COMPRESSED BARYONIC MATTER EXPERIMENT

CBM-TN-20nnn
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Counter production readiness document

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Abstract

This document describes the production readiness of the counter types MRPC2 to be build at the Nuctech company in Beijing, and MRPC3 and MRPC4 to be build at the University of Science and Technology of China (USTC). It is the bases for the production readiness review (PRR).

Contents

1 Introduction

This document describes the engineering design of the multi-gap resistive plate chambers (MRPC) of type 2,3 and 4 for CBM-TOF. It is the basis for the PRR.

The CBM-TOF wall is subdivided into two parts called inner wall and outer wall:

- Inner wall: the inner wall covers the region where the charged particle fluxes range between 5 kHz/cm^2 and 30 kHz/cm^2 (cf. Fig. 1). The counters designed for this region will be part of a second CBM-TOF PRR and will not be discussed here in more deteil.
- Outer wall: the outer wall covers the area where the charged particle fluxes ranges between 0.1 kHz/cm^2 and 5 kHz/cm^2 (cf. Fig. 1). In this regions the MRPC types MRPC2, MRPC3 and MRPC4 will be installed.

Fig. 1 shows the simulated charged particle flux at the position of the CBM-TOF wall. The border of the inner and outer wall are marked by the red rectangles.

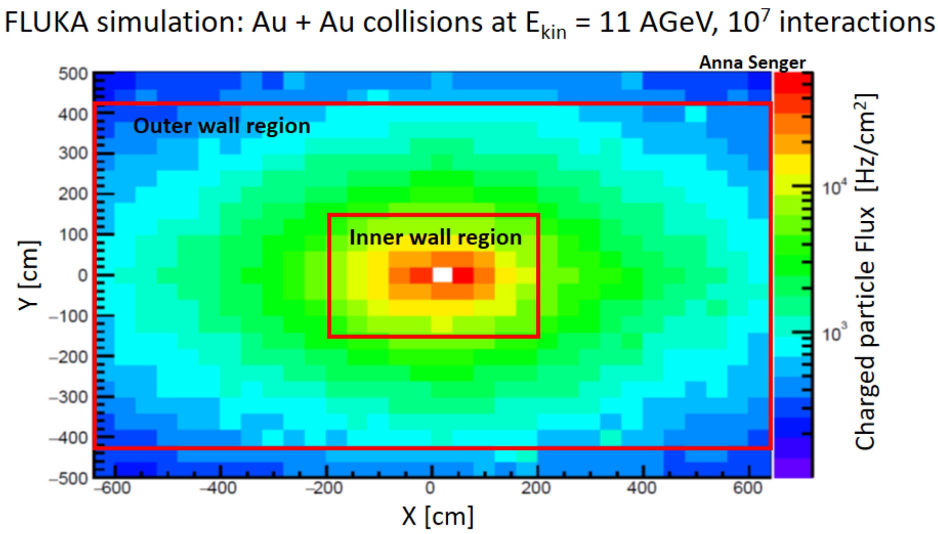


Figure 1: Simulated charged particle flux at the position of the CBM-TOF wall. The red marked areas represent the boarder of the inner and outer wall.

Based on simulations shown in Fig. 1, and the requirement to have an efficient separation of pions from kaons up to 4 GeV/c keeping a occupancy below 5 % following system requirements have to be fulfilled:

- Efficiency higher 95 %
- System time resolution better than 80 ps
- Rate capability up to 5 kHz/cm^2
- Granularity adopted to the location in the (outer) TOF wall

Figure 2 shows the conceptual design of the outer TOF wall. Boxes (rectangles) represents modules (labeled M4 to M6 depending on the position in the wall). The yellow colored region covers the area with particle fluxes between 1 kHz/cm^2 and 5 kHz/cm^2 and is covered with MRPCs of type MRPC2 which contains low resistive glass as electrodes (see Section 2). The blue colored area faces particle

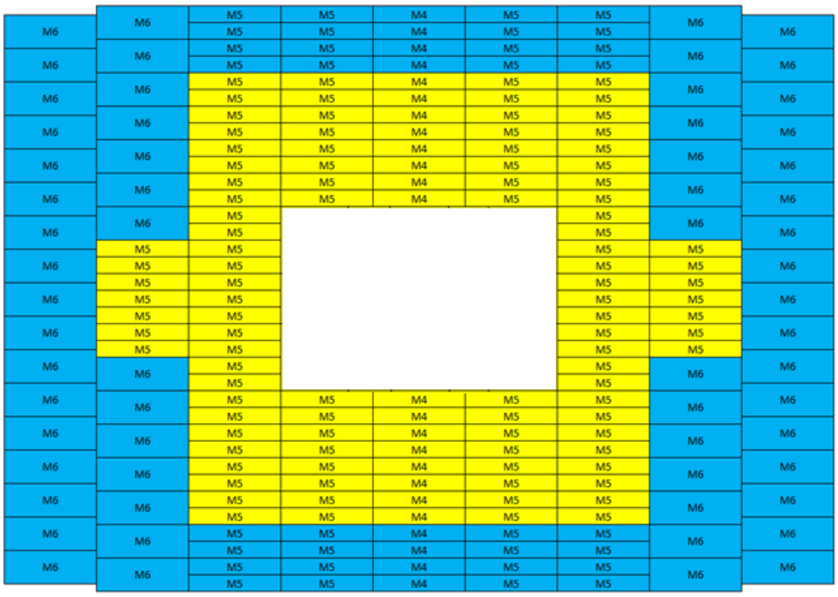


Figure 2: The conceptual design of CBM-TOF wall. The yellow colored region is covered with MRPC2 type. The blue marked region is covered by the MRPC3 counter and MRPC4 counter.

	MRPC2	MRPC3	MRPC4
Efficiency	$> 95\%$	$> 95\%$	$> 95\%$
Time resolution	better than 60 ps	better than 60 ps	better than 60 ps
Rate capability	7 kHz/cm^2	2 kHz/cm^2	2 kHz/cm^2
Granularity	$< 30cm^2$	$< 50cm^2$	$< 100cm^2$

Table 1: Main requirements for the MRPC detectors of different types.

fluxes between 0.1 kHz/cm^2 and 1.5 kHz/cm^2 and is covered with RPCs of type MRPC3 (M4 and M5 modules) and MRPC4 (M6 modules). These counters contain thin float glass electrodes (see Section 3) and differ only in their readout strip length. More information on the conceptual design of the TOF wall can be found here [1].

The requirements of the counters are summarized in Table 1:

2 Production readiness at Tsinghua University

2.1 Description of MRPC2

2.1.1 MRPC2 in CBM-TOF wall

The yellow colored area of the outer TOF wall (see Fig. 2) is composed of 116 modules of type M4 and M5 each equipped with 5 MRPC2 counter which results in 580 MRPC2s in total. With proper design of the number of gas gaps and gap thickness, the efficiency and time resolution requirements can be achieved while keeping in the same time an impedance of 50 Ω. The granularity of the readout strip is a balance between occupancy requirement, Front End Electronics (FEE) bandwidth limitation and mechanical practicability in the module design. A detailed description on MRPC2 geometry is given in the following subsection.

An impressive feature for CBM-TOF is the unprecedented luminosity condition, which results in a challenge of the rate capability for MRPCs. A valid way to improve the rate capability, from around 1 kHz/cm^2 to tens of kHz/cm^2, is to develop novel electrodes with low bulk resistivity. Such target has been successfully reached by the group at Tsinghua University, Beijing. The low-resistive glass has a resistivity in the order of 10^{10} Ωcm, 2 orders less than the common float glass electrodes. Thus, the high-rate MRPC assembled with this material can reach up to 70 kHz/cm^2 in rate capability. With many years of R&D, the low-resistive glass has been proven in terms of stability and reliability in mass production.

2.1.2 Structure and materials of MRPC2

The main parts of the unsealed MRPC2 are the 2 glass stacks, the readout PCBs, and for stabilization, the honeycomb plates. Due to the double stack configuration a top, a middle and a bottom readout PCB sandwiching both 2 glass stacks are soldered to each other by double pins and glue nails. The signals of top PCB and bottom PCB are transmitted to the middle PCB via soldered pins. On the middle PCB a 9-double row pin connector makes the connection to the pre-amplifier PCB. 6 mm thick honeycomb plates are glued to the outer PCBs giving the MRPC its stiff structure. In the first batch of mass production unsealed MRPC2 are produced. The main parameters of the unsealed MRPC2 are summarized in Tab. 2. Figure 3 shows the cross section and the structure of MRPC2. The main materials used in MRPC2 detectors are introduced below.

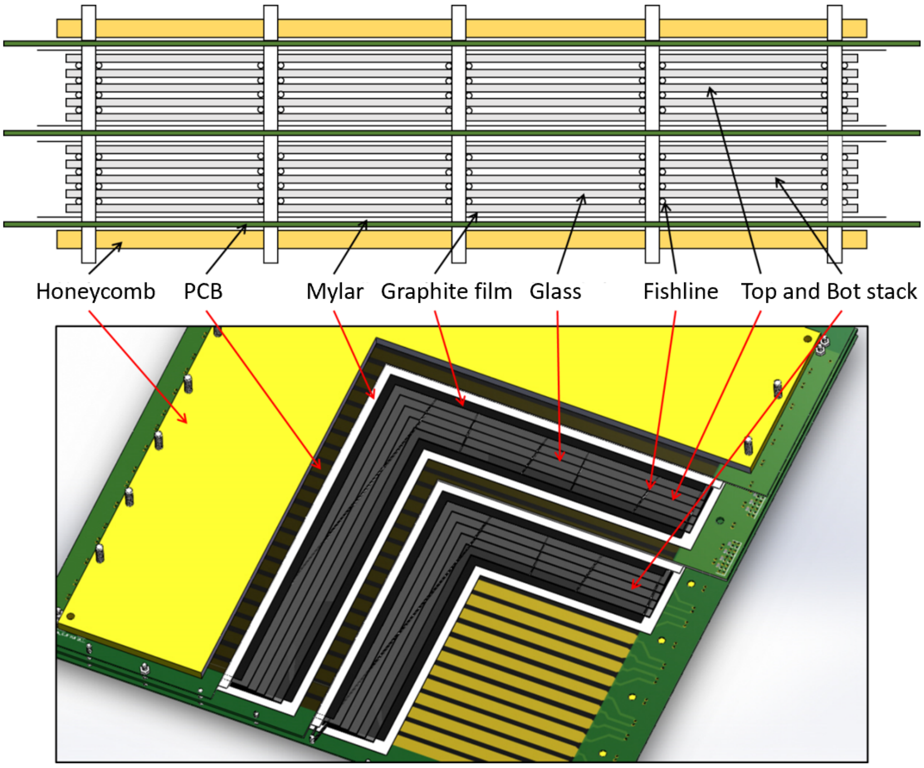


Figure 3: The cross-section and structure view of the MRPC2.

- Glass and pad spacer

As mentioned, the number and width of gas gaps in MRPC2 are carefully designed to achieve time resolution and efficiency requirements. The low-resistance glass is used as the electrode, and pad spacers are used between the two pieces of glass to form gas gaps. The size of the glass is 330 mm × 276 mm and the thickness is 0.7 mm. Its characteristic is that it has an approximately 2 orders of magnitude lower resistivity than ordinary glass, which can increase its field strength recovery speed at a high rate and increase its performance under high particle flux. The size of the pad spacers is a disc with a diameter of 4 mm, and a thickness of 0.25 mm, and its material is Mylar. In each stack, 5 pieces of glass and 4 sets of pad spacers are stacked to form 4 gas gaps. There are two stacks in each MRPC2.

Table 2: Main design parameters for MRPC2.

Design parameter	Unit	Value
Dimension	[mm^2]	360 × 338
Thickness	[mm]	26
Weight	[kg]	3.3
Sensitive area	[mm^2]	330 × 276
Glass size	[mm^2]	330 × 276
Num. of gas gaps		2 × 4
Gap thickness	[mm]	0.25
Strip and gap width	[mm]	7+3
Strip length	[mm]	270
Num. of strips		32
Operational electric field	[kV/cm]	110

- Mylar film

Mylar film is a high-resistance plastic film used to separate high-voltage glass electrodes and PCB boards. Mylar film prevents the high voltage on the electrode glass from being transmitted to the PCB board. The size of Mylar film is 340 mm × 286 mm, which is slightly larger than the size of the electrode glass, and its thickness is 0.25 mm. The number of layers of Mylar film is related to the high-voltage connection method. There is one layer of Mylar on both sides of the middle PCB, while the top and bottom PCBs are each protected by two layers of Mylar on the side close to the glass.

- PCB board and honeycomb board

PCB boards are used to pick up the avalanche signals via conductive strips and guide them to connectors where the pre-amplifier is connected (see Fig. 4. In addition the PCB is used to transmit high voltage to the stacks. The active area of the PCB board comprises 32 strips with a width of 7 mm (a pitch of 1 cm) and a length of 27.6 cm. The signals collected on the outer PCBs are conducted to the intermediate circuit board, and read out by front-end electronics. Figure 4 shows the PCB design. On the middle PCB protection resistances of 200 kΩ are connected to a conductive layer which is connected to the pre-amplifier ground. The electrical schema is depicted in Fig. 5. The Points A.B,C,D can be used to crosscheck the the connectivity of all resistances by measuring the total resistance. Values are given in Table 3.

In order to guaranty the counter stiffness a 6 mm thick honey comb structure is glued to the outer side of the PCB boards. The size of the honey comb plate is 333 mm × 310 mm.

