The High-Rate Sealed MRPC to Promote Pollutant Exchange in Gas Gaps: Status on the Development and Observations

Botan Wang, Xiaolong Chen *, Yi Wang, Dong Han, Baohong Guo and Yancheng Yu

Key Laboratory of Particle and Radiation Imaging, Department of Engineering Physics, Tsinghua University, Beijing 100084, China; wbt19@mails.tsinghua.edu.cn (B.W.); yiwang@mail.tsinghua.edu.cn (Y.W.); handong@mail.tsinghua.edu.cn (D.H.); txdyshuai@126.com (B.G.); yu-yc16@mails.tsinghua.edu.cn (Y.Y.)

* Correspondence: xiaolongc@mail.tsinghua.edu.cn

Abstract: This work reports the latest observations on the behavior of two Multigap Resistive Plate Chambers (MRPC) under wide high-luminosity exposures, which motivate the development and in-beam test of the sealed MRPC prototype assembled with low-resistive glass. The operation currently being monitored, together with previous simulation results, shows the impact of gas pollution caused by avalanches in gas gaps, and the necessity to shrink the gas-streaming volume. With the lateral edge of the detector sealed by a 3D-printed frame, a reduced gas-streaming volume of ~170 mL has been achieved for a direct gas flow to the active area. A high-rate test of the sealed MRPC prototype shows that, ensuring a 97% efficiency and 70 ps time resolution, the sealed design results in a stable operation current behavior at a counting rate of 3–5 kHz/cm². The sealed MRPC will become a potential solution for future high luminosity applications.

Keywords: multigap resistive plate chamber; high energy physics experiments; gaseous detector; gas pollution; time resolution

1. Introduction

Multigap Resistive Plate Chamber (MRPC) technology has been widely used in high energy physics experiments for high precision Time-of-flight (TOF) measurements since its development in 1996 [1]. The time resolution, including the detector and the readout electronics, commonly reaches less than 100 ps, such as 60 ps at RHIC-STAR and 56 ps at LHC-ALICE [2–4]. For future experiments, the interaction rate by collision is designed to increase by orders of magnitude in order to reach specific states of nuclear matter or to detect rare probes which feature an extremely low yield. Thus, rate capability becomes a new challenge to the application of MRPC. There are two main challenges we must solve: the rate capability of the detector, and timely gas exchange in the gaps. Based on the Ohmic Model [5], one can decrease the bulk resistivity of the resistive plates to improve an MRPC’s rate capability. Thus, new materials such as low-resistive glass [6] and ceramic [7] have been developed. Alternatively, the proposal of warming the detector has been discussed [8]. Thanks to these successful studies, the rate capability of the MRPC, tested in-beam, expands from the original level of 1 kHz/cm² to a stunning 100 kHz/cm² level [9], making it possible to be applied to those experiments with unprecedented luminosity, such as FAIR-CBM [10] and JLab-SoLID [11].

However, due to the restriction of the current beam test setup, the experimental level of wide and long-term exposure under high luminosity cannot be realized smoothly. Either the smaller size of irradiation limited within the beam profile (e.g., the 3.5 cm diameter beam spot in [9]), or the less avalanche charge in the gas gaps caused by the shorter irradiation time, leads to the under-estimation of the pollutant production in MRPC’s operation. In successive flux, it is expected that more working gas molecules will be ionized in the 100 µm level gas gaps. However, the quantity of the ionized products, their diffusion conditions, and the potential risks for detectors at high rate, still need detailed
investigation. In Section 2, some simulation results and experimental observations are reviewed concerning gas pollution at high rate. Although a consistent and quantitative conclusion cannot be obtained from these works carried out at different times, we can still find the potential link between the risks in MRPC operation and gas pollution. Further, it can be inferred that a smaller gas volume will promote the gas exchange and pollutant discharge from the gas gaps.

