High-rate tolerant multiwire proportional chamber and its performance evaluation

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Abstract

The DeeMe experiment to search for muon-to-electron conversions with a sensitivity 10–100 times better than those achieved by previous experiments is in preparation at the Japan Proton Accelerator Research Complex. A magnetic spectrometer used by the DeeMe consists of an electromagnet and four multiwire proportional chambers (MWPCs). The newly developed MWPCs are operated with a HV switching technique and have good high-rate tolerance. In this article, the final design of the MWPCs, amplifiers for readout, and HV switching modules are described. Also, some results of MWPC performance evaluation are presented.

1 Introduction

The Muon-to-electron ($\mu$-$e$) conversion is one of charged-lepton-flavor-violating (CLFV) processes which are forbidden in the Standard Model of elementary particle physics (SM) \cite{1}. There are, however, a number of theoretical models beyond the SM predicting CLFV processes with large branching ratios \cite{2, 3}. An observation at a large rate should, therefore, provide clear evidence of the existence of new physics.

DeeMe (Direct electron emission from muonic atoms through Muon-to-electron conversion) is an experiment to search for the $\mu$-$e$ conversion in nuclear field using muons trapped in atomic orbits to form muonic atoms. A signal of the $\mu$-$e$ conversion we search for is a monoenergetic 105-MeV electron emerging from a muonic atom with a delayed timing of an order of microsecond after muonic-atom formation. The experiment is planned to be conducted at the Materials and Life Science Experimental Facility (MLF) of the Japan Proton Accelerator Research Complex (J-PARC). We directly use muonic atoms produced in a primary proton-target itself which is hit by pulsed proton-beams from the Rapid Cycling Synchrotron (RCS) of J-PARC. For the electron detection and momentum measurement, we use a magnetic spectrometer consisting of an electromagnet and four sets of multiwire proportional chambers (MWPCs).
Generally in experiments searching for the \( \mu \rightarrow e \) conversion, pion-production target, pion-decay and muon-transport section, and muon-stopping target are introduced in order to produce muonic atoms. We, on the other hand, use muonic atoms that are directly produced in the primary pion-production target itself, which realizes a more compact and cost-effective secondary beam-line. However, large amounts of beam-prompt charged-particles from the primary proton-target hit the MWPC. The number of charged particles hitting the detectors is estimated, by simulation, to be approximately \( 10^8 \) particles per proton bunch with an RCS power of 1 MW [4]. The MWPCs must detect a signal electron after exposure to such a high rate of charged particles and it is critical to manage space-charge effects in the MWPCs. To achieve this, we quickly change gas multiplication between the numbers on the order of 1 and \( 10^4 \) by switching high-voltage (HV) applied to the MWPCs.

The basic concept of the chamber design, the method of the fast HV switching, and proof-of-principle tests using a prototype MWPC are described in [4]. In this article, the production of the final MWPCs with updated chamber design including electrical configuration, readout amplifiers, HV switching modules, and more details of the chamber performance are reported.

2 HV-Switching Multiwire Proportional Chamber

2.1 Chamber Structure

Anode and potential wires are placed alternately in a center plane between two cathode planes 6 mm apart. Spacing between the anode and potential wires is 0.7 mm for two out of four MWPCs, and 0.75 mm for the other two. Tungsten-rhenium gold-plating wires with a diameter of 15 \( \mu \)m are used for the anode, while tungsten gold-plating wires with a diameter of 50 \( \mu \)m are used for the potential.

Since the MWPCs are operated with switching HV on potential wires, one should be careful for the resonance frequency of wires to be different from the HV switching cycle. Resonance frequencies can be expressed in \( n \sqrt{T/\rho}/2L \) \((n = 1, 2, \cdots)\), where \( L \) is the wire length, \( T \) the wire tension, and \( \rho \) the mass per unit length \([5]\). For the potential wires, by substituting \( L = 300 \) mm, \( T = 0.78 \) N, and \( \rho = 19.3 \) g/cm\(^3\) \((50/2 \) \( \mu \)m\)\(^2\) \times \pi = 3.8 \times 10^{-5} \) kg/m, the resonance frequencies are obtained to be 240 Hz, 480 Hz, \cdots. Similarly, by substituting \( L = 300 \) mm, \( T = 0.29 \) N, and \( \rho = 19.3 \) g/cm\(^3\) \((15/2 \) \( \mu \)m\)\(^2\) \times \pi = 3.4 \times 10^{-6} \) kg/m, the resonance frequencies for anode wires are 490 Hz, 970 Hz, \cdots. The wires therefore do not resonate when the HV switching is synchronized with the RCS beam cycle of 25 Hz.