Table 3: Values of resistance between distinct points

Connection points	A - B	A - C or B - C or A - D or B - D	C - D
Total resistance value	6.25 kΩ	101.56 kΩ	200 kΩ

- High voltage connection

High-voltage lines have different high-voltage connection methods for the middle PCB and the top and bottom PCBs. For the MRPC2 detector, the top PCB and bottom PCB are connected to positive high voltage, while the middle PCB is connected to negative high voltage. The length of the high voltage lines is 1.5 m. The high voltage line uses Alpha Wire 39X2215 single-core cable with a voltage resistance of 15 kV. The top and bottom positive high voltages are led out by one wire, and the middle negative high

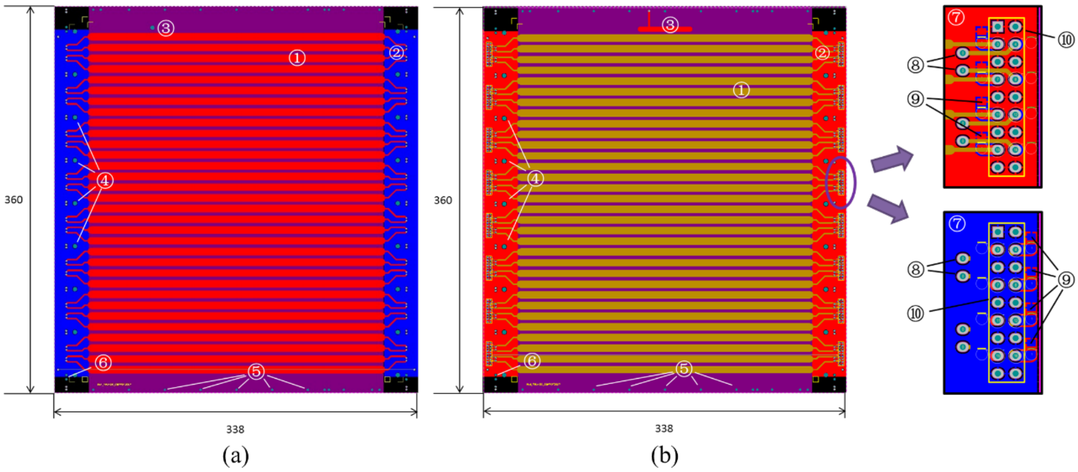


Figure 4: The PCB design of MRPC2. (a) TOP and BOT PCB. (b) MID PCB. The marked structures are: ① readout strips; ② transmission lines; ③ pad for HV application; ④ screw hole for mechanics; ⑤ fishline screw hole; ⑥ installation hole for mechanic spacers; ⑦ grounded pour; ⑧ signal pin hole; ⑨ 200 kΩ for spark protection; ⑩ 2 × 9 pin signal connector.

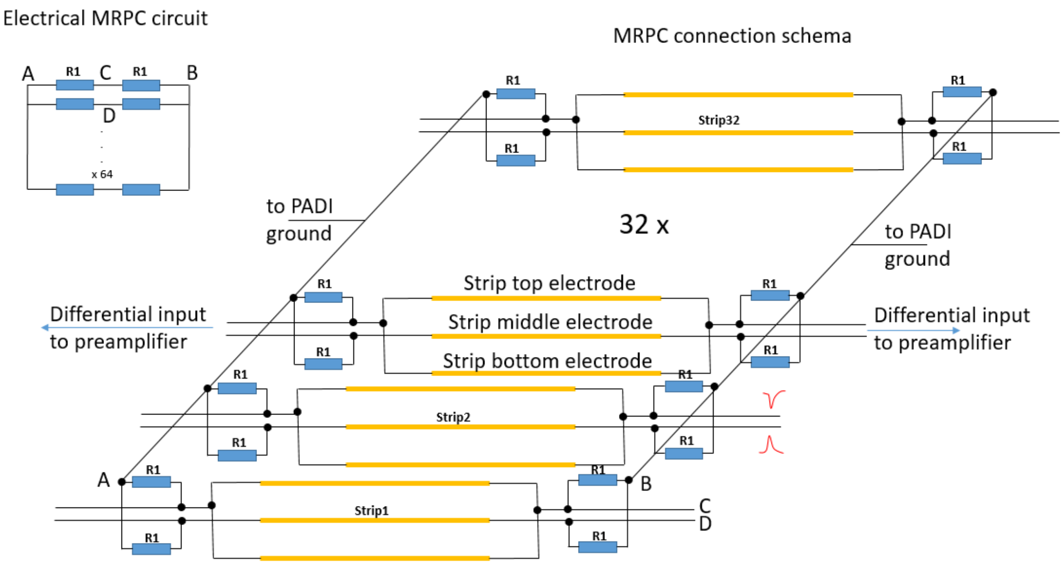


Figure 5: Electrical circuit (top left) and electrical connection schema of MRPC2. The value of R1 is 200 kΩ. The Points A.B,C,D can be used to crosscheck the the connectivity of all resistances.

voltage is led out by another wire. For the top and bottom PCB, The high voltage wires pass through PCBs and are soldered to the carbon film tape on the carbon film glass. For the middle PCB, The high voltage line is connected to the high voltage pad of the middle PCB and then transmitted from the high voltage pad to the carbon film glass by the copper skin. Figure 6 shows the high voltage connection.

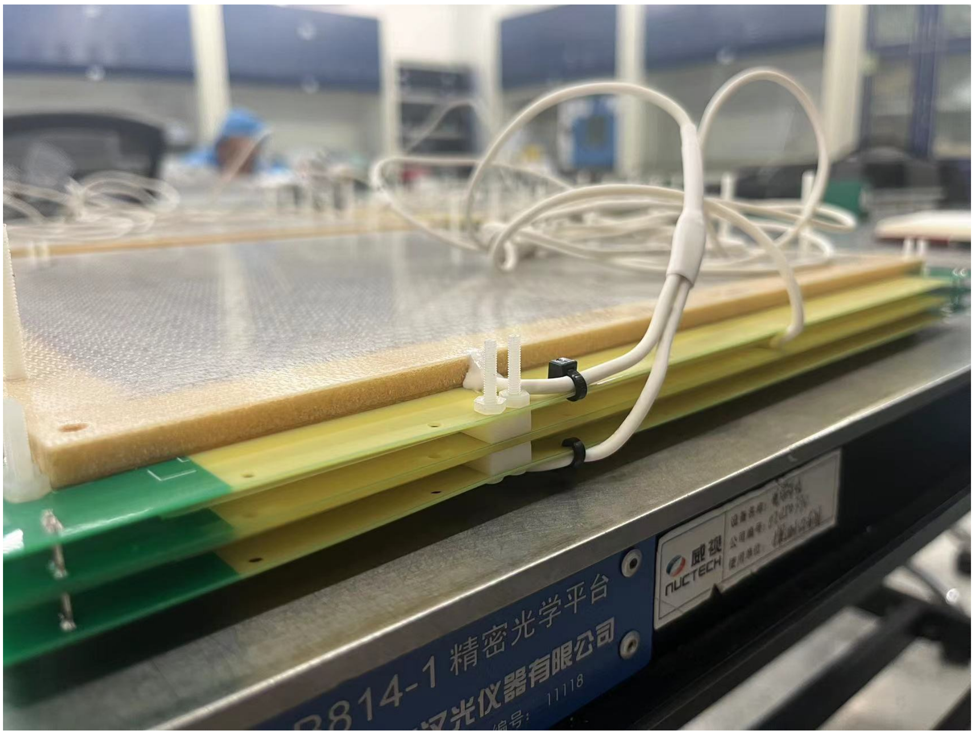


Figure 6: High voltage connection of MRPC2 detector.

- Pins, glue nails, and blocks

These components are used to fix the structure of the detector and to transmit the signals induced on the readout strips to the front-end electronics. Specifically, single pins are used for signal transmission and positioning between the top PCB board, middle PCB board, and bottom PCB board; glue nails are used to fix the detector to the ToF module; 2×9 dual-row pins are used to extract signals and connect to the front-end electronics; and blocks are used to fix the low-resistance glass to prevent it from moving.

Table 4 summarises all used MRPC2 components together with their dimensions and quantity.

2.2 Production of MRPC2

The mass production of MRPC2 will be carried out at the Nuctech's 100k-level clean room located in Miyun District, Beijing. To ensure a standardized production process, we have formulated a detailed standard production process, and the flow chart is shown in Figure 7.

The production of MRPC2 contains three main parts: material preparation, production, QA and QC. The materials are prepared in the workshop, and the MRPC2 will be produced in the 100k-level clean room.

2.2.1 Material preparation

The material preparation mainly contains the quality inspection and cleaning preparations before being assembled. The work includes spraying carbon film onto the glass, cleaning and pre-processing the PCB boards, honeycomb boards, blocks, pins, and other materials. Our material preparation process flow is shown in Figure 8. Table 4 shows the materials required for MRPC2. Figure 9 shows the low-resistive glass cleaning. For the MRPC2, we need to focus on the low-resistive glass. Each detector contains

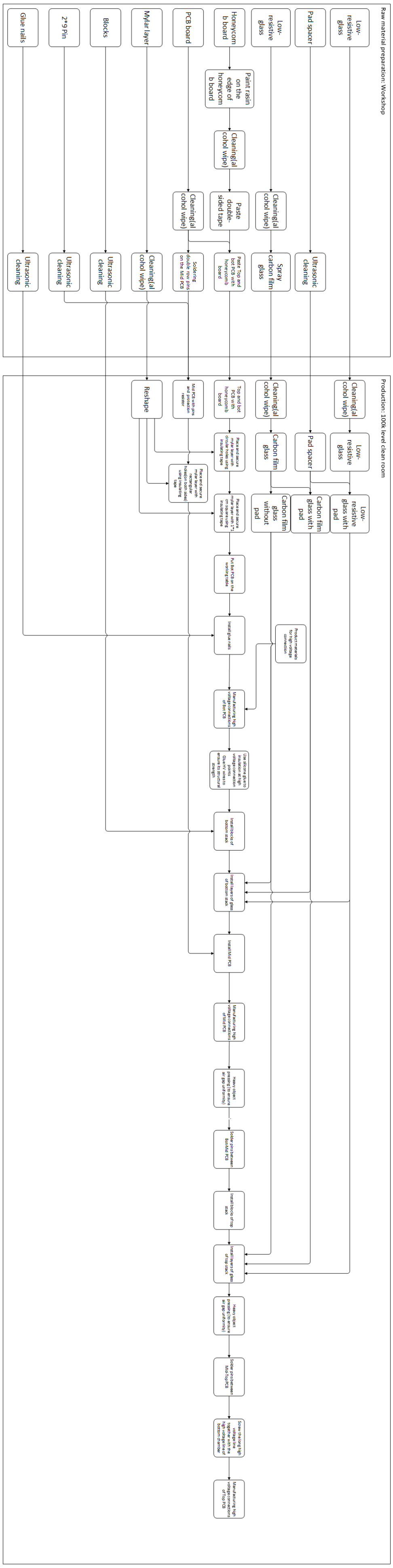


Figure 7: Work flow of MRPC2 production.

Table 4: Main design parameters for MRPC2.

Material	Length /[mm]	Width /[mm]	Thickness /[mm]	Amount	Others
Low-resistive glass	330 ± 0.2	276 ± 0.2	0.7 ± 0.02	10	$\sim 2{\times}10^{10}\Omega cm$
Carbon film glass	324±0.5	270±0.5	0.005	4	$\leq 20M\Omega\ /sq$
TOP PCB	360±0.2	338±0.2	0.8±0.05	1	
Bottom PCB	360±0.2	338±0.2	0.8±0.05	1	
Middle PCB	360±0.2	338±0.2	1.6±0.05	1	
Honeycomb board	333±1	310±1	6±0.2	2	
Mylar	340±0.2	286±0.2	0.25±0.02	8	
Carbon film tape	50	50	0.13±0.2	/	$\sim 100k\Omega$/sq
A type fix block	23±0.2	10±0.2	4±0.05	4	PTFE
B type fix block	14±0.2	10±0.2	4±0.05	4	PTFE
Pad spacers	4±0.1	4±0.1	0.25±0.005	56	Mylar
High voltage line	1000	3	/	3	
M2.5 Screws / Nuts	40	2.5	/	32	
M4 Screws / Nuts	40	4	/	16	
$2{\times}9\ signal pin$	/	/	/	16	
fix pin	19	0.6	/	100	
Protection resistor	/	/	/	128	200k Ω 0603

10 pieces of low-resistive glass, and 4 sprayed carbon film glass acts as high-voltage electrodes. The overall steps for spraying are as follows: First, clean the glass. Use a dust-free cloth soaked with alcohol to wipe the low-resistivity glass. After wiping, tape the four edges of the glass and place them in the spraying machine. Second, prepare the conductive solution. Pour the evenly shaken graphite emulsion and 4-methyl-2-pentanone sequentially into a beaker and stir clockwise with a glass rod. The mixing ratio is 2:3. Next, use the spraying machine for spraying. Set the air valve's unloaded pressure between 0.35-0.45. After pressing the spray button, observe the air valve pressure at the feed port dropping to between 0.17-0.25. Turn on the conveyor belt and the spray switch to start the spraying operation. Then, use an oven for baking. Set the oven temperature to 80°C and bake for 20 minutes until the surface is completely hardened. Remove and let it cool down. Finally, conduct surface resistance testing. Use a megohmmeter with a range above 2500V to test the resistance of the cooled glass. The surface resistance should be between 2MΩ/sq and 5MΩ/sq. The spray machine is shown in Figure 39. Then we assemble the honeycomb board and the PCB board with an aluminum positioning frame.

