Development and performance tests of $\mu$-PIC with DLC electrodes

A Ochi, F Yamane, Y Ishitobi and H Setsuda
Kobe University, Kobe 657-8501, JAPAN
E-mail: ochi@kobe-u.ac.jp

Abstract. Micro pixel chambers ($\mu$-PIC) with resistive cathodes have been developed as particle tracking/imaging detectors in high-rate high ionizing particle (HIP) environments. A main target of their development is as a forward muon detector in the ATLAS phase-2 upgrade. The cathode is made from DLC (diamond-like carbon) thin foil by the liftoff method. Using the resistive cathodes, the discharge (spark) probability within the HIP environment was reduced (10-1000 times) and two-dimensional readouts for the incident particles are available using a 400-micron pitch separated pixel array. We measured the tracking performances for the charged particles using a 140 GeV muon beam in CERN’s H4 beam line and also measured the imaging properties of 8 keV X-rays. Two-dimensional fine position resolutions ($<100$ micron) were obtained. These results show that the resistive $\mu$-PIC is one of strong candidate for forthcoming high-rate particle experiments.

1. Introduction
The micro pixel chamber ($\mu$-PIC) is a micro-pattern gas detector (MPGD) with two-dimensional readout. The $\mu$-PIC’s original design was introduced in 2001 [1, 2] using printed circuit board technology and has been used in many applications, such as gamma-ray astronomy, neutron detection, and dark matter searches (see, e.g., [3, 4, 5]). One of its most characteristic properties is that it does not require floating components, such as micro mesh or foil. Thus, a large detector (over $m^2$ order) can be constructed by assembling $\mu$-PIC units (currently $10 \times 10 \text{cm}^2$) edge-to-edge with small gap, and is an ideal candidate as a large-area detector for future collider experiments.

Our aim is to develop a new detector for the ATLAS high-eta muon detector [6]. In this case, higher gaseous gain ($> 10^3$) is needed for detecting minimum ionizing muon particles, where there are many highly ionizing particles (HIPs), such as recoil nuclei from fast neutron. HIPs in high gaseous gain cause the detector to spark between electrodes. This phenomenon is known as the Raether limit [7, 8, 9]. Using resistive material to create the electrodes is a good solution to this problem. Currently, there are many types of resistive electrodes used for MPGDs (e.g., ATLAS NSW Micromegas [10]).

A $\mu$-PIC with resistive cathodes was developed using resistive polyimide in 2012 [11, 12]. The structure of the resistive $\mu$-PIC is shown schematically in Figure 1. Cathode signal is induced on pick-up electrodes, which are laid below the resistive cathode across a thin substrate. Anode pins are connected to readout strips running perpendicular to the cathode strips. Using the signals from the anodes and cathode-pickups, a two-dimensional position of the incident particle can be determined. An advantage of the resistive $\mu$-PIC is that the output signal is not affected by charge diffusion on the resistive electrodes. Usually, signal charges on resistive electrodes
Figure 1. Structure of the resistive cathode $\mu$-PIC.

Figure 2. Charge distribution of output signals, and number of hit strips for (a) two-dimensional Micromegas (MM) and (b) resistive cathode $\mu$-PIC. Figures on the left column show the two-dimensional plot for time development of charge distribution along resistive strips for the MM and $\mu$-PIC for axis perpendicular to the resistive strips using the muon beam. Those on the right column show the typical distribution of the number of hit distribution for these two axes.

diffuse over time. In the case of Micromegas with resistive strips, the 2-dimensional output is read by induced charge. The charge spreads along the resistive strips and the induced charges on the pickup electrodes perpendicular to the resistive electrodes also spreads over time. Position resolution is worsened for the dimension perpendicular to the resistive strips (see Figure 2 (a)). On the other hand, in the case of resistive $\mu$-PIC, while the charge on the resistive cathodes also diffuses, the signals on the strips perpendicular to the cathodes strips appear only at the anode pixel where electron avalanche occurred. It does not spread to neighbor strips (see Figure 2(b)).

Early prototypes demonstrated excellent spark reduction [13]. However, due to difficulties in the production process, only limited area (less than several cm$^2$) was operational. The detectors
were therefore not practical for the measurements of imaging and tracking performance. Thus, imaging and tracking performances could not be measured. In order to improve the accuracy of the electrode formation, diamond-like carbon (DLC) was adopted for the resistive cathodes in the beginning of 2014 [14, 15], together with improved production process and design of readout electrodes [16]. Now, full readout from a 10 cm × 10 cm two-dimensional prototype (400 μm pitch, 512 readouts) is available, allowing for tracking and imaging performance measurements.

Recent improvement of production for resistive μ-PIC and results of performance tests using charged particle and X-rays are reported in this paper. And also feasibility of applying it for future particle experiment (ATLAS high eta muon detector in phase-II upgrade) is briefly discussed.

2. Detector design and improvement
Details of the detector design have been described in other papers [15, 16]. Further improvements now enable us to achieve full readout with few defects. We discuss only these advanced improvements in this paper.

Figure 3 shows a schematic cross section of the resistive μ-PIC. The anode strips are each connected to positive high voltage via resistors. In the former design a large number of external HV bias resistors were necessary. In the new design these resistors are replaced by the DLC patterns. However a critical issue with this ideas was how to ensure a good electrical connection between the DLC and the metal strip pattern connecting to the anode strips. The DLC thickness is typically 0.1 μm whereas the metal (copper or nickel) pattern is typically 5 μm thick. The width of the strips is 300 μm. The cross-section of the electrical contact is therefore only 0.1 μm × 300 μm, the risk of disconnection between the two parts is not low. Indeed there were high rate of such disconnection observed in the prototype with this design. In order to mitigate the problem, in our latest design we use a zigzag pattern of the interconnect, increasing the length of the electrical contact to effectively by a factor of 10, as shown in Figure 4.

