size is 250 µm. More information about the counter design and test beam results can be found in [4–7]. For the TOF wall glass MRPCs are foreseen. The high and intermediate rate regions (between 30 kHz/cm$^2$ and 1 kHz/cm$^2$) will be composed of MRPCs equipped with low resistivity glass ($\rho \approx 10^{10} \Omega/cm$) while below 1 kHz/cm$^2$ float glass MRPCs will be used. Details on the conceptual design of the wall can be found in [8, 9]. Different full size MRPC prototypes, including test results, foreseen for the high, intermediate and low rate region of the wall will be discussed in the following subsections.

### 2.1 The MRPC1 prototype for the high rate region

In the high rate region particle fluxes will be between 30 kHz/cm$^2$ and 5 kHz/cm$^2$ (see figure 1). Here MRPCs with granularities between 6 and 20 cm$^2$ are foreseen. The MRPC1 prototype developed in Bucharest (described in [10, 11]) is equipped with low resistivity glass ($\rho = 3 \times 10^{10} \Omega/cm$) of 0.7 mm thickness and has a granularity of about 6 cm$^2$. Figure 2 depicts the structure and a photograph of the MRPC1 prototype called DSMRPC2015. A novel method was developed to adapt the impedance of a MRPC independently from its read out structure [12]. That this method
Figure 2. Left side: structure of the MRPC1 prototype developed at Bucharest. The HV electrode is consists of metal stripes with the same pitch as the readout electrode. Right side: photograph of 2 MRPC1 prototypes called DSMRPC2015 and superimposed a different prototype called SSMRPC2015.

works was demonstrated by the first time on this detector where the impedance was adjusted to 100Ω. The impedance matching is achieved by manufacturing a high voltage (HV) electrode from metal (e.g. a PCB with copper strips) which is subdivided in strips with the same strip pitch like the overlaying readout electrode. However, the strip width of both electrodes (HV and readout) can differ. The granularity of the detector is now defined by the HV electrode structure while the impedance is fixed by the ratio between the two strip widths. This prototype was tested among others at SPS/CERN with 30 AGeV Pb ions impinging on a 4 mm thick Pb target. The spray of reaction products takes care for full illumination of the detector area with a gradient towards the beam axis. The gas mixture was 85% R134a, 10% SF6 and 5% i-Butane. Figure 3 shows the efficiency (left side) and the time resolution (right side) in a long term run of about 10 hours at the beginning of the beam time at modest particle fluxes of about few 100 Hz/cm². While the efficiency of about 97% stays constant a significant decrease in the system time resolution from 72 ps to 69 ps is observed. As a reference a second MRPC (also seen in figure 2 right side) was used. The observed behavior is considered to be a conditioning effect. After a day of operation the system time resolution becomes stable. The efficiency and the system time resolution as function of the applied electric field is depicted in figure 4. The efficiency enters a plateau at about 153 kV/cm and reaches a value of 97%. The high electric field is necessary since the gap size of this MRPC is only 140 μm. The system time resolution is constant and has a value of 67 ps. Assuming a equal performance of both MRPCs this value can be divided by √2 in order to obtain the individual counter resolution which
is about 47 ps including the jitter of the electronics chain. These are very encouraging results since hit multiplicities (number of independent reconstructed hits on the counter surface per event) of about 5 in average was measured [13] and was confirmed in MC simulation.

2.2 The MRPC3a prototype for the intermediate rate region

In the intermediate rate region the particle flux is between 5 and 1 kHz/cm$^2$ will be reached. Here MRPCs with strip geometries of $1 \times 27$ cm$^2$ are foreseen. The MRPC3a prototype developed at Tsinghua University has 32 readout strips and a low resistive glass stack of $2 \times 4$ gaps with 250 $\mu$m gap size. The glass has a bulk resistivity of about $2 \times 10^{10}$ $\Omega$ cm and a thickness of 0.7 mm. MRPC3a is impedance matched to 50 $\Omega$. Beam time results for prototypes with similar structure obtained at SIS18 facility/GSI were presented in [14, 15]. For the FAIR phase 0 program (see section 3) 72 MRPC3a detectors are being produced providing a solid basis for quality evaluation of the production line.

Extensive cosmic-ray test of the MRPC3a prototype together with the MRPC3b prototype were performed in Heidelberg. The results will be discussed in the next subsection.