2.2.2 Production

The production takes place in the 100k-level clean room. The production workflow is shown in Figure 11. The production process shown in workflow includes cleaning of production materials in the clean room, preparation of Mylar membrane, pasting of pad spacers, connection preparation of high-voltage lines, assembly of the overall detector structure, and installation of pins and glue nails. In addition to this workflow, the content that needs a detailed explanation includes the connection and lead-out method of high-voltage lines. To isolate the copper readout strip on the PCB from the graphite film on the electrode glass, two layers of Mylar are used in between to prevent the flaws on the single layer from conducting high voltage to the readout strip, which will cause discharge. On Mylar, a slot is opened at the position corresponding to the high-voltage pad or through-hole on the PCB. The middle PCB's high voltage connection method differs from the top and bottom ones. For the top and bottom PCB boards, the high-voltage cables will pass through the PCB and Mylar, to the copper foil fixed on the surface of

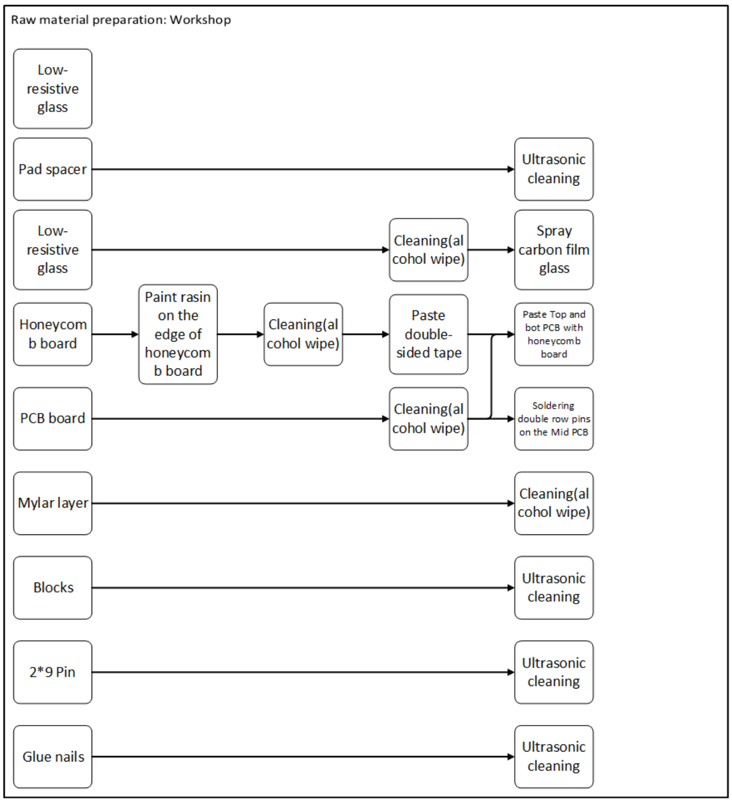


Figure 8: Work flow of MRPC2 material preparation.

Figure 9: Cleaning the low resistive glass.

the electrode glass carbon film. For the middle PCB, its surface contains a copper pad. The carbon film tape is filled in the high voltage installation slot of the Mylar, connecting the PCB high voltage copper pad and the electrode glass graphite film. The high-voltage cable is then welded to the HV pad on the middle PCB board, providing the high voltage. Another thing that needs an explanation is the production and paste of pad spacers. For MRPC2, pad spacers are round pieces with a diameter of 4 mm and a thickness of 0.25 mm. These pad spacers are punched in batches by a punching machine and pasted on the upper side of a bottom high-voltage electrode glass and three middle glasses before assembly, as shown in Figure 12. The pad spacer is pasted by epoxy glue and only one side is glued to the glass. In

Figure 10: The spray machine.

order to ensure the orderliness of the pad spacer matrix on the glass, a mold as shown in Figure 13 is used. The process is: first align and fix the mold with the glass, then put epoxy glue into the small holes of the mold, and finally place the pad spacers into the small holes on the mold and press them tightly, waiting for the glue to solidify naturally. After that, the low-resistive glass are put into the stack one by one and stuck by blocks, forming four gas gaps.

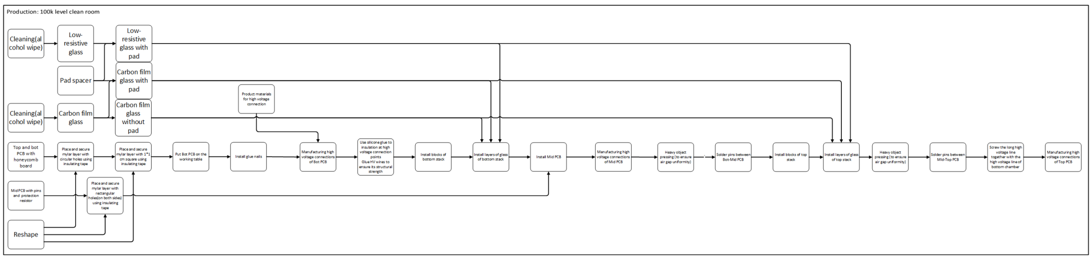
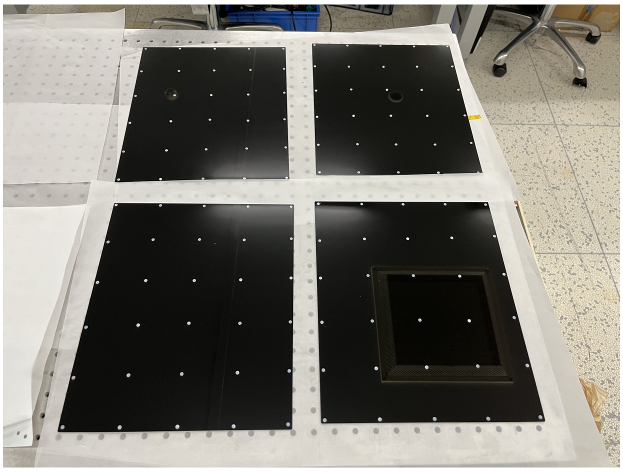


Figure 11: Work flow of MRPC2 material preparation.

2.2.3 *QA and QC*

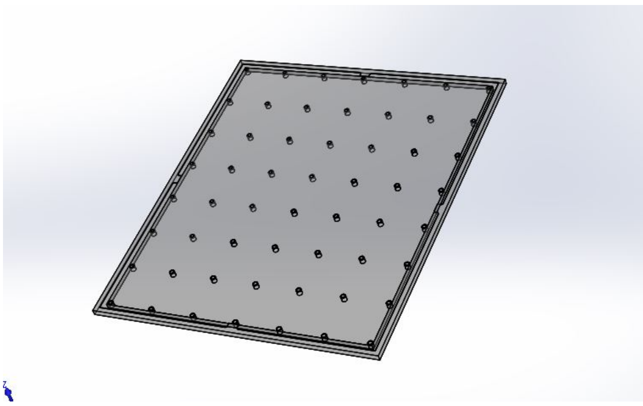
To ensure the quality of the mass-produced MRPC2, the production process is controlled and inspected in real-time. Before assembling, a careful inspection of key materials must be conducted. As shown in Table 5, a standard for key material inspection is given. For the most critical low resistive glass, each batch of glass undergoes sampling inspection, divided into two steps. The first step is bulk resistivity testing, where 10 pieces are randomly selected from each production batch of 400 pieces of low-resistivity glass for bulk resistivity measurement. As shown in Figure 14, the bulk resistivity of each sampled glass piece is measured at 5 different points, and the bulk resistivity is required to be between $10^{10}\Omega$cm and $3\times10^{10}\Omega$cm . The second step is high-voltage testing with a double-gap device, where each batch of glass is required to have a dark current of less than 80 nA under a high voltage of ±6000 V. Similarly, 10 pieces are randomly selected from each batch of 400 pieces of glass for this test. Each batch of glass must

(a) MRPC2 punching machine.

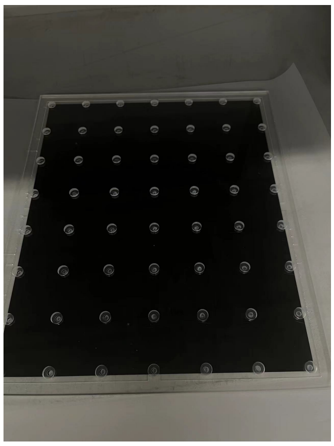


(b) Pad spacers pasted on the glass.

Figure 12: Modeling pictures of high time resolution MRPC.



(a) Modeling picture of pad spacer mold.



(b) Physical picture of pad spacer mold on the glass.

Figure 13: Modeling diagram of high time resolution MRPC.

pass the above two sampling inspection steps. Otherwise, all the glasses in this batch will not participate in assembling production of MRPC2.

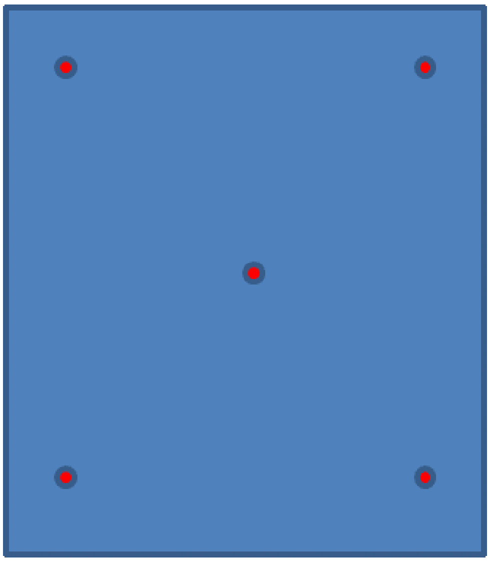


Figure 14: Bulk resistivity test.

Another noteworthy point is the inspection of the detector's signal connection and output sections. We do not plan to test the impedance of the detector, but we will inspect the soldering condition of the protection resistors and signal pins. The single-ended impedance of the detector readout strip is 59Ω. The impedance of the detector is related to parameters such as the PCB material and the width of the readout strip, which is calculated using microstrip transmission line theory and tested with a time-domain reflectometer. Given the high stability of PCB manufacturing, the signal amplitude error caused by the detector impedance can be ignored. For the detector, the use of protection resistors is more important. When the detector is in operation, the readout strip acts as a current source, and the PADI-FEE is connected in parallel with the protection resistor as a load. The protection resistor of the detector is 200kΩ, and the impedance of the PADI-FEE is 50Ω under operating conditions, but far greater than 200kΩ when powered off. The protection resistor can divert most of the current generated by the readout strip source when the PADI-FEE is powered off, preventing damage to the PADI-FEE. Meanwhile, its resistance is much larger than the working impedance of the PADI-FEE, so it does not affect the amplitude of the working signal. Additionally, the soldering of the 2×9 signal pins is also very important. If there is a poor solder joint, it may cause significant noise in a particular channel of the detector, greatly increasing the counting pressure on the PADI-FEE board. For the above reasons, the impedance of the readout strip and the protection resistor in the MRPC2 will not be tested. However, the soldering condition of the protection resistor and signal pins will be inspected. The tests conducted on the solder joints include using a multimeter to check for short circuits (continuity) between the corresponding output pins at both ends of the detector readout strip and measuring the resistance value across the protection resistor to ensure it is correct.

In the process of detector assembly, it is necessary to control the installation accuracy of the accessories and the readout PCB. One of the most important is to ensure the uniformity of the detector gas gap. A wide gap will reduce the performance and counting rate of the detector, otherwise a narrow gap will cause discharge phenomenon and lead to high voltage breakdown. Many factors may cause uneven gas gaps. In order to accurately measure the gas gap thickness of the detector, a new method of directly observing gap with a digital microscope was adopted during the quality inspection. As shown in Figure 15, five layers of gray low resistive glasses and 4 black gas gaps are shown clearly in the picture. The boundary recognition function can measure the gas gap width intuitively and accurately to judge its uniformity. Each MRPC2 produced will go through a 12-hour long high voltage test at Tsinghua University, and the performance is required to meet the following indicators.

a. $\leq$ 12 hour test time;

b. $\leq$ 60 nA dark current;

Also, a cosmic ray test system based on PADI-FEE and TDM is built in the lab of Tsinghua University, half the amount of the MRPC2 produced will go through cosmic ray test, and the performance is required to meet the following indicators.

c. $\leq 2\ \mathrm{Hz/cm^2}$ noise rate;

d. $>$ 95% efficiency;

e. $\leq$ 90 ps time resolution;

The quality inspection data of each MRPC2 will be strictly recorded in the table shown in Figure 44. The QR code is made by the production site, and all QC protocols including HV tests from the lab and other QC tests by the production site will be recorded and correspond to the specific detector. You can log in to the Tsinghua University-CBM cooperative detector research and development website http://hepd.ep.tsinghua.edu.cn/ CBM_TOF/ for quality inspection data. Only fully qualified detectors can be packaged and transported. The detector will come with two stickers with the detector number and QR code, one of the stickers is glued on top of the MRPC2, and another will be affixed to the outside of the module when the detector is installed for subsequent inspection.