For quality assurance of the cathode pickup electrodes, we added a test pad to an end of each strip electrode at the other side of the readout pad. In the earlier production of μ-PIC boards, a number of cathode pickup electrodes are often found to be broken, likely caused by the use of inappropriate parameters such as pressure in the process of gluing the multilayer flexible film. As the cathode pickup strips are embedded underneath the insulator layer, it is not possible to inspect the electrical continuity once the electrodes are covered. The defects were recognized only after the detector is operated, and defects were always found. Using the test pads, the continuity of the cathode readout electrodes can be easily checked during the production and the production parameter optimized, resulting in a dramatic decrease of the defects in the produced μ-PIC boards.

![Figure 3. Structure of the resistive cathode μ-PIC.](image)

![Figure 4. Microscope picture of the resistive μ-PIC around the anode bias resistors formed by DLC.](image)
Figure 5. One-dimensional projection of an X-ray image using (a) previous and (b) current (improved) resistive $\mu$-PIC prototype. We found no defect in the strip for the new prototype.

These improvements enable us to read all electrodes with very few defects. Figure 5 (b) shows a histogram of incident X-rays for the cathode axis with obvious improvement over the previous prototype, as shown in Figure 5 (a). We can therefore measure and discuss imaging and tracking performances using the new prototypes.

3. Imaging performance

We measured imaging performance using an X-ray source from a generator at the CERN RD51 laboratory. We used the Scalable Readout System (SRS) with an APV25 chip [17, 18] as a multichannel readout system. The source X-ray was generated by 16 keV electrons with a copper target. The X-ray was directly irradiated to the resistive $\mu$-PIC prototype without a filter. The operation gas was a mixture of Argon (93%) and CO$_2$ (7%). A drift electrode was set to 5 mm from the $\mu$-PIC cathodes. The drift voltage was set to $-600$ V with respect to the $\mu$-PIC cathodes.

Figure 6 shows transparent X-ray images of a bat and a test pattern. Figure 7 shows a transparent X-ray image of a metal bar along both the anode ($x$-axis) and cathode ($y$-axis) direction (upper row and lower low). The histograms of the projection from both the images and differentials are also shown in this figure. Using the knife edge method, the position resolutions along both the $x$-axis and $y$-axis can be obtained from the images. The position resolution with this method (using 8 keV X-rays) was 189 $\mu$m (along the anode) and 158 $\mu$m (along the cathode).

4. Tracking performances using muon beam

We performed the position resolution test using a muon beam in the SPS H4 beam line (RD51 beam line) at CERN. The test was performed from the 9th - 16th October 2017, 2nd - 9th May 2018, and 8th - 22nd August 2018. Figure 8(a) shows the setup of the beam test. Two Micromegas chambers (Tmm) of two-dimensional readout (250 $\mu$m pitch) were set in the beam forming a telescope. Our $\mu$-PIC test chambers were placed inside the telescope as in figure 8(b). The signals from the $\mu$-PIC and the telescope chambers were connected to the SRS system via APV25 frontend cards [17, 18]. Trigger signal was generated from the coincidence of the two plastic scintillators on the beam line. The operation gas for the beam test was an Argon (70%) and Ethane (30%) gas mixture.

We measured the position resolution of the $\mu$-PIC using the residuals of the muon beam tracks from the telescope chambers. The position resolution for the muon beam incident at a right angle was measured around 70 - 90 $\mu$m using the center of mass method for both the anode axis and cathode axis. Details are described in a previous publication [16].
Figure 6. Transparent X-ray images using the resistive $\mu$-PIC for (a) a bat sample and (b) a test pattern.

Figure 7. Position resolution for the $x$-axis and $y$-axis using the knife edge method. The left figures are transparent X-ray images of a metal bar, the center figures are projections of the images (along the bar), and the right images are the differentials of each projection histogram, which indicate the position resolutions.

Figure 8. (a) Setup of the test beam. (b) Picture of the detectors in the test beam.

We also measured the position resolution for the inclined detector in these test beams. The $\mu$-PIC detector can be inclined in our setup up to 30 degrees. Since the readout data from the SRS have charge and timing information, the inclined track inside the $\mu$-PIC drift region can be reconstructed by the micro time projection chamber (TPC) method. Figure 9 shows the position resolution for the muon beam using the centroid method and TPC method. In this figure, a result of the first hit method is also shown, where the position of the first hit strip is regarded as the muon hit position. These preliminary results show that the TPC method provides the best resolution for the inclined tracks.
Figure 9. Position resolutions for the muon beam with the resistive $\mu$-PIC using the residual method from telescope (Micromegas) chambers. For the inclined $\mu$-PIC setup, the position resolution was analyzed in three ways: the TPC method, centroid method, and first hit method. The best position resolution was obtained using the TPC method for the inclined beam.

5. Discussion and summary
The required performances for a high-eta muon detector in the ATLAS phase-II upgrade are mainly high granularity (less than 100 $\mu$m) for tracking performance and operation tolerance under 10 MHz/cm$^2$ of signal background [6]. The position resolution for a muon incident at a right angle is fine for both of the two-dimensional axis. Resolution for the inclined muon (10 degrees) also satisfies the requirements using the TPC method. The tolerance for high particle rate, high particle density, high particle flux were also confirmed by spark rate reduction, but we need further study to optimize the surface resistivity. From these developments and the test results, we conclude that the resistive $\mu$-PIC performs sufficiently for forthcoming high-rate particle experiments.

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