Radiation Tests for a Single-GEM-Loaded Gaseous Detector

Kyong Sei Lee,* Byungsik Hong and Sung Keun Park
Korea University, Seoul 136-701, Korea
Sang Yeol Kim
Notice Korea, Anyang 431-815, Korea

(Received 28 July 2014, in final form 12 August 2014)

We report on a systematic study of a single-gas-electron-multiplier (GEM)-loaded gaseous detector developed for precision measurements of high-energy particle beams and for dose verification in particle therapy. In the present study, a 256-channel prototype detector having an active area of 16 × 16 cm² and operating using a continuous current-integration-mode signal-processing method was manufactured and tested with X-rays emitted from a 70-kV X-ray generator and 43-MeV protons provided by the MC50 proton cyclotron at the Korea Institute of Radiological and Medical Science (KIRAMS). The amplified detector response was measured for X-rays with an intensity of about 5 × 10⁶ Hz cm⁻². The linearity of the detector response to the particle flux was examined and validated by using 43-MeV proton beams. The non-uniform development of the amplification for the gas electrons in space was corrected by applying a proper calibration to the channel responses of the measured beam-profile data. We conclude from the radiation tests that the detector developed in the present study will allow us to perform quality measurements of various high-energy particle beams and to apply the technology to dose-verification measurements in particle therapy.

I. INTRODUCTION

Ionization detectors with a thin material thickness are suitable for measurements of high-energy particle-beam profiles and for precision dose verification in particle therapy. Instead of the conventional counting mode in which the maximum affordable counting rate per detector channel is restricted to a level of about 10⁷ Hz, we adapt a continuous current-integration mode for the signal process [1–4], which allows a wider measurable range of particle fluxes.

When using a gas-electron-multiplier (GEM) electrode, the magnitude of amplification for gas electrons by required for quality measurements for particle beams with fluxes of lower than 10⁶ Hz cm⁻² is about 20. On the other hand, the gain can be closely adjusted to 1 for particle fluxes of higher than 10⁸ Hz cm⁻², when the dose rate is in the range of particle therapy. With the assistance of a single-step GEM, the minimum and the maximum particle fluxes guaranteeing quality measurements with a statistical fluctuation of a few percent in the channel response are 10⁵ Hz cm⁻² and 10¹⁰ Hz cm⁻², respectively.

In a proper detector for beam measurements, a small material thickness is essential to minimize the influence of the detector material on the incident beams, i.e., the energy loss due to ionization and the broadening of the beam emittance due to multiple Coulomb scatterings [5]. While the effect of multiple Coulomb scatterings rapidly decreases as the energy of hadrons increases, the ionization energy loss remains saturated value at 2.0 MeV g⁻¹ cm². Therefore, a detector with a material thickness of less than 0.1 g cm⁻² and a scattering length of about 5 × 10⁻³ X₀ [6] is a relevant choice for the measurements of proton and heavy-ion beams with energies of about 100 AMeV.

*E-mail: kslee0421@korea.ac.kr
II. DETECTOR AND ELECTRONICS FOR THE SIGNAL PROCESS

The structure of a single-GEM-loaded detector is illustrated with a schematic diagram in Fig. 1. The thickness for the drift and induction regions was adjusted to 3.2 mm. As shown in Fig. 1, a resistor chain composed of two 4.0-MΩ resistors and one 2.0-MΩ resistor provides electrical potentials to the drift and the induction regions and to the GEM electrode with a ratio of 2:1:2.

The GEM foil was manufactured with a 50-μm-thick Kapton film double-side coated with 5-μm-thick copper layers. The diameter of GEM holes and the size of the two-dimensional spacing are 50 μm and 140 μm, respectively. The GEM foil was tightly attached on a 1.6-mm-thick printed-circuit board (PCB) with adhesive glue with no sagging. The cathode plane was manufactured with a 25-μm-thick aluminized polyester film in the same way as the GEM foil. The electric potential to be applied across the GEM electrode ranged from 300 to 440 V when a gas mixture of 70% Ar + 30% CO₂ was used for the detector operation.