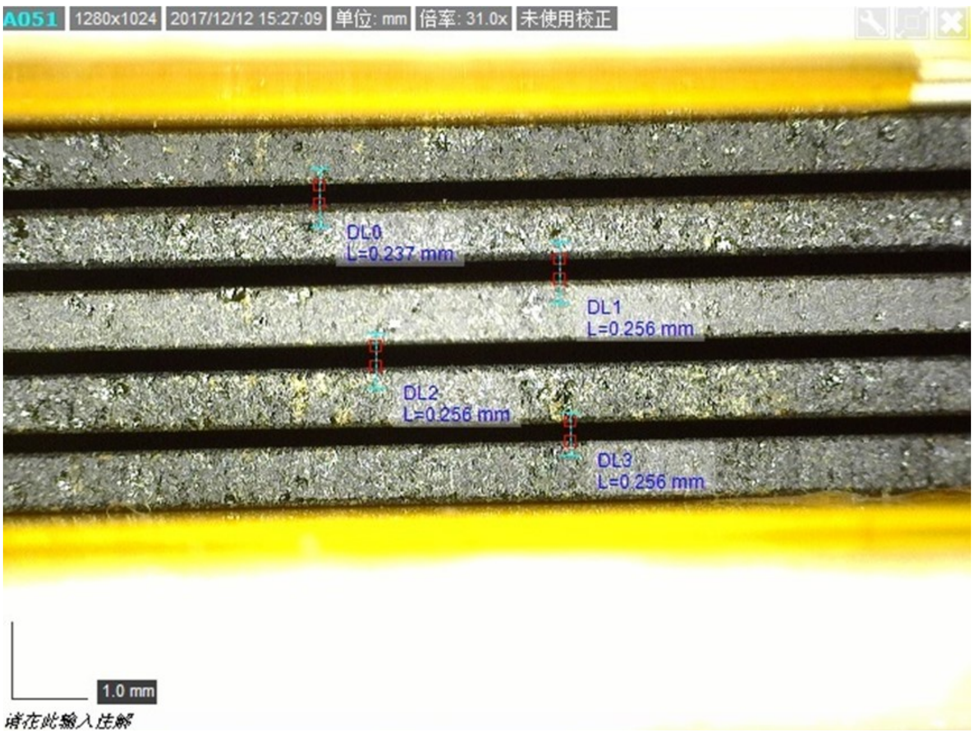


Figure 15: MRPC gap image detected by electron microscope, it can directly measure the gap width.

Table 5: MRPC2 material quality inspection standards and inspection methods.

Material	Quality inspection standard	Inspection method
Low-resistive glass	Length err$\leq \pm$ 0.2 mm, thickness err $\leq \pm$0.02 mm, No scratches, cracks and perforations	Spiral Micrometer and eye
Readout PCB board	Length err$\leq \pm$ 0.2 mm, thickness err $\leq \pm$0.05 mm, No scratches, cracks.no open circuit or short circuit, protection resistive value correct	Vernier caliper,eye and Multimeter
Honeycomb board	Length err$\leq \pm$ 1 mm, thickness err $\leq \pm$0.02 mm, surface smooth and without scratches	Vernier caliper and eye
Mylar	Length err$\leq \pm$ 0.2 mm, thickness err $\leq \pm$0.02 mm, No scratches, cracks and perforations	Spiral Micrometer and eye
Carbon film tape	thickness err $\leq \pm$0.02 mm,surface resistivity$\sim$ 100$k\Omega$/sq	Spiral Micrometer and High resistance meter
Carbon film	Spray evenly without scratches and bumps,surface resistivity$\leq$ 10$M\Omega$/sq	High resistance meter and eye
Pad spacer	Thickness err$\leq \pm$ 0.005 mm	Spiral Micrometer sampling detection

2.2.4 Production plan

120 MRPC2s will be mass-produced, a production phase that started on May 1, 2024 and will end before December 31, 2024.

2.3 Performance of MRPC2

Since MRPC2 was chosen to take part in FAIR-Phase0 programs such as STAR-eTOF and mTOF, close to one hundred of MRPC2 prototypes with fishing line spacers have been produced for tests in different places, generating dozens of results that validates the performance and reliability. Here we describe results from 3 representative tests.

2.3.1 Beam test at SPS

A fixed target beam test was carried out at SPS facility in 2015. The 30 AGeV lead beam aimed at a lead target with a thickness of 1 mm. This collision system created a secondary particle flux which translated to a 10 kHz/cm^2 rate condition at MRPC2. Multiple working conditions had been studied, including the HV scan and PADI threshold scan. Figure 16 records the efficiency and time resolution of the MRPC2 prototype with the corresponding HV and threshold conditions. The prototype behaved well at working point of 5500 V with 400 mV threshold.

2.3.2 Mass test on prototypes for STAR-eTOF

The whole STAR-eTOF project calls for 108 MRPCs which includes 48 MRPC2. The installation of STAR-eTOF finished in 2019. Before that, MRPC2 detectors has been validated their performances using the TRB3 cosmic test system in Tsinghua.

Thanks to the system shown in Figure 17, we are able to collect performances for most of the detectors

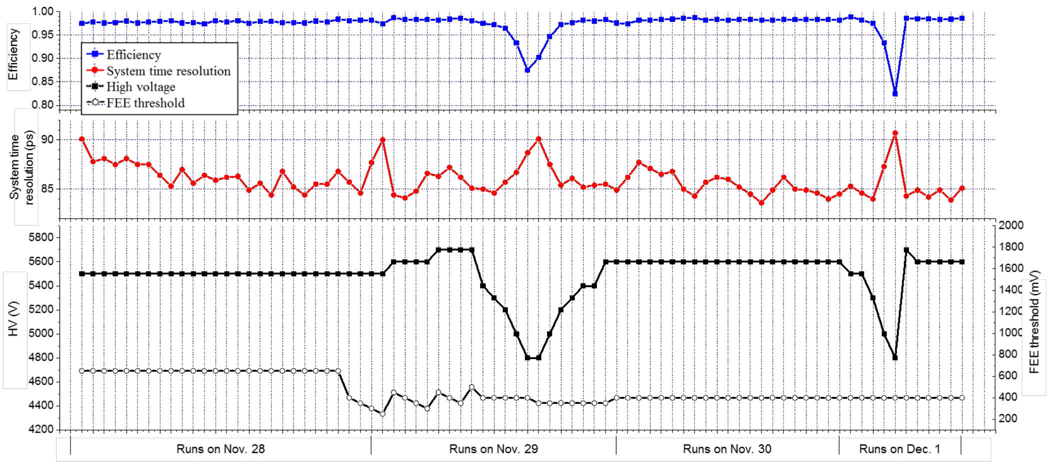


Figure 16: Beam test performances of MRPC2 in conditions of different HV and threshold.

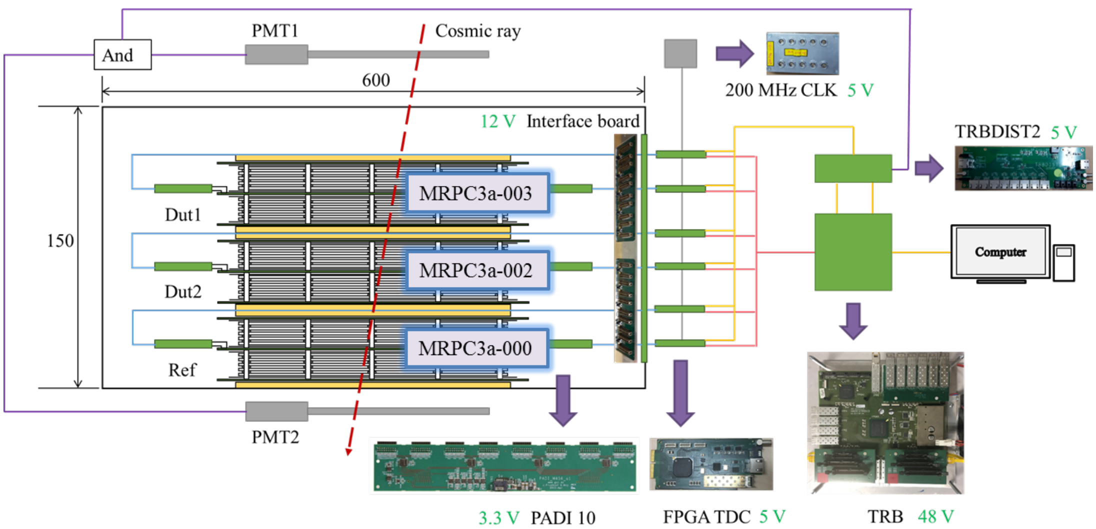


Figure 17: Scheme of the TRB3 system. Three MRPC2s (MRPC3a is the former name) can be tested for each run.

for STAR-eTOF, which are distributed in Figure 18. Each point in the figure stands for a detector, and all the performances lay within the shadowed area that meets the requirements. Among the detectors, we selected 3 counters to investigate the noise and dark current behavior during a HV training of 180 h. From the result shown in Figure 19, the noise rate and current are found to decrease with time as expected.

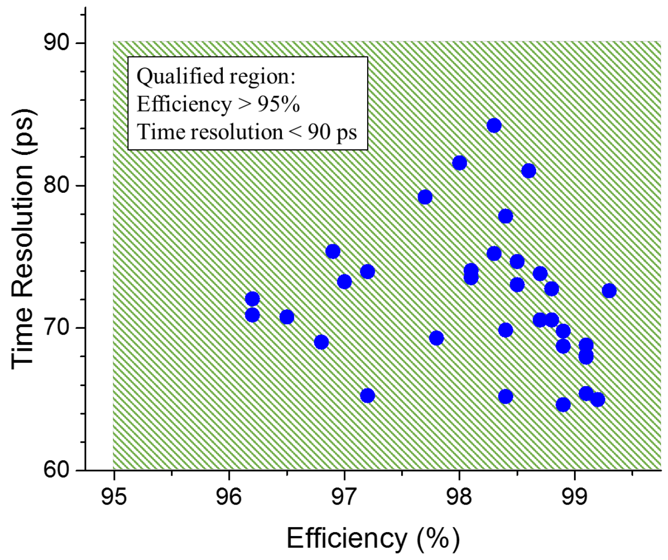


Figure 18: Performances of detectors in the mass cosmic test.

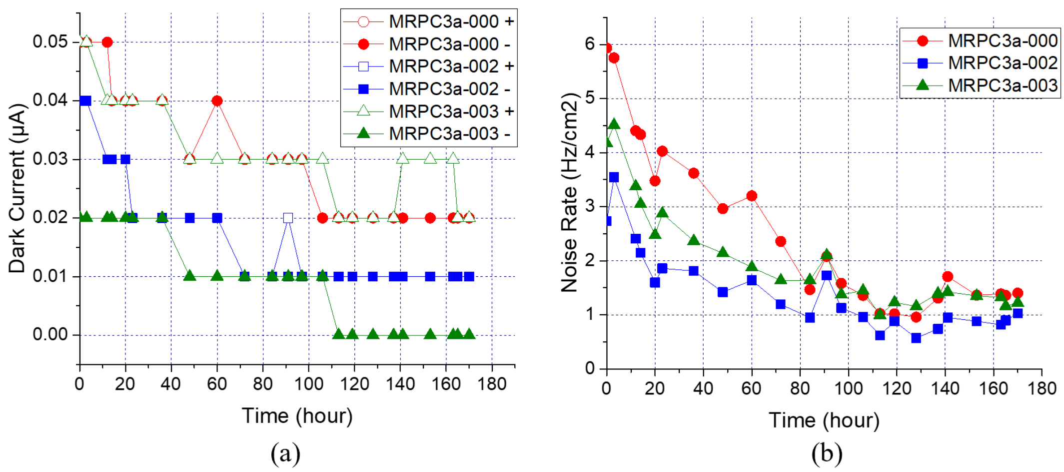


Figure 19: Dark current (a) and noise rate (b) behavior of MRPC2 during the training, at a HV of ± 5600 V.

2.3.3 Operation at STAR-eTOF and mCBM

eTOF has been taking part in the beamtime at STAR since Run18. The first result came from 9 MRPC2s installed in 3 sectors at STAR endcap. 600 k valid events of Au-Au collision at 27 GeV were collected. For each event, we found valid hits of eTOF that could match tracks from TPC, and TPC tracks contained T0 information which had been recorded in advance from VPD. In this way, we could calculate the flight time between VPD and eTOF. The time resolution of VPD is about 61 ps. After carrying out corrections which cover track length, time slewing effect, electronics gains and so on, the final result of the flight time distribution is shown in Figure 20. Time resolution for MRPC2 is $\sqrt{85^2 - 61^2} = 59$ ps.

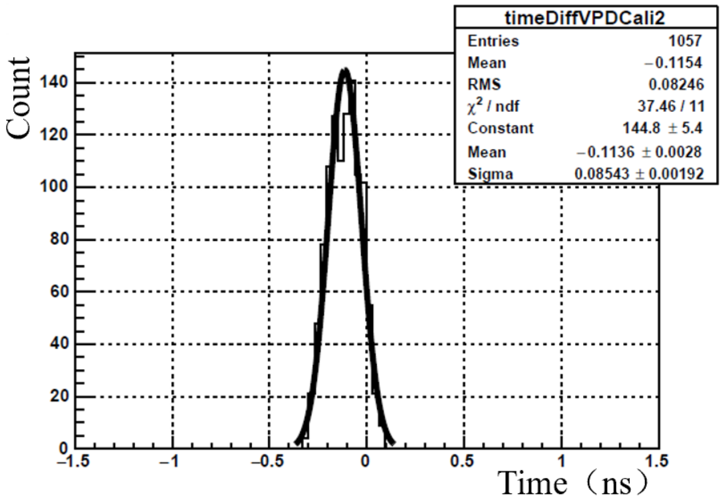


Figure 20: Flight time distribution between VPD and eTOF.

With the validated timing performance, eTOF successfully plays its role in the particle identification. Figure 21 shows the very first PID result of the high rate MRPC. Since the installation of eTOF, the phase space coverage has been expanded, which supports the BES-II project.