A newly developed sealed MRPC is aimed at an extremely low gas volume. In the context, “sealed” refers to the mostly enclosed lateral side of the MRPC with only inlets placed, so that the working gas can be directly streamed into the MRPC gas gaps. With the development and test of the sealed MRPC [12], especially the long-term test with extremely low gas flow, it is further believed that the exchange rate of the working gas will be accelerated thanks to the much lower gas volume. However, the proposed application of this type at first is in low flux experiments, and the focused benefit is to reduce the working gas consumption. The findings in Section 2 have given a new perspective to the sealed design. A high-rate sealed MRPC, featured with low gas volume and equipped with the low-resistive glass instead to enhance the rate capability, is proposed to solve the gas pollution effect. Thus, the development and test of the high-rate sealed MRPC can properly validate the link between the negative detector behavior and the gas pollution.

Based on the motivation, a high-rate sealed MRPC prototype has been produced and tested in cosmic rays to verify the performance. Afterwards, the current behavior of the prototype in X-rays has been examined. In Section 3, the results are shown and the current behaviors of the sealed type are compared with that of the common MRPCs described in Section 2.

2. Simulation and Observations Related to Gas Pollution

Gas pollution is formed mostly by the ionization and avalanche of the working gas molecules [13]. For MRPCs, the working gas usually contains Freon (C2H2F4), i-C4H10, and SF6. Freon as the main component dissociates into F− and other fragments after ionization. The glass plates can be corroded by the F−; hence, the noise rate increases and the fragments may attenuate the electronegative feature of the working gas [14]. The i-C4H10 serves as the photon absorber and its consumption may affect the avalanche development as well.

A flow field simulation to the MRPC gas volume based on the ANSYS Fluent software has been executed by former work [15,16]. It treats the gas molecules in the volume, ignoring its specific components and fraction, as the combination of “working” molecules and “pollutant” molecules. With one avalanche, about 107 “working” molecules are tagged as “pollutant” so that the gas behavior with flux can be simplified to the uniform production of the pollutant molecules in the gas gap. On the other hand, the diffusion of the gas for both types is simulated in strict Computational Fluid Dynamics (CFD), which provides the basic rationality to the gas model. In this thought, two models have been built with the same active area of 33 × 27 cm², defined by the size of resistive electrodes, but with different sizes of gas box volume: 41 × 37 × 10 cm³ which represents the common practice of placing the MRPC into a gas-streaming box, and 34 × 28 × 1.2 cm³ as a model of a well-enclosed structure. Correspondingly, the net gas volumes excluding the detector solid are 14.4 L and 414 mL. For both geometries, the working gas flows from the inlet on the one side of the volume to the outlet on the opposite side. The pollution can be quantified by the maximum pollutant concentration \( n_{\text{pollutant}}/n_{\text{total}} \) at steady state in the active area. Figure 1 shows the rate and flow scan results, where the pollutant concentration rises linearly with the flux rate and declines with higher flow. In comparison with the box model, the enclosed structure with lower gas volume has less pollution when provided with the same counting rate and gas flow, and there is no obvious lower limit of pollutant concentration such as the box model when increasing the gas flow at high rate. The limit might be explained by the mechanism of the gas exchange: with a larger gas box, the pollutant is exchanged by diffusion where the concentration gradient limits the exchange rate; with a reduced
gas volume, the direct flow through the gas gaps may be realized and the exchange is promoted with a higher gas flow.

Figure 1. The flow scan and rate scan results: (a) the flow scan of two models, at a fixed rate of 30 kHz/cm$^2$; (b) the rate scan of two models, at a fixed gas flow of 60 mL/min. The simulation has been through iterations to a high precision, so the error bars are contained within the symbols.