In the final design of the MWPCs, the cathode planes with strip patterns are used for read out. One of the two cathode planes is stripped into 80 channels with a width of 3 mm for measurement of the \( x \) coordinate (the horizontal direction). The strips for the \( y \) coordinate (the vertical direction) are 16 channels with a width of 15 mm.

2.2 Amplifier

The readout amplifiers connected to the cathode strips have 80 and 16 channels for the \( x \) and \( y \) axis, respectively. They are directly mounted on the connectors of the MWPCs. The outputs are sent to 100-MHz 10-bit flash ADCs to record waveforms through long cables with a length of about 15 m.
Stray capacitance between the cathode strip and the potential wire exists due to the distance of 3 mm between them. When the voltage on the potential wires is switched, a large current flows into the amplifier through the stray capacitance. The amplifier must be therefore designed to have sufficient tolerance to large currents induced by the HV switching.

We modify the amplifier that was originally developed for the readout of VENUS vertex chamber in the TRISTAN experiment at High Energy Accelerator Research Organization (KEK) [6]. There are three points for modification in particular: 1) to use bipolar junction transistors with more tolerance to electric currents, 2) to increase the gain of the amplifier by changing the resistance of the second stage, and 3) to insert a pole-zero-cancellation circuit (PZC) to shorten the long tail of the MWPC output due to a large number of prompt charged particles [7]. Recently, the negative range of the amplifier is increased to prevent the output waveform from saturating, and this version of amplifier is mass-produced (Fig. 1).

![Amplifier circuit for one channel of the MWPCs.](image)

2.3 HV Switching

The upper part of Fig. 2 schematically illustrates the time line of charged particles that will hit the detectors. The RCS beam has a double bunch structure and the interval between the two bunches is 600 ns. The repetition is 25 Hz, therefore, the next double pulse comes after 40 ms. The protons hit the target and generate prompt charged particles. The charged particles with momenta around $10^5$ MeV/c pass through the secondary beam line (High momentum muon beamline, H-Line, under construction) and hit the detectors. After that, we search for an electron of $\mu$-$e$ conversion.

The lower plot in Fig. 2 shows the scheme to apply the HV for the MWPCs. In order to control the gas multiplication dynamically, the voltage on the potential wires is switched between the same HV as the one for the anode wires and 0 V. The spacing between the potential and anode wires is small compared to the gap between the wire and the cathode planes, the electric field around the anode wire is determined almost only by the voltages applied to the potential and anode wires. When the voltages applied to the potential and anode wires are the same, the gradient of the electric potential between the two wires positioned closely is small enough to turn off the gas multiplication. Although the voltage
of the cathode strips connected to the readout electronics is kept small compared to the HV to the wires, it does not result in the gas multiplication due to the large distance between the wires and the cathode. Rather, it helps to sweep out ions that are generated by prompt incident particles to minimize the space charge effect. The large voltage difference induced by switching the voltage on the potential wires to 0 V creates a strong electric field around the anode wires to enable the gas multiplication.

When the voltage difference between potential and anode wires is large, attractive electrostatic forces between them also become large. Assuming that wires are long enough, the capacitance between the two wires per unit length $C$ is given by $C \approx \pi \epsilon / \ln(s/a)$, where $\epsilon$ is the dielectric constant of the filling gas, $s$ is the wire spacing, and $a$ is the radius of the wire. Ignoring the difference of diameters between the anode and potential wires, and substituting $\epsilon = 8.85 \times 10^{-12}$ F/m, $s = 0.7$ mm, and $a = 7.5 \mu$m (the anode wire radius), we have $C = 6$ pF/m. The length of wires is 300 mm, thus the capacitance between the two wires is approximately 2 pF. For the case of applying 1500 V to anode wires and 0 V to potential wires, electric charge of 2 pF $\times$ 1500 V = 3 nC is accumulated. The red line in Fig. 3 shows the sum of forces acting on the anode wire by the two adjacent potential wires as a function of wire sag calculated by the method of images, where a simple geometrical configuration is considered as illustrated in Fig. 4 and the sag is defined to be the displacement ($\delta$) of the middle point of the anode wire from the nominal position toward the one of the potential wires. The blue line represents the restoring force by wire tension, 30 g for the anode wire. The magnitude of the force is estimated to be $30 \text{ g} \times 9.8 \text{ m/s}^2 \times \delta/(300 \text{ mm}/2) = 2.0 \text{ N/m} \cdot \delta$ and the direction is opposite to that of the wire sag. The magenta line shows the sum of the electrostatic force and the restoring force. This graph indicates that the stability of the MWPCs may be broken when the wire sag becomes larger than 0.1 mm as the attractive electrostatic forces overcome the restoring forces. When there is no voltage difference between the two wires, on the other hand, the position of wires should become stable due to balanced repulsive forces. As shown in the lower plot of Fig. 2, the duration of time when there is a large voltage difference between the anode and potential wires is minimized and limited to the search analysis window, on the order of 10 $\mu$m, to ensure the stable MWPC operation.