2.3 The MRPC3b prototype for the low rate region

In the low rate region of the TOF wall the particle flux is below 1 kHz/cm$^2$. This area will be covered by MRPCs equipped with commercial thin float glass (0.28 mm) as electrode material. Foreseen are two different versions which differ only in the strip length of the pickup electrode (MRPC3b has a strip length of 27 cm and MRPC4 has a strip length of 50 cm). Both prototypes are developed and built at the University of Science and Technology of China (USTC). The detectors have $2 \times 5$ gaps with a gap size of 230 $\mu$m and 32 readout channels with strips of 1 cm pitch. Also this prototypes are impedance matched to 50 $\Omega$, which is adjusted on the preamplifier stage with a resistor. For the FAIR phase 0 program (see section 3) 80 MRPC3b prototypes are being produced.

These prototypes were tested in a cosmic-ray stand by arranging them in a stack of 6 stations (2 MRPC3a and 4 MRPC3b detectors with a total distance of 40 cm between the top and the bottom one) in our laboratory in Heidelberg. Within this acceptance about 100000 particle tracks (mostly muons) per day passing through all 6 stations could be accumulated. The gas mixture was 90% R134a, 5% SF$_6$ and 5% i-Butane. The system is not triggered that means the data flow is free streaming as foreseen in the CBM experiment. The FEE consists of the PADIX preamplifier/discriminator.
chip [16] and the self-triggered GET4 TDC [17]. The data unpacker builds events when at least 4 signals from different detectors were found. The data are calibrated regarding time and position offsets and time walk. After calibration a track finding algorithm is applied and the resulting tracks are used to determine efficiency, time and position resolution. The efficiency of each counter is determined by comparing tracks with multiplicity 5 to those with multiplicity 6. In other words, 5 counters define a track (acting as a reference) which is inter-/extrapolated to the detector under test (DUT) taking the geometrical acceptance into account. When a hit on DUT is found close in space and time the counter is considered to be efficient. Further more, residuals between the hits measured on the DUT and the track formed by the other 5 hits, can be determined. The width of the Gaussian shaped residuals deliver the time and spatial resolution of each counter. This method has the advantage that first a multi differential analysis can be performed i.e. the efficiency and time resolution can be determined as a function of the position on the counter surface (in order to study boarder effects) and not only globally but also as a function of the incident angle of the particle. Second, by construction of this method the incident angle and the velocity spread of the cosmic rays are automatically taken into account which contribute in the time difference spectra (time of flight spread).

Figure 5 shows the efficiency (left) and the counter time resolution (right) as function of the electric field for the MRPC3a and MRPC3b prototypes. The efficiency of the MRPC3a is slightly lower than the one for MRPC3b which could be explained by the fact that MRPC3a has only 8 instead of 10 gaps. In addition MRPC3a has a smaller weighting field due to the thicker glass plates. However both prototypes fulfill the CBM TOF requirements. The counter time resolution is constantly decreasing and reaches a value of about (50 ± 1) ps for both prototypes which is expected since both MRPCs have similar gap sizes. The cluster size (left), which is defined as the number of consecutive firing strips where the hits match in time and space, and the dark rate (right) as function of the applied electric field is depicted in figure 6. Since both MRPCs prototype have the same read out structure the cluster size is identical and rises linearly with the electric field strength. In the efficiency plateau the cluster size values are between 1.3 and 1.5. The noise/dark rate is, however, very different between the two MRPCs. While for MRPC3b equipped with float glass electrodes the noise rate is very low (< 0.3 Hz/cm²) the noise rate for the MRPC3a equipped with
low resistivity glass electrodes increases faster with an almost quadratic behavior. At operation conditions (between 105 and 115 kV/cm) the noise rate of the two MRPC detectors differ by almost an order of magnitude. The reason might be that the low resistive glass is polished and the surface is not as homogeneous as the one of float glass. However, a noise rate of 5 Hz/cm$^2$ is still tolerable since it is on the per mill level of the foreseen working rate.

![Figure 6](image)

**Figure 6.** Left side: mean cluster size as a function of the electric field for the prototypes MRPC3a (low resistivity glass) and MRPC3b (thin float glass). Right side: noise rate as a function of the electric field for the MRPC3a and MRPC3b prototypes.

## 3 The FAIR phase 0 program of CBM TOF

The FAIR phase 0 program is intended to install and operate detectors into existing experiments. CBM-TOF is involved in two projects:

1. The installation of 36 CBM TOF modules (about 7000 readout channels) at the east pol end cap at the STAR experiment at Brookhaven National Laboratory (BNL) extending the PID capability to the region of $-1.5 \leq \eta \leq -1.0$. The so called eTOF wheel will be operational during the beam energy scan (BESII) campaign starting in February 2019.