In experimental operation, the negative behavior of MRPC that may come from gas pollution has been observed and examined. At STAR, the Muon Telescope Detector (MTD) and TOF are both constructed with MRPCs [17], but the former has a larger active area, thus is equipped with a larger gas box. In Run-12 with a rate range in 20–100 Hz/cm$^2$, the MTD had an increasing noise rate which failed to recover in 1–2 days with the beam off. Meanwhile, the TOF MRPCs were controlled within a reasonable noise level of less than 2 Hz/cm$^2$, as shown in Figure 2a. The noise problem of the MTD detectors was solved after blocking the extra space in the gas boxes (see Figure 2b). It can be noticed that the MTD-26 detector shows a relatively lower noise in the MTDs, which might come from the high-quality production. Despite the peculiarity, an irreversible rise in Figure 2a and significant improvement in Figure 2b can still be observed in MTD-26. A valid explanation of the results might be explained by the gas pollution effect: the noise increased with pollutants accumulated and, when the beam was off, pollution was relieved, but the gas exchange was still slow before the gas volume was reduced.

Figure 2. (a) The noise of MTD and TOF counters. Red shades mark the response operated with the beam off on that day; (b) The noise of MTD counters after blocking the extra gas volume. Figures are reproduced from [18].
In the laboratory, high-rate MRPCs [19,20] were being tested using an X-ray source when unexpected current growth, recorded by the High-Voltage (HV) power source, was observed. As shown in Figure 3, the current of the SoLID prototype grows linearly in a stable counting rate which was monitored by a Time-to-digital Converter (TDC). The geometric information of the detectors mentioned in this paper can be found in Table 1, and we also report the X-ray tests performed on them in Table 2. The current behavior in a longer term, with the negative impacts, still needs investigations, but it can be inferred that noise and aging might become problems due to their relations to the MRPC current.

Figure 3. The current response of a SoLID prototype in full X-ray irradiation, in an estimated counting rate of 1 kHz/cm².

Table 1. The geometry parameters of the MRPC prototypes discussed in the paper.

| Detector                              | CBM-MRPC2 [19] | SoLID Prototype [20] | (High-Rate) Sealed MRPC [12] |
|---------------------------------------|----------------|----------------------|-----------------------------|
| Active area (cm²)                     | 32 × 27        | 25.8 × 8             | 32 × 27                     |
| Gas gaps                              | 4 × 2 stacks   | 8 × 4 stacks         | 4 × 2 stacks                |
| Gas gap width (mm)                    | 0.25           | 0.128                | 0.25                        |
| Glass type                            | Low resistive  | Low resistive        | Low resistive/float         |
| Strip pitch (mm)                      | 10             | 10                   | 10                          |
| Strip length (cm)                     | 27             | 25                   | 27                          |
| Gas box volume (cm³)                  | 60 × 60 × 10   | 35 × 50 × 10         | No box                      |
| Net gas volume (L)                    | 33.6           | 16.5                 | 0.17                        |
| Gas flow (mL/min)                     | 50             | 100                  | 30/5                        |

Table 2. The summary of the current behavior tests in X-ray exposure.

| Detector                              | CBM-MRPC2 | SoLID Prototype |
|---------------------------------------|-----------|-----------------|
| X-ray exposure range                  | full      | Full            |
| Estimated rate (kHz/cm²)              | 5.48      | 1               |
| Irradiation time (h)                  | 4         | 72              |
| Initial current respond (µA)          | 6.46      | 5.25            |
| Growth rate of current (nA/h)         | 40        | 18              |
|                                       |           | 10              |
For CBM-MRPC2, it is estimated to run in a flux at 2–8 kHz/cm$^2$, and the current design of an MRPC2 module can be translated to a 19 L gas volume per counter. Thus, the results above have brought the concern of pollutant concentration in future operations. For this reason, the development and examination on the high-rate sealed MRPC have been encouraged. It is hoped that a better gas exchange and stable response to the high luminosity will be realized, while maintaining its good timing performance.