2.3.1 HV Pulser

A HV power supply provides DC voltages to the anode wires, while a HV switching module is inserted between the HV power supply and the potential wires. A circuit diagram of the HV switching module is given in Fig. 5.

The drain of the upper MOSFET is connected to the external HV line, while the source of the lower MOSFET is grounded. The drain-source connection in the MOSFET is altered by the gate-source voltage. The circuit output is connected to the source of the upper MOSFET and the drain of the lower MOSFET. By controlling the drain-source connection of the two MOSFETs appropriately, the output voltage is switched between the HV and 0 V.

2.3.2 Electric Component

To prevent the voltage on anode wires from fluctuating, a low pass filter with a 2 M$\Omega$ resistor and a 2 nF capacitor is attached to each anode wire. As mentioned in [4], the capacitor value was changed to 10 nF to suppress electric oscillation observed in output
Figure 2: Schematic illustration of time structure of prompt charged particles to hit the MWPCs and how the HV switching is performed.

Figure 3: The electric force acting on an anode wire by two adjacent potential wires when the HV on the anode wire is 1500 V and the potential wire is at 0 V (red), the restoring force by the anode wire tension (blue), and the sum of these forces (magenta) as a function of the anode wire sag.
Figure 4: Geometry considered to calculate the electrostatic forces acting on the anode wire by the two adjacent potential wires.

Figure 5: The circuit for the HV switching. It is inserted between the high-voltage power supply and potential wires.
waveform that is induced by the HV switching. In the final design, it is changed back to 2 nF and an extra 1 kΩ resistor is included for reducing the total charges stored on the wires with suppressing the oscillation at the same time. In addition, the snubber circuits on the voltage inputs to anode and potential wires, as shown in Fig. 6, are introduced for further suppression of the output oscillation.

Figure 6: Equivalent circuit of the MWPC. The 713-type and 724-type in the figure refers to the two types of MWPCs with 0.7 mm and 0.75 mm wire spacing, respectively.

2.3.3 Output Waveform

Figure 7 shows a typical output waveform of the detector. When the voltage on the potential wires falls, the negative current flows into the amplifier and the negative saturation occurs. After that, due to the PZC, the waveform turns to a rapid increase to overshoot then settles down. When the voltage is returned to the original HV, the waveform saturates positively. The gas multiplication occurs during the time between the negative and positive saturation.

The oscillation of the output after switching voltage is observed. It appears to be caused by the fluctuation of the circuit for HV switching and it is under investigation. It is still possible to find a signal by subtracting a template waveform consisting of the most frequent amplitude obtained from a few hundred of waveforms, since the shape of the oscillation is rather stable and unchanged.

2.4 Operational Conditions

2.4.1 Discharge Test

Since the wire pitch between the anode and the potential wires is rather small, it is important to know discharge voltages for stable operation of the MWPCs.
Figure 7: Typical waveform of the detector and the voltage applied to the anode and the potential wires.

Figure 8: Discharge voltages for several different gas-mixtures at the atmospheric pressure. Variation of the data points of the same marker type for a given wire spacing represents the reproducibility of the measurement.
Figure 8 shows measured discharge-voltages as a function of the distance between the wires for several different gas-mixtures at the atmospheric pressure. This measurement was performed by using an anode and a potential wires tensed on a glass epoxy board in a small chamber. We set the potential wire at 0 V, while we increased the voltage to the anode wire at a ramping speed of 1 V/s [8].

From the Paschen’s law [9], the discharge voltage is proportional to the distance between the electrodes if the distance is in a range between 0.1 and 1 mm. For a distance of 0.7 mm, the lowest discharge voltage is therefore 1770 V for the argon/ethane = 50%/50%, 1790 V for the argon/isobutane = 80%/20%, 1380 V for the argon/isobutane = 90%/10%, and 660 V for the argon = 100%.

2.4.2 Gas Gain

When a charged particle is incident on the MWPC, electron-ion pairs are created. The mean number of electron-ion pairs created between the two cathode planes with a gap of 6 mm is about 61 pairs. For a minimum ionizing particle that passes through the MWPC, the average energy loss on the gas and the parts of MWPC is expected to be 40 keV.