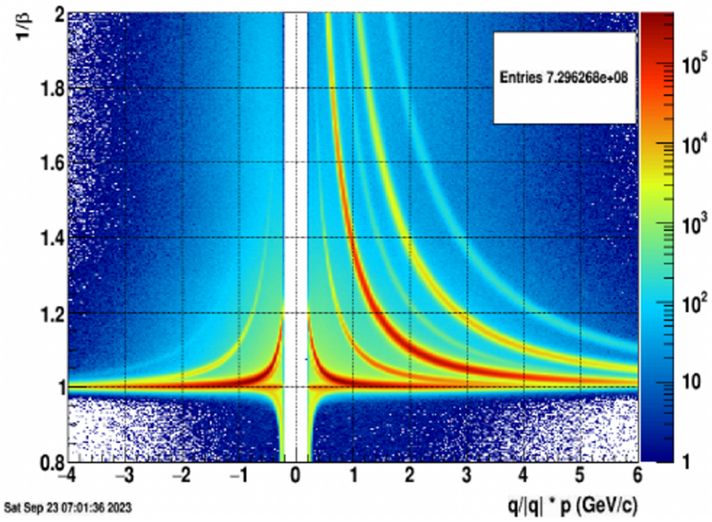
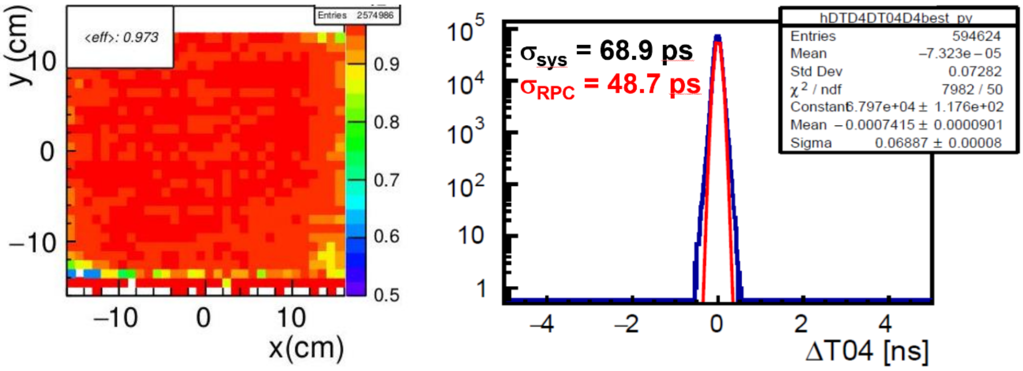


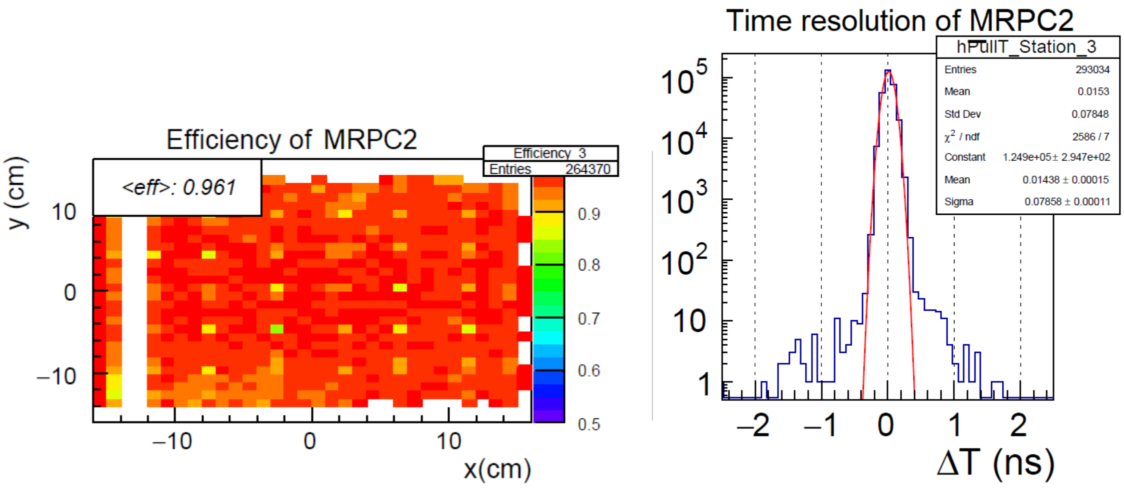
Figure 21: Particle identification demonstration of STAR-eTOF.

mCBM as another FAIR-Phase0 project contains modules from the major subsystems including TOF. The mTOF system was built with 25 MRPC2s into 5 modules. Two modules are settled close to the beamline in order to accept high flux. They are marked as M4 and M5 from upstream to downstream. With the same direction settles M1, M2 and M3 at further angle close to M4 and M5. Fixed-target collisions were produced between the gold beam up to 1.24 AGeV and the gold target. Working in the free-running mode, mTOF data analysis follows the Digi time flow, builds the detector hits and reconstruct tracks through their time-space correlation. The performance of the mTOF MRPC2 will then be obtained after proper corrections. Here we take use of the hits M1 and M3 to reach better track reconstruction, and to give more dedicated correction to M2 hits. Figure 22(a) shows the efficiency distribution with the active area of an MRPC2 at M2, where not only high efficiency but good uniformity is validated. Figure 22(b) shows the time resolution of the MRPC2 at M2, where excellent time resolution can be found. This performance, however, was obtained with unsealed MRPC2 prototypes with fishing line spacers. Simular performance plot were also obtained with sealed MRPC2 prototypes with pad spacers (see Fig. 23(a) and Fig. 23(b)).



(a) Efficiency map for MRPC2 (b) Time resolution of MRPC2

Figure 22: Performance of sealed MRPC2 counter with fishing line spacers.



(a) Efficiency map for MRPC2 (b) Time resolution of MRPC2

Figure 23: Performance of sealed MRPC2 counter with pad spacers.

3 Production readiness at USTC

3.1 Introduction to MRPC3 and MRPC4

3.1.1 MRPC3 and MRPC4 in CBM-TOF wall

The blue area of the outer TOF wall (see Fig. 2) consists of 40 M5 modules, each containing 5 MRPC3 counters, and 62 M6 modules, each equipped with 5 MRPC4 counters, totaling 200 MRPC3s and 310 MRPC4s. By appropriately designing the gas gaps and gap thickness, efficiency and time resolution requirements can be met while maintaining a 50 Ω impedance. The granularity of the readout strip is optimized to balance occupancy, FEE bandwidth limitations, and mechanical feasibility. Further details on the geometry of MRPC3 and MRPC4 are provided in the following subsection.

The MRPC3 and MRPC4, foreseen to be integrated in the low rate region, have to cope with charged particle fluxes up to 1.5 $\mathrm{kHz/cm^2}$. Lowering the resistance of the resistive plates is one effective method to increase the rate capability of MRPCs, a second way is to decrease the thickness of the resistive plate if the rate conditions are still moderate. Therefore, 0.23 mm thickness ultra-thin float glass will be constructed as resistive electrode material since it is by far cheaper compared to the low resistive glass used for MRPC2. Under high beam intensity, MRPCs face aging challenges, leading to decline of efficiency and time resolution. To address this issue, based on MRPC3, a new MRPC prototype with cylinder thermal bonding spacers (TBS) was proposed, called TBS MRPC. Relevant research shows, under high irradiation flux environments, the TBS MRPC detector shows better anti-aging performance compared to traditional MRPCs with fishline spacers. A detailed description on MRPC3 and MRPC4 geometry is given in the following section.

3.1.2 Structure of MRPC3 and MRPC4

MRPC3 is a detector with a double-layer structure, which is constructed with two honeycomb panels, three PCBs, and several pieces of ultra-thin float glasses. They are secured using adhesive screws and metal pins. The signal from the top and bottom PCBs are transmitted to the middle board through metal pins. Subsequently, signals are relayed to external electronics through pins soldered onto the middle board. Ground lines on the other three PCBs are linked with copper strips. The ground line on the middle board connects to the signal pins and achieves grounding through an external pre-amplifier. The following table 6 lists some main parameters of MRPC3

Table 6: Main parameters for MRPC3.

Parameter	Unit	Value
Dimension	[$\mathrm{mm^2}$]	$377\times$ 324
Thickness	[mm]	22
Sensitive area	[$\mathrm{mm^2}$]	320×270
Glass size	[$\mathrm{mm^2}$]	353×276
Num. of gas gaps		2×5
Gap thickness	[mm]	0.23
Strip and gap width	[mm]	7+3
Strip length	[mm]	270
Num. of strips		32
Operational electric field	[kV/cm]	108

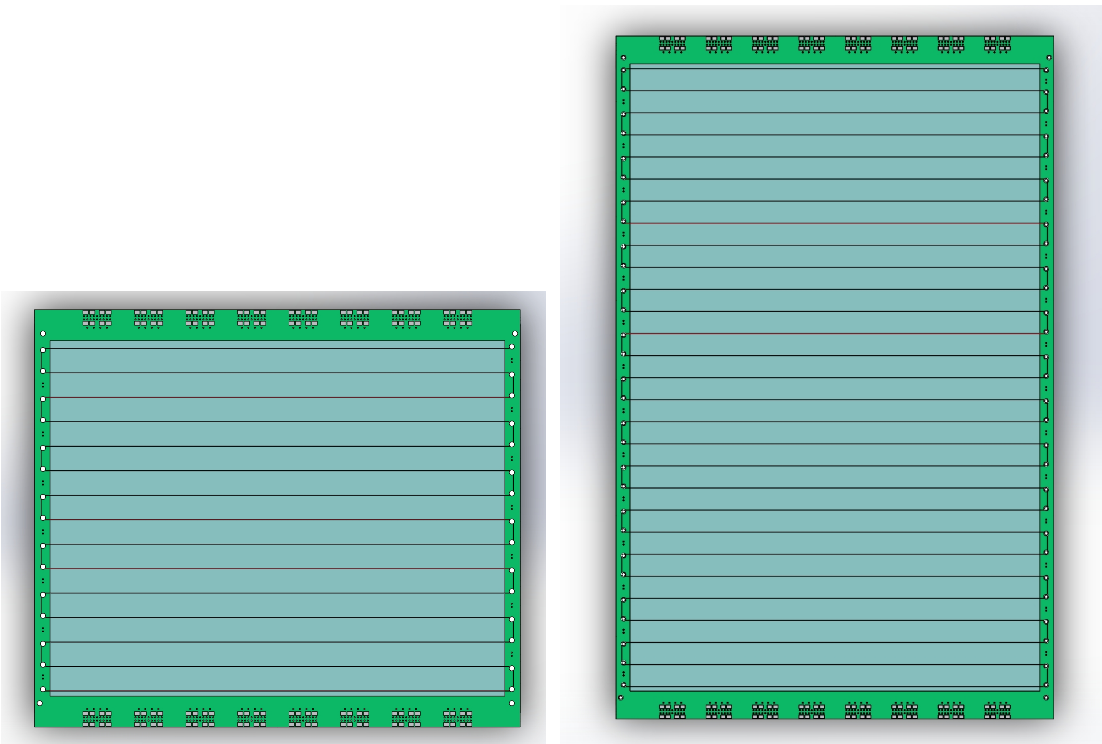
MRPC4 is an enlarged version of MRPC3. Compared with MRPC3, it is positioned at the outermost layer of the TOF-wall (M6 modules see Fig. 2), requiring a lower count rate. To achieve this, the entire

MRPC3 is doubled in size, meaning the sensitive area is expanded by enlarging the strip length by a factor of two, resulting in MRPC4. In other aspects, there isn't a significant difference between the two detectors. The following table 7 lists some relevant parameters of MRPC4.

Table 7: Main parameters for MRPC4.

Parameter	Unit	Value
Dimension	[mm^2]	377× 588
Thickness	[mm]	22
Sensitive area	[mm^2]	320×540
Glass size	[mm^2]	353×540
Num. of gas gaps		2×5
Gap thickness	[mm]	0.23
Strip and gap width	[mm]	7+3
Strip length	[mm]	540
Num. of strips		32
Operational electric field	[kV/cm]	108

The following Figure 24 illustrates the models of MRPC3 and MRPC4, along with a shared side-view schematic(Figure 25).



(a) MRPC3 (b) MRPC4

Figure 24: Mold of MRPC3 and MRPC4.