3. The High-Rate Sealed MRPC

3.1. Structural Design

As shown in Figure 4, each gas stack of a sealed MRPC will form a sealed chamber with gas inlets. In operation, the working gas flows into the sealed chamber through one of the inlets and out by the other. To obtain a higher rate capability, the new sealed prototype should be assembled with low-resistive glass. Based on the same idea of enclosure as before, the sealing frame has been designed and produced by 3D Printing [21]. However, the low-resistive glass plate, with 0.7 mm thickness, is weaker in mechanical strength compared with the float glass; thus, it cannot be used as the panel for the sealed chamber. For this reason, the PMMA plates of 1 mm in thickness are used instead. On the inner surface of each panel, a square-shaped groove is reserved for the placement of HV conductor, as shown in Figure 4. The prototype has the same geometry as CBM-MRPC2 mentioned in Table 1, but the total gas volume is as low as ~170 mL. Thus, faster gas exchange can be expected. In former tests on the sealed prototype with float glass [12], the HV application could be safely started within 2 h after we purged the chamber with a 20 mL/min gas flow. This favorable feature has been maintained on the high-rate sealed MRPC prototype.

3.2. Cosmic Test

The high-rate sealed MRPC prototype was tested in cosmic rays (i.e., with a flux as low as ~1.5 Hz/m$^2$) along with 2 CBM-MRPC2 counters for the Triggering and Readout Board (TRB3) [22] test stand [23], as shown in Figure 5. PADI Front-end Electronics [24] provides a conversion gain of 30 mV/fC, and the threshold is set to 300 mV during the test. For the investigation of the time resolution, the start-time (T0) is provided by one of the MRPC2 counters, and the other is served as the event selector. The three MRPCs are piled with the prototype under test on the top. This layout is for the X-ray test in the next
part. Standard gas mixture (Freon/iC_4H_{10}/SF_6 in a fraction of 90/5/5) is streamed to the counters with a 10 mL/min flow for the prototype and 60 mL/min for the gas box that places the two MRPC2 counters. The sealed prototype has been verified for its good gas tightness with HV applied in the atmosphere.

**Figure 5.** The TRB3 test stand. For the cosmic test, trigger is provided by the coincidence of two scintillators. In the X-ray test discussed afterward, the scintillators are replaced by an X-ray source, and the TDC operates in the free-running mode for the record of counting rate.

Figure 6 shows the HV scan results, which indicate a good performance under the low flux cosmic rays. As described above, the test used three MRPC counters, so the efficiency is defined by the number of coincidences by three counters over that by two MRPC2s. To determine a coincidence, the time and space correlation of the detection between counters is examined. The cluster size is defined by the number of continuous fired strips in one detection. The prototype reaches the working condition at 5.4 kV, which corresponds to an electric field of 108 kV/cm in gas gaps. The plateau efficiency is 97%, with a 1.6 cluster size and a 100 ps flight-time resolution. Mentioned that the tested prototype and the T0 counter have the same geometry, if we reasonably expect their same timing precision, the time resolution of the prototype is about \( \frac{100}{\sqrt{2}} \sim 70 \) ps. During the test, the dark current and the noise rate were kept in reasonable levels at around 20 nA and 1.5 Hz/cm², respectively.

**Figure 6.** Cosmic test results of the high-rate sealed MRPC prototype: (a) the efficiency curve and cluster size; (b) the resolution of the flight time between the prototype and the T0 counter, with fluctuation from the readout chain included.
Moreover, a flow scan to the prototype has been carried out at the working point. The HV is set to 5.4 kV with different gas flows. Results of efficiency and flight-time resolution of the high-rate sealed MRPC are shown in Figure 7. There is no significant flow dependence within the efficiency uncertainty and a 5% measurement error of time resolution on the performance at low counting rate, probably because of the slow pollutant generation in cosmic ray tests.

![Figure 7](image)

**Figure 7.** Performances of the high-rate sealed prototype working in different flow rates.

### 3.3. X-ray Test

To examine the current behavior of the prototype at high rate, a Spellman XRB80N100 X-ray source with Tungsten as the target material was placed on the top of the counter. The operating HV and current of the source is no higher than 50 kV and 1 mA. Accordingly, the X-ray and secondary charged particles have lower energy than to even penetrate a detector. Hence, only the sealed prototype on the top will get the proper high rate. The X-rays cover a large area to realize full irradiation to the prototype. In the test, the counting rate was recorded by a TDC, and the current of the counter was monitored by the HV power source in the precision of 10 nA. In the cosmic background, they are both very low, as described previously. The gas flow to the sealed prototype is 30 mL/min during the X-ray test, which indicates that the gas exchange of the whole gas volume can be realized in several minutes in order to protect the detector.