Gas multiplication occurs if a strong electric field exists around the anode wire. Figure 9 shows the mean gain of gas multiplication as a function of applied voltage to anode wires estimated by simulation [10] for several cases of gas mixtures, where the voltage of the potential wire is set to 0 V. In this simulation, electrons are randomly placed at the distance of 150 µm from the center of the anode wires in a chamber in which the anode and potential wires are tensed alternately with an interval of 0.7 mm or 0.75 mm, and the number of ions created after avalanche multiplication is counted.

![Figure 9: The simulated gain of gas multiplication as a function of applied voltage to the anode wires, with the potential wires at 0 V, for a wire spacing of 0.75 mm (left) or 0.7 mm (right).](image)

For a gas gain of $5 \times 10^4$ with a wire spacing of 0.7 mm, the required voltage is 1580 V with argon/ethane = 50%/50%, 1500 V with argon/isobutane = 80%/20%, or 1440 V with argon/isobutane = 90%/10%. By looking at the discharge voltages we discussed in § 2.4.1, the margin voltages to discharge are 190 V, 290 V and −60 V (unstable due to discharge), respectively.
The amplitude of oscillation in the output waveform becomes larger as the applied voltage is higher as shown in Fig. 10. In order to avoid negative saturation of the waveform as a result of the oscillation, we want to lower the HVs as much as possible with keeping sufficient gain and ensuring stable operation. Thus, argon/isobutane = 80%/20% is adopted as the base gas mixtures.

![Figure 10: Typical waveforms for different applied HV voltage values.](image)

3 Hit Finding in Waveform

A hit finding algorithm is applied to the output waveforms of the MWPCs as follows:

1. Subtraction of the template waveform.
   
   The template waveform (the red line in Fig. 11) is constructed by identifying the most frequent ADC count at each FADC sample point obtained from several hundred waveforms. The blue line in Fig. 11 is the waveform after subtracting the template from a given waveform shown as the black line.

2. Cluster construction.

   We define a "cluster" at each strip and FADC sample point. As shown in Fig. 12, using five $x$-strips around a given strip, the ADC counts of the three center channels are summed up with subtracting the average ADC count calculated from the outer two channels as a noise level. Then, these 3-stripe sums are added over ten sample points in the time direction, since the FWHM of signal responses is approximately 100 ns independent of pulse heights as shown in Fig. 13.

3. Hit finding.

   We look for a cluster that is larger than a threshold. If we find one, we identify the local maximum around the cluster within a region of ±2 strips and ±2 sample points. The local maximum cluster is accepted as a hit if three consecutive clusters in the time direction around the local maximum cluster be larger than the threshold. The hit position for a strip channel $i$ is calculated by the center of mass method using the three strips of the cluster as $\sum_{j=i-1}^{i+1} (j \cdot Q_j) / \sum_{j=i-1}^{i+1} Q_j$, where $Q_j$ and $j$ is the strip ADC count (summed over 10 FADC sample point) and the strip channel number, respectively.
Figure 11: The template waveform (red) consisting of the most frequent ADC counts, a waveform in a certain trigger (black), and the subtracted waveform (blue).

Figure 12: An example of pulse heights in five cathode strips with a signal.
4 Test and Performance Evaluation

We evaluated the performance of MWPCs at Kyoto University Institute for Integrated Radiation and Nuclear Science. The electron beam with an energy of 16 MeV or 30 MeV was collimated with lead blocks. At the exit of beam, the MWPCs were placed with scintillation or plastic counters for counting the number of electrons.

4.1 Hit Efficiency

The hit finding efficiency is estimated by looking at the fraction of coincidences between the two counters with a hit found in the MWPC. Figure 14 shows the efficiency as a function of time. The MWPC with a wire spacing of 0.75 mm is filled with a mixed gas containing argon/isobutane = 80%/20%. A DC of 1540 V and a switching voltage as shown in Fig. 2 with a width of 10 µs are applied to the anode and potential wires, respectively. The efficiency for a single electron is about 98% after turning on the operation of the MWPC.

4.2 Position Resolution

We put three MWPCs in series along the beam line. Position resolution is calculated by the difference between the hit position on the middle chamber and the expected position estimated by the straight line connecting two hits found in the first and third chambers. Figures 15 show histograms of position resolution for energies of 16 MeV and 30 MeV. We found the standard deviations of position resolution of (1209 ± 19) µm and (899 ± 12) µm after fitting the histograms with a Gaussian plus constant.
Figure 14: Single hit efficiency of the MWPC as a function of time.

Figure 15: Histograms of the position resolution for an electron energy of 16 MeV (left) and 30 MeV (right).
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