2. The installation of 5 modules (25 MRPCs) in the miniCBM setup which is currently set up at SIS18 at GSI. The goal of this experiment is in the first period (2019/2020) the systematic synchronization of the free-streaming data flow of the individual subsystems (see figure 7), event reconstruction and data processing. In the second part (2021/2022) the goal is the reconstruction of $\Lambda$ particle at sub-threshold energies with the technique elaborated in the first period. In addition it opens the possibility for detector test at rates that are anticipated for the running conditions at SIS100 (up to 30 kHz/cm$^2$ see figure 1 blue line).

The left side of figure 7 depicts one sector (3 CBM TOF modules) mounted at the 6 o’clock position on the east side end cap yoke of the STAR solenoid. This sector was installed at the beginning of 2018 and tested during the STAR run18 beam time (February–June). Test results demonstrated the successful integration of CBMs free streaming DAQ systems into the triggered environment of the STAR experiment. The right hand side of figure 7 shows the mCBM setup that will be operational in Sep 2018.
4 Conclusions

The CBM Time-of-Flight system has to unprecedentedly cope with particle fluxes of up to 100 kHz/cm$^2$. Such conditions require new electrode materials for MRPCs which triggered the development of a new MRPC generation. In this paper we presented the possible solutions for CBM. A time resolution in the order of 50 ps was measured at low and moderate rates. With the opportunity to test in the high rate environment at SIS18 (mCBM) by the end of this year and the experience gained at BNL the design of the new MRPCs will be finalized and the mass production can start at the end of next year. The CBM TOF systems are targeted to be ready for operation by end of 2023.

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References

[1] CBM collaboration, Challenges in QCD matter physics — The scientific programme of the Compressed Baryonic Matter experiment at FAIR, Eur. Phys. J. A 53 (2017) 60 [arXiv:1607.01487].
[2] https://www.gsi.de/work/forschung/cbmqm/cbm.htm.
[3] N. Herrmann, Technical Design Report for the CBM Time-of-Flight System (TOF), GSI-2015-01999 (2014).
[4] L. Naumann, R. Rotte, D. Stach and J. Wüstenfeld, High-rate timing RPC with ceramics electrodes, Nucl. Instrum. Meth. A 635 (2011) S113.
[5] A. Akindinov et al., Radiation-hard ceramic Resistive Plate Chambers for forward TOF and T0 systems, Nucl. Instrum. Meth. A 845 (2017) 203.
[6] R. Sultanov, TOF occupancy at SIS-100 and SIS-300, in CBM Progress Report 2013 (2014), p. 78.
[7] R. Sultanov et al., *A Timing RPC with low resistive ceramic electrodes*, in proceedings of the 14th Workshop on Resistive Plate Chambers and Related Detectors, Puerto Vallarta, Jalisco state, Mexico, 19–23 February 2018 [arXiv:1806.02629].

[8] I. Deppner et al., *The CBM time-of-flight wall*, *Nucl. Instrum. Meth. A* 661 (2012) S121.

[9] I. Deppner et al., *The CBM Time-of-Flight wall - a conceptual design*, 2014 *JINST* 9 C10014.

[10] M. Petris et al., *CERN-SPS in-beam performance test of the new strip readout MRPC prototypes for the inner zone of the CBM-TOF wall*, in *CBM Progress Report 2016* (2017), p. 131.

[11] M. Petris et al., *Performance test of the MGMSRPCs using a free-streaming readout*, in *CBM Progress Report 2017* (2018), p. 102.

[12] D. Bartos et al., *A method to adjust the impedance of the signal transmission line in a Multi-strip Multi-gap Resistive Plate Counter*, *Romanian J. Phys.* 63 (2018) 901.

[13] M. Petris et al., *In-beam test of the RPC architecture foreseen to be used for the CBM-TOF inner wall*, *J. Phys. Conf. Ser.* 1023 (2018) 012007.

[14] I. Deppner, N. Herrmann, J. Frühauf, M. Kiš, P. Lyu, P.A. Loizeau et al., *Performance studies of MRPC prototypes for CBM*, 2016 *JINST* 11 C10006 [arXiv:1606.04917].

[15] Y. Wang et al., *Development and test of a real-size MRPC for CBM-TOF*, 2016 *JINST* 11 C08007 [arXiv:1605.02395].

[16] M. Ciobanu et al., *PADI, an Ultrafast Preamplifier - Discriminator ASIC for Time-of-Flight Measurements*, *IEEE Trans. Nucl. Sci.* 61 (2014) 1015.

[17] H. Deppe and H. Flemming, *The GSI event-driven TDC with 4 channels GET4*, *IEEE Nucl. Sci. Symp. Conf. Rec.* (2009) 295.