The counting rate of the detector has a positive correlation with the operating current, as shown in Figure 8. The misalignment to strict linearity is possibly due to the increase in energy of the incident particles when magnifying the HV of the X-ray tube, as more gas gaps will be penetrated and more avalanches will develop, which lead to a higher current at high-rate situations. In general, the sealed prototype has a normal response to the incident flux. The prototype was then tested in a continuous run that lasts for 9 h. Figure 9 shows the current behavior since the X-ray was on. The prototype was first luminated for more than 6 h, with the X-ray source operated in 42 kV/0.3 mA. The counting rate was kept at 3.4 kHz/cm$^2$; simultaneously, the current of the counter was stable around 5 µA. For 6 h, there was no sign of rising on the MRPC current, and the fluctuation was ranged within 20 nA. Afterward, the flux was reinforced or intermitted several times to check the current response, with the details in Figure 8. It can be found that the current was quite stable at three rate stages (<10 nA/7.08 µA~<0.14% measurement precision at 4.3 kHz/cm$^2$, and 15 nA/8.58 µA ~0.2% at 5 kHz/cm$^2$) and responded with high sensitivity in the changes of X-ray flux. Moreover, it should be mentioned that the current–rate correlation agrees well with that in Figure 8. In Figure 10, when the X-ray was shut down, the current of the sealed prototype dropped to the dark current level of 30 nA in less than a half minute. It should be mentioned that the same decay patterns were performed in all the three shutdown actions in Figure 9. An enlarged decay process can be seen in Figure 10a. In comparison, the...
current relaxation procedure of the SoLID MRPC in Figure 10b took hours after exposed in high rate, which may indicate the existence of pollutant accumulation, and the full recovery to the dark current level took about a day. The X-ray test has offered the potential prospect of the sealed MRPC to deal with mass pollutant production at a high rate.

Figure 8. The relation of the counting rate with respect to the operating current of the detector. The error bars are contained within the size of the symbol.

Figure 9. The current of the high-rate sealed prototype under full-area X-ray irradiation. The current at the early 6 h remains unchanged as well.

Figure 10. The current decay comparison since the X-ray was shut down. (a) The high-rate sealed MRPC; (b) the SoLID prototype.
4. Conclusions

With the increase in MRPC counting rate in future applications, the risk of the gas pollutant generation has motivated studies by simulation and detector observations. The development of the sealed MRPC is devoted to the realization of a lower gas volume in gas gaps with the aim to promote the gas exchange. A high-rate sealed MRPC prototype has been tested in cosmic and X-rays. Excellent performance of 97% efficiency and 70 ps time resolution is validated at the cosmic-level rate, with no dependency on the gas flow within the measurement precision of 5%. Stable current behavior within a relative fluctuation of 0.4% has been verified under the full irradiation of X-ray at 3–5 kHz/cm² rate conditions, which is a promising development that solves the current problem for MRPCs in gas-streaming boxes. The sealed MRPC may develop as a solution for high-rate timing uses such as high luminosity CBM-TOF.

However, the exact effect of the current growth on MRPCs at high rate is still opaque to us. More investigations and tests in terms of material, aging, and performance should be quickly started, and some of them can be predictably destructive to the detector. For these reasons, a new test stand is in construction to study the in-beam performance of the high-rate sealed MRPC, and more prototypes are being produced in case of the scheduled tests. At the same time, we are seeking facilities that can provide beam with intense flux and large coverage. It is also believed that the manufacturing technique can be further improved and made more proficient during this process, in terms of the quality control of the sealing frame, the modularized assembly of the sealing chamber, the material selection, and so on.

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