- PCB board and honeycomb panel

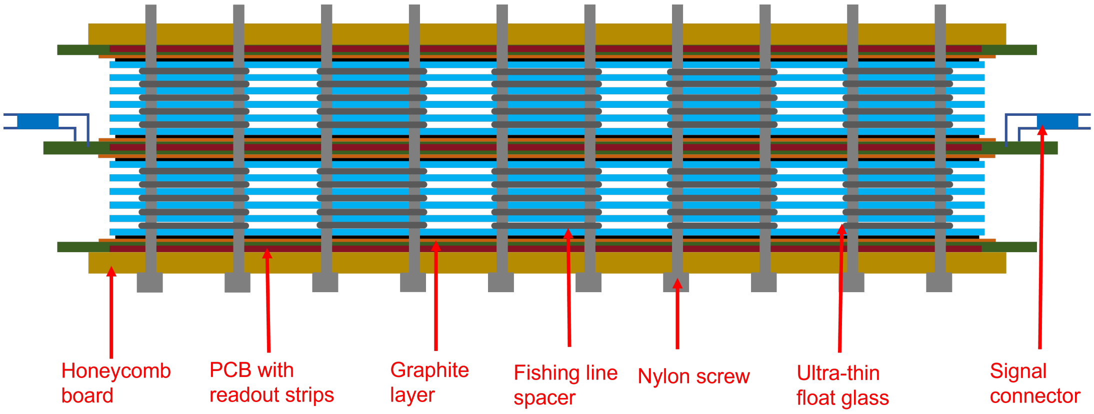
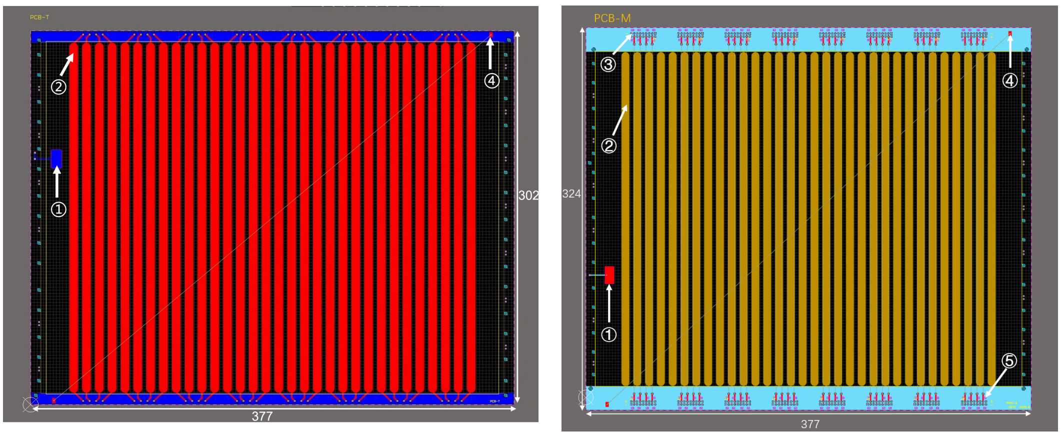


Figure 25: Side-view schematic of both MRPC3 and MRPC4

The PCB board has metal (Cu) readout strips for inducing currents and transmitting signals. With 32 readout strips, induced currents are sent to both ends of the PCB and then relayed to external electronics via signal connectors for readout. Protective 1 MΩ resistors R1 (see Fig. 27) at both ends prevent excessive current. The Points A.B,C,D can be used to crosscheck the the connectivity of all resistances by measuring the total resistance. Values are given in Table 8. There's also a small rectangular electrode on the PCB supplying the required high voltage for the detector. An external high-voltage source connects to the PCB, applying high voltage to the glass with graphite layer. This creates a uniform electric field across the entire glass. Due to the mirror symmetry of the top and bottom PCBs, their design are roughly similar. Schematic diagrams (Figure 24) for the two PCB layers (Top and Middle) are provided below.



(a) MRPC3-Top PCB (b) MRPC3-Middle PCB

Figure 26: Top (a) and Middle (b) PCB design of MRPC3. ① HV electrode; ② Readout strip; ③ Signal connector; ④ Ground pad; ⑤ Protection resistor.

Table 8: Values of resistance between distinct points

Connection points	A - B	A - C or B - C or A - D or B - D	C - D
Total resistance value	31.25 kΩ	680.63 kΩ	1 MΩ

Two honeycomb panels are glued to the top and bottom surfaces of the PCB boards, ensuring the overall stability of the detector structure.

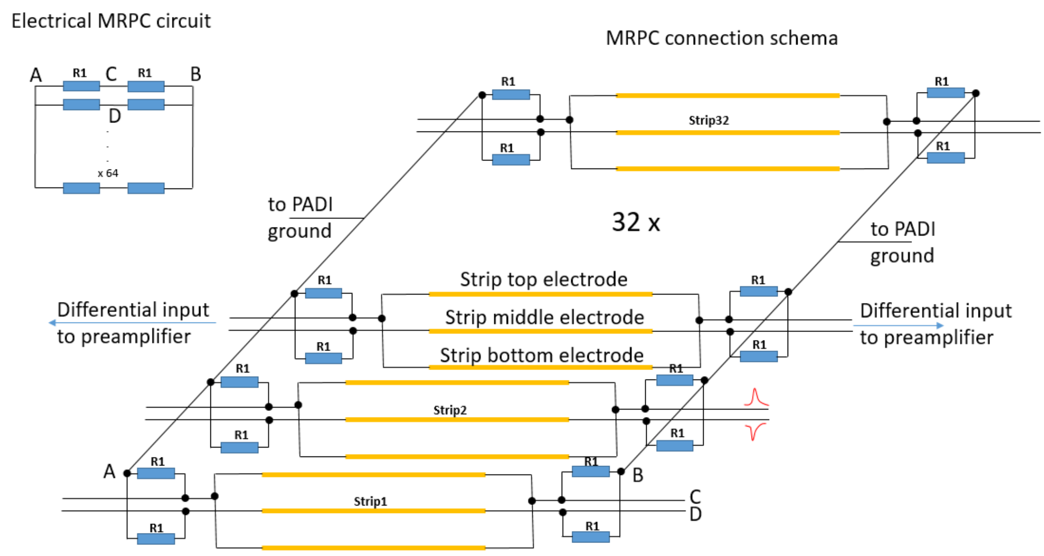


Figure 27: Electrical circuit (top left) and electrical connection schema of MRPC3 and MRPC4. The value of R1 is 1 MΩ. The Points A.B,C,D can be used to crosscheck the the connectivity of all resistances.

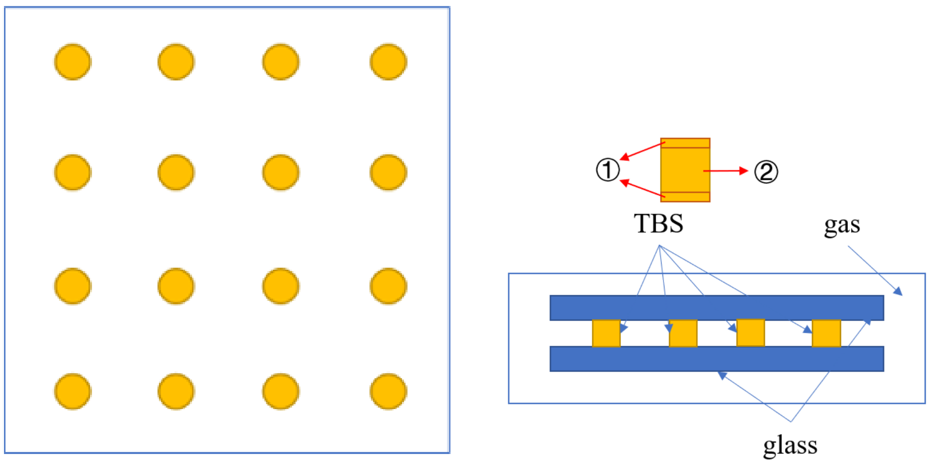
Figure 28: Honeycomb board pasted to PCB

3.1.3 TBS MRPC3

Spacers of MRPC3 are used to support ultra-thin float glass, creating uniform gaps to prevent glass deformation and ensure a uniform electric field between the gaps. For traditional MRPCs, fishing line is commonly used as spacer. However, the presence of gaps between the fishing lines and the glass resulted in non-uniform electric fields, leading to increased dark current and background noise under high radiation environment. To address these issues, a cylindrical-shaped spacer was adopted.

The spacer has a structure with a cylindrical shape, a diameter of 2 mm, and a thickness of 0.24 mm, featuring a three-layer structure: thermal bonding film (①) - PET (②) - thermal bonding film (①), as shown in figure 29 (b). After cooling, the thermal bonding adhesive solidifies, securing the glass on it, thus forming gas gaps between the glasses. Due to its special use of thermal bonding adhesive material, it is called thermal bonding spacer(TBS). This spacer has good thickness uniformity and insulation properties, and contains no chemical agents, making it an excellent material.These spacers are placed in the positions previously occupied by fishing lines, spaced 19 mm apart from each other. In each gap, 285 spacers are arranged in a grid pattern.The figure 30 shows the spacer layer of TBS MRPC3. Relevant simulation results indicate that the maximum deformation of the TBS MRPC is comparable to that of the fishing line MRPC, while its electric field is more uniform.

Apart from different spacers, the two types of MRPC share a similar structure. The figure 31 illustrates the models of both detectors.



(a) (b)

Figure 29: Top view (a) and side view (b) of TBS MRPC.

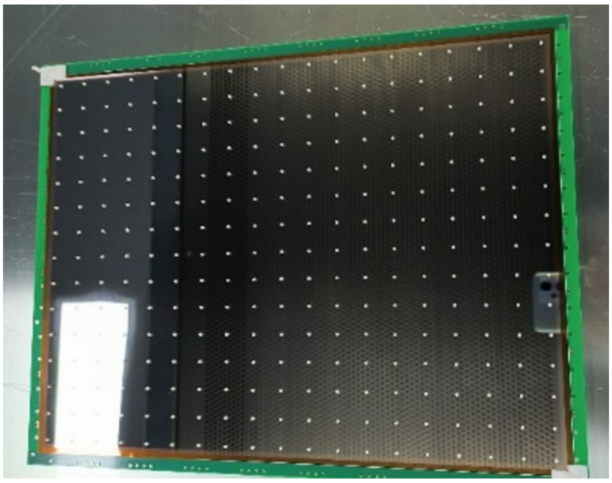
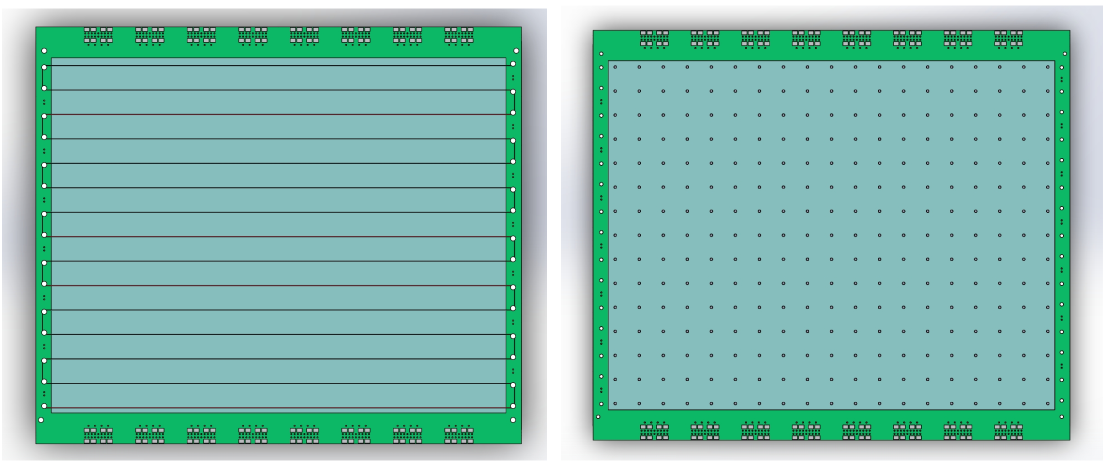


Figure 30: A spacers pasted layer of TBS MRPC3



(a)

(b)

Figure 31: Spacer layer of MRPC3 with fishline spacers (a) and TBS MRPC3 (b).

3.1.4 Performance of MRPC3

- Beam test at BEPC-II

To assess the performance of MRPC3 (referred to as MRPC3 now), relevant beam tests were conducted using the Beijing Spectrometer. MRPC3b prototypes were tested in beam at the BEPC-II, CAS in Beijing, with the 700 MeV hadron beam. The experimental area located at the end of the E3 line. The test system and results are presented below in Figure 32 and Figure 33.

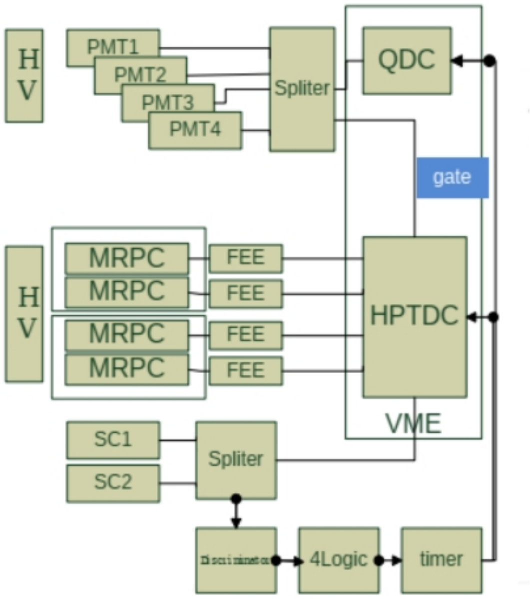


Figure 32: MRPC3-Beam test system.

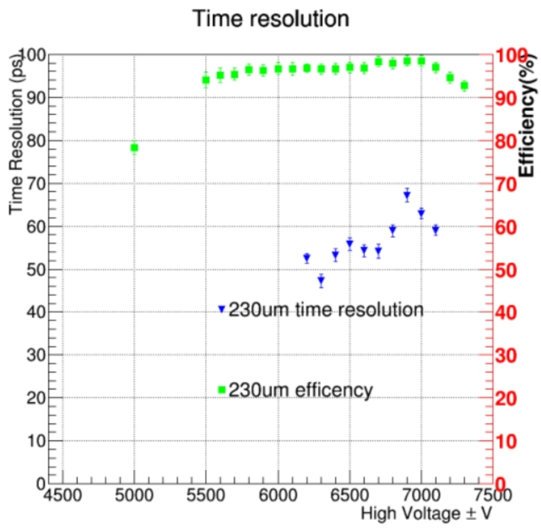
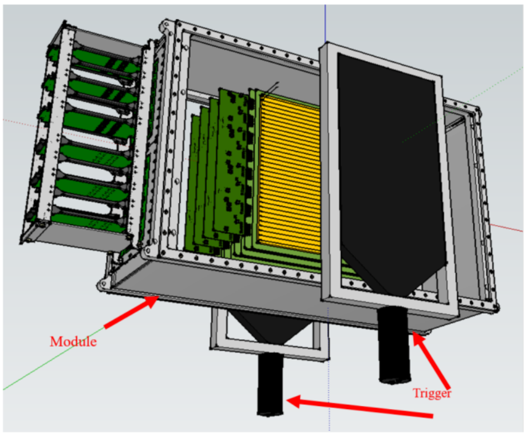


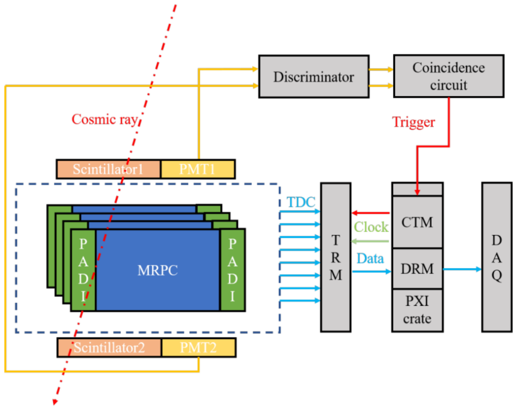
Figure 33: Efficiency and time resolution of MRPC3.

- MRPC3b batch test result for STAR-eTOF

Before MRPC3b (referred to as MRPC3 now) was applied in the construction of CBM-TOF, approximately 80 MRPC3bs were assembled for the STAR endcap TOF (STAR-eTOF) upgrade at RHIC as part of the FAIR Phase-0 program for CBM-TOF. This provided a valuable opportunity for testing the long term stability of the detector under moderate flux environments. Here is the batch test of the MRPC3bs for STAR-eTOF upgrade. Time resolution of better than 70 ps and efficiency of around 95% are achieved.

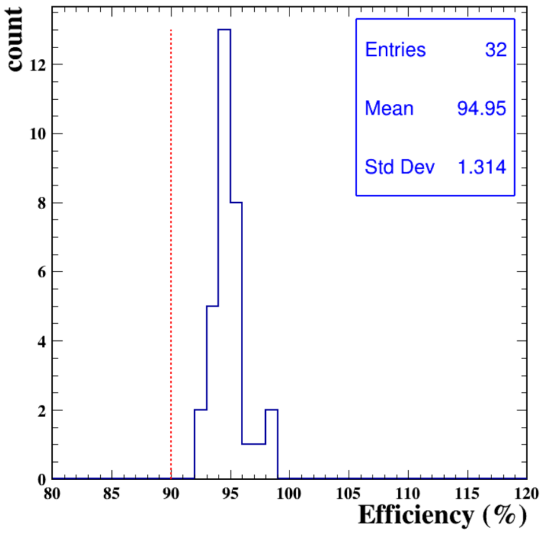


(a)

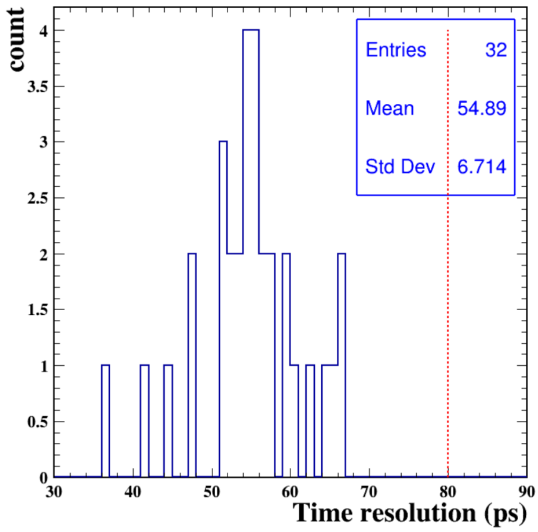


(b)

Figure 34: Cosmic ray test system for MRPC3b batch test.



(a)



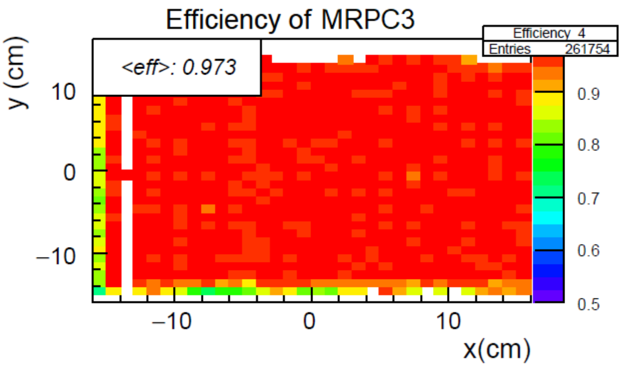
(b)

Figure 35: (a) Efficiency of 32 tested MRPC3bs, with the red line representing 90% eficiency. (b) Time resolution of the 32 tested MRPC3bs, with the red line representing time resolution of 80 ps.

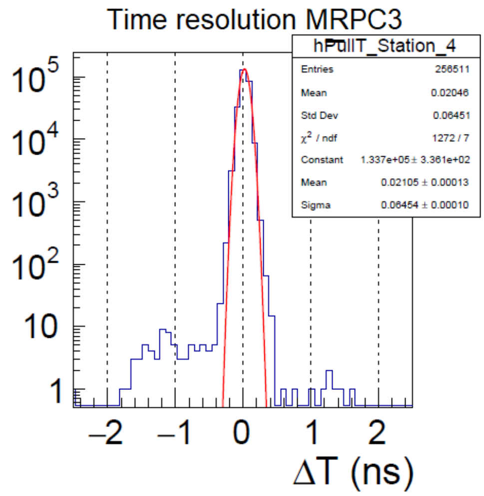
- MRPC3 and MRPC4 performance test at mCBM

The MRPC3 and MRPC4 counter were tested at mCBM as well. Figure 36 shows the performances of a TBS MRPC3 counter (final version) in terms of efficiency and time resolution. An average efficiency of above 97 % was reached while showing a time resolution of about 65 ps.

The thin float glass counter were also tested at various charged particle fluxes. Fig. 37 shows in (a) the efficiency and (b) the time resolution vs. the charged particle flux. An expected degradation is visible, however, a rate capability of about 4 kHz/cm^2 can be deduced (degradation of 5 % in efficiency or 20 ps in time resolution).

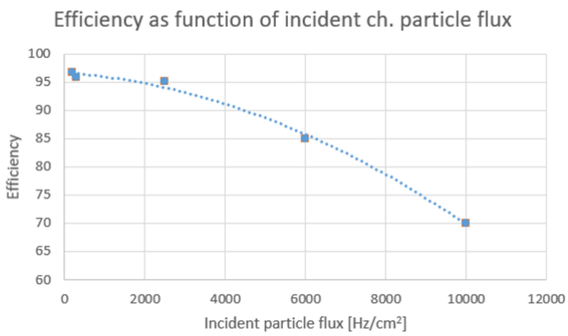


(a) Efficiency map for MRPC3

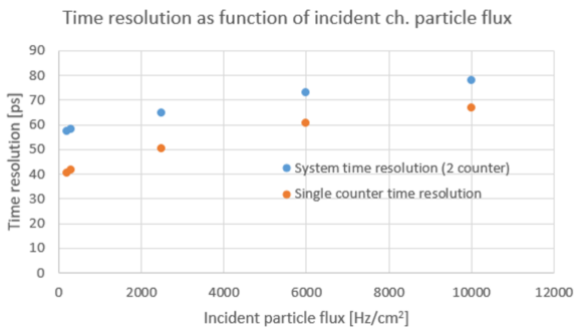


(b) Time resolution of MRPC3

Figure 36: Performance of TBS MRPC3 counter.



(a) Efficiency vs. ch. particle flux



(b) Time resolution vs. ch. particle flux

Figure 37: Performance of thin float glass counter.

3.2 Production of MRPC3 and MRPC4

3.2.1 Production preparations

Based on the STAR-eTOF production experience, assembly documents including 21 assembly steps have been formulated in detail for QC & QA. All assembling will be carried out at new 10 K clean room of about 90 m^2 clean room for cleaning.Table 9 shows the materials required for MRPC3. All the materials will be checked, labeled, measured, recorded and signed before being assembled as shown in Figure 38, and all measured data will be recorded in 7 corresponding “Record Tables”. After the MRPC has been assembled, it is necessary to measure the dimensions of the detector to assure gas gap uniform. Last but not least, the records will be updated into the online database so that each counter can be traced back to the raw material and operators.

Table 9: Main design parameters for MRPC3.

Material	Length /[mm]	Width /[mm]	Thickness /[mm]	Amount	Others
float glass	353±0.4	276±0.4	0.23±0.02	12	$\sim 1\times10^{13}\Omega cm$
Graphite layer	349±0.5	272±0.5	0.005	4	$\leq 10M\Omega$ /sq
TOP PCB	377±0.1	302±0.1	0.9±0.05	1	
Bottom PCB	377±0.1	302±0.1	0.9±0.05	1	
Middle PCB	377±0.1	324±0.1	1.6±0.05	1	
Honeycomb board	353±1	285±1	6±0.1	2	
Kapton foil	361±0.5	284±0.5	0.050±0.01	4	
	361±0.5	284±0.5	0.075±0.02	4	
Carbon tape	15	8	0.13±0.2	4	$\sim 100k\Omega$/sq
Fishing line	55000	0.23±0.005	/	/	Nylon
HV wire	1200	/	/	2	
M3 Screws	20	3	/	34	Nylon
fix pin	11	0.8	/	90	
Protection resistor	/	/	/	128	1MΩ 0805

- Honeycomb board Place both sides of the honeycomb panel onto optical platform, and check if all edges and corners of the panel fit closely to the glass. Panels with noticeable warping should be marked as defective. Carefully inspect the surface of the qualified honeycomb panels, and use a scalpel to remove any remaining particles, glue spots, or other residues, ensuring no raised residues are left behind. Then, place the honeycomb panel with the better surface facing up, clean it with alcohol, blow it dry with nitrogen, and apply double-sided tape.

- PCB board Send the PCB boards to the factory to have the protective resistors and signal connectors soldered onto PCB-M. Upon receiving the finished products, use multi-meter to check the connections. Next, perform a surface quality inspection on the PCBs, checking for defects, deep scratches, and hard-to-remove dirt. Ensure all pads are intact and free of solder mask residues. Discard any faulty PCBs. Use a scalpel to carefully scrape off particulate protrusions like solder mask residue and copper particles from the PCB surface. Finally, clean the surface with alcohol and blow it dry with nitrogen.

- Fishing line Each fishing line should be sequentially numbered as ”CBMxxx.” Measure the diameter of the fishing line using a micrometer, taking measurements at 10 different points for each fishing line and record the measurement results in a table.

- Graphite electrode glass Graphite electrodes are made by spraying graphite evenly on the surface of float glass, and the spray machine is shown in Figure 39. Inspect the graphite layer on the surface of the electrode glass for any impurities or defects, and mark any defective pieces as non-compliant. Carefully wipe the surface of the graphite electrode with tissue paper, ensuring an even wipe, and then blow it clean with nitrogen gas. Measure the surface resistivity of the graphite electrode using a multi-meter and a surface resistivity measurement module. Measure a total of 9 points in a 3x3 grid on each electrode, and record the measurement results in a table. Figure 40 shows the test of the surface resistance of the graphite electrode.

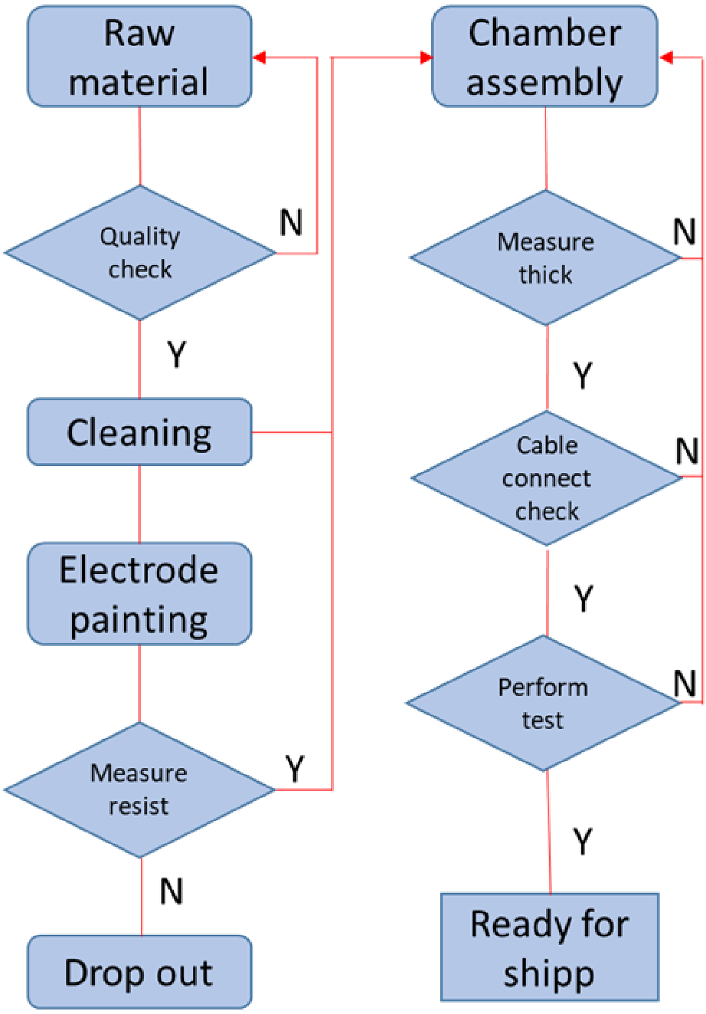


Figure 38: Mass production progress

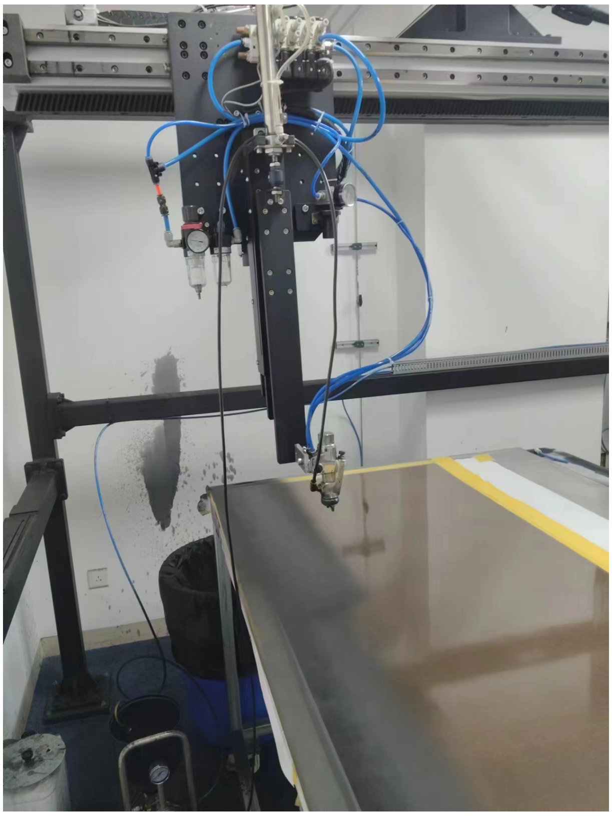
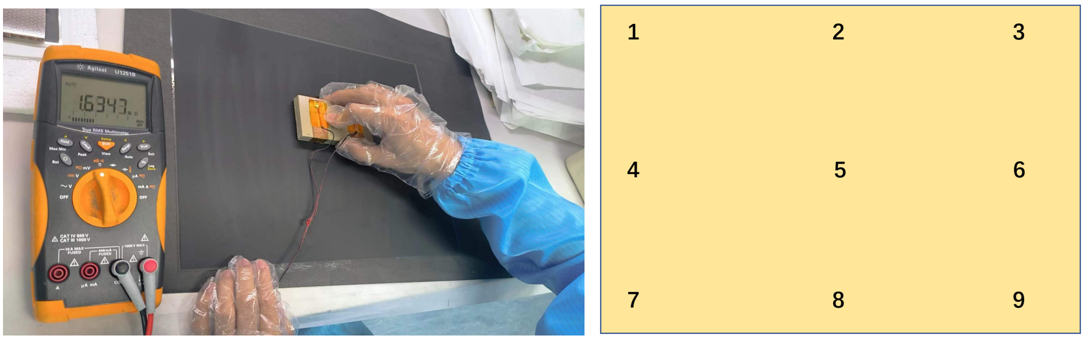


Figure 39: Auto spray machine for graphite electrode.



(a) The surface resistance of graphite electrode measurement (b) Test points

Figure 40: Test for graphite electrode glass.

3.2.2 Assembly process

After materials preparation, the honeycomb board will be affixed to the PCB board using double sides adhesive tape to make structure strongly. In order to fix the fishing line and block, we should punch the nylon screw into the holes of PCB board. A slot is opened on kapton foil, carbon tape sticked on the HV pad is filled in this slot to connect the PCB HV pad and the graphite layer. Then the block is fixed through the screw for glass fixing accuracy. The HV wire is soldered to the HV pad on the PCB board, providing the high voltage. Two layers of Kapton foil are used in between the PCB and the carbon electrode glass to prevent discharge and cross talk. After that the block is fixed and the first carbon electrode is placed on. For TBS MRPC3, the TBS spacer has a 2 mm diameter and 0.24 mm thickness. A module as shown in Figure 42 is used in order to ensure the orderliness of the TBS spacer matrix and the TBS spacer can be stuck onto the glass by heat gun as shown in Figure 42. After pasting the TBS spacers on the glass, four layers of glass with the spacers attached are stacked successively. For MRPC4 the spacer is a 0.23 mm diameter thick fishing line, we can stack 5 layers of fishing line and 4 glasses one layer after another. Finally the top electrode glass is placed on and two layers of Kapton foil and middle PCB will be stack through the screws. After 24 hours compression by Pb brick for gas gap uniformity, pins will be welded for tightness and signal connection. Then we have finished one stack of MRPC, and another stack assembly have the same steps. The quality inspection data of each MRPC3 and MRPC4 will be strictly recorded in the table shown in Figure 43. All quality inspection data can be obtained by scanning the QR code label on the detector. Also, you can browse the website http://pnp.ustc.edu.cn/detdb/ for quality inspection data.

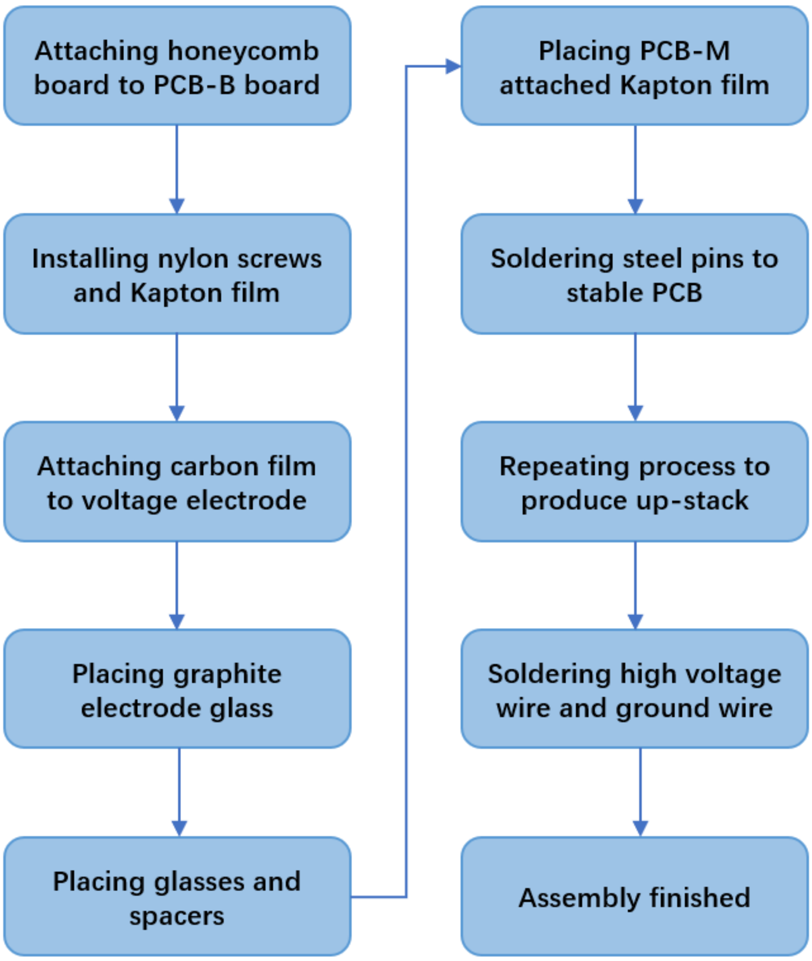
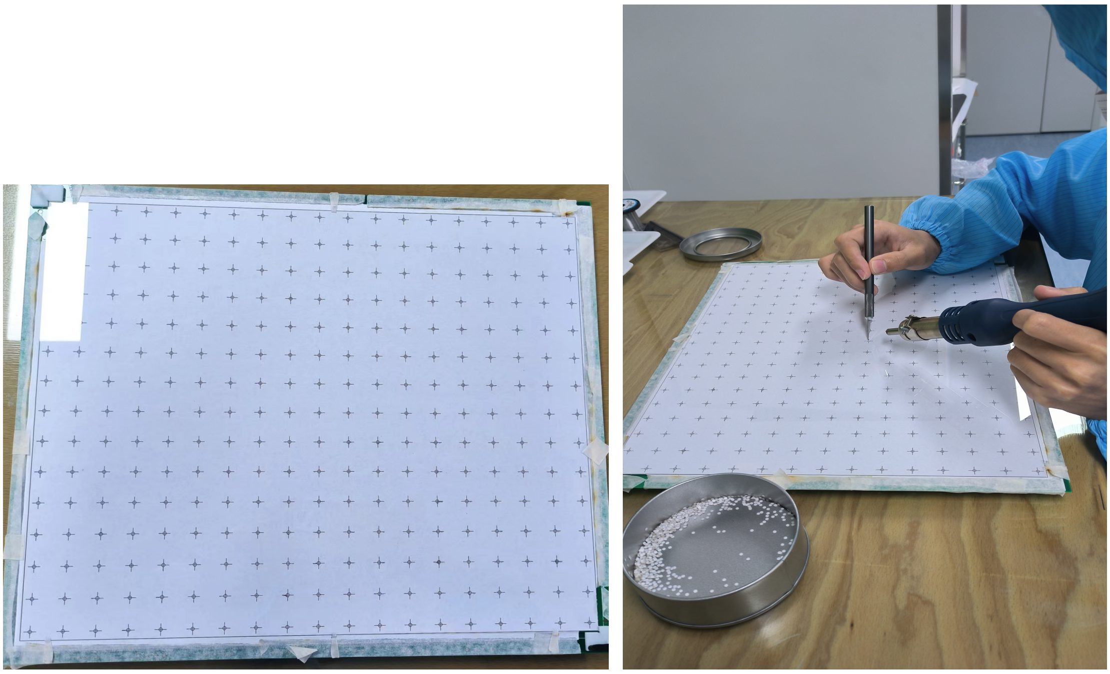


Figure 41: Mass production progress



(a) The spacer pasting module of TBS MRPC3

(b) The TBS spacer is being stuck on the glass of MRPC3

Figure 42: Placing TBS.

附件表七：CBM-TOF MRPC3 装配记录表

MRPC 编号	3#20				
蜂窝板	下	编号	F20	厚度	
	上	编号	F40	厚度	
PCB 板	下	编号	B20	厚度	
	中	编号	M01	厚度	
	上	编号	T20	厚度	
石墨电极	编号	G49	G48	G25	G24
	平均电阻				
Kapton 膜					
玻璃					
鱼线	编号	L01 L02	直径		
参加装配人员（签名）					
玻璃清洁：			焊钢针：		
Kapton 膜清洁：			高压线焊接		
尼龙螺丝安装：			信号接头焊接：		
厚度(mm) (PCB to PCB)	9.26	9.25	9.18	9.27	
	9.24	9.19	9.06	9.08	
	9.10	9.17	9.14	9.12	
厚度(mm) (Total)	21.80	21.81	21.89	21.90	
	21.81	21.73	21.80	21.87	
	21.78	21.84	21.93	21.76	
超净室条件					
装配负责人			日期		
备注					

Figure 43: The assembly table of MRPC3

4 Summary

This document summarizes the construction procedure of MRPC2, MRPC3 and MRPC4 counter for the outer CBM-TOF wall. Pre-productions for eTOF and mTOF have demonstrated that the performance of these fishing line counters are satisfactory and fulfill their requirements. Aging tests with high intensity beam at mCBM suggest to use pad/disk spacers for all MRPC types, however, for practicability reasons only the MRPC2 and MRPC3 will be equipped with this kind of spacer. Additionally a sealed version of MRPC2 was developed diminishing the aging process even further, however, more R&D is necessary before launching a mass production. The current planning foresees to have a first batch of 125 MRPC2 counter without sealing and a second batch with. Performance test with pad spacers counters were performed as well and showed satisfactory results.

References

[1] N. Herrmann, *Technical Design Report for the CBM Time-of-Flight System (TOF)*, SI-2015-01999, 182 S. (2014), https://repository.gsi.de/record/109024

5 Appendix:

MRPC生产记录表 / MRPC2 Quality Assurance Table

MRPC ID	24#							
玻璃 / Glass	来自箱号与批次 / Glass Batch No.			14#	用料数量/Amount			6
	来自箱号与批次 / Glass Batch No.			151219	用料数量/Amount			
	来自箱号与批次 / Glass Batch No.			电极18# 151219	用料数量/Amount			4
电极玻璃 / Electrode	面电阻 / Surface Resistance (MΩ/sq)			Point 1	Point 2	Point 3	Point 4	Point 5
	电极玻璃1 / Electrode 1			3	4	3	4	3
	电极玻璃2 / Electrode 2			2	2	2	2	3
	电极玻璃3 / Electrode 3			2	2	4	3	3
	电极玻璃4 / Electrode 4			2	5	2	3	2
蜂窝板 / Honeycomb								
PCB上下板 / Top & Bottom PCB								
PCB中间板 / Middle PCB	焊接保护电阻 / Protection Resistor		外侧64路信号与地之间电阻是否均为100kΩ /				问题数量 / Unqualified	
			内侧64路信号与地之间电阻是否均为200kΩ /				问题数量 / Unqualified	
	焊接双排插针 / Connector		16个插座与电路板的厚度是否均<6.7mm / Thickness of the connectors				问题数量 / Unqualified	
Mylar膜 / Mylar								
PCB上下板高压 / Top & Bottom HV								
PCB中间板高压 / Middle HV								
鱼线 / Spacer								
厚度 / Thickness	Point 1	Point 2	Point 3	Point 4	Point 5	Point 6	Point 7	Point 8
上下PCB / Between Top & Bottom PCB	11.75	11.9	12	11.9	11.56	11.83	11.61	11.98
上中PCB / Between Top & Middle PCB	5.01	4.93	5.1	5.11	4.92	4.9	5	5.1
下中PCB / / Between Bottom & Middle PCB	4.9	5	4.92	5.01	4.96	4.98	4.81	4.97
总厚度 / Total Thickness	26.38	25.82	26.15	26.2	25.86	25.8	25.86	25.48
组装人员签字 / Signature								
日期 / Date								
备注 / Note								

Figure 44: MRPC2 Quality Assurance Table.