The signal plate manufactured with a 200-μm-thick PCB was composed of 1.25-mm pitch strips and pad arrays printed on the top layer of the PCB plate, as illustrated in Fig. 2. The strips and the pad arrays, 128 each, were assigned to measure the separate detector responses in the vertical (y) and the horizontal (x) directions, respectively. The 100-μm-wide traces required for the electrical connections for the pads were printed on the bottom layer. The estimated total material thickness of a single-GEM loaded detector was 0.077 g cm⁻².

The 256-channel electronics for the signal process was composed of four 64-channel charge integrators, eight amplifiers, an eight-channel analog-digital-converter (ADC) processor, a field-programmable-gate-array (FPGA) digital processor, and a USB3 interface processor. The details for the signal processing electronics are described in a previous report [7].

III. TEST OF THE SINGLE-GEM-LOADED DETECTOR WITH X-RAYS

The single-GEM-loaded detector was placed at a distance of 10 cm from the exit window of a 70-kV X-ray generator. The gas for the detector operation was a mixture of 70% Ar + 30% CO₂. The signal rate of X-rays with a mean energy of about 20 keV emitted from the X-ray generator and detected near the central region of detection (in the full width at half maximum: FWHM) was expected to be about 5 × 10⁶ Hz cm⁻². The X-ray signals collected in the strips and pad arrays of the detectors were integrated every 114.4 μs and converted to the integrated charge values (channel responses). The maximum sensitivity of the radiation-induced current per channel was adjusted to 96 nA.

Figure 3 shows the total detector response (charge) measured for 4.9 s as a function of the voltage applied to the GEM electrode ($V_{GEM}$). The induced charges of
Fig. 4. Spatial distributions of detector responses for the X-rays in the \( x \) (top) and the \( y \) (bottom) directions measured at \( V_{GEM} = 20, 340, 380, \) and 420 V for 4.9 s.

Fig. 5. Distributions of charges induced in channel 64 of \( x \) (\( q_{x64} \), top) and in channel 64 of \( y \) (\( q_{y64} \), bottom) for 114.4 \( \mu s \) when \( V_{GEM} \) was set to 20, 260, 300, 340, 380, and 420 V from the left to the right.

Fig. 6. Time responses of channel 60 of \( x \) (top) and channel 60 of \( y \) (bottom) for X-rays at \( V_{GEM} = 420 \) V. The irradiation of X-rays was initiated about 2 s after the DAQ had started. \( V_{GEM} = 420 \) V was the highest voltage for an operation without discharges when operating with a gas mixture of 70% Ar + 30% CO\(_2\). Discharges ruin the time spectra of the channel responses because of recording overflows in the data.

about 65 fC measured at voltages lower than 150 V were mainly due to the contribution of photoelectrons induced in the gas in the induction region, in the GEM foil, and in the signal plate. The ratio of the total detector response at \( V_{GEM} = 420 \) V to that at \( V_{GEM} = 20 \) V was measured as 22.5.

Figure 4 shows the spatial distributions of the detector responses for the X-rays in the \( x \) (top) and the \( y \) (bottom) directions, measured at \( V_{GEM} = 20, 340, 380, \) and 420 V for 4.9 s. The mean ratios of the increases in the voltage interval between 340 and 420 V measured for the \( x \)- and the \( y \)-direction responses were 5.5 and 5.4, respectively.

As shown in Fig. 4, non-uniform channel responses resulted from the spatially inhomogeneous gain and transparency for the gas electrons through the GEM holes. If the precision of the measurements is to be improved, proper corrections for the non-uniform channel responses are necessary. The correction procedure and the results for proton-beam data are discussed in Section V.

Figure 5 shows the distributions of charges induced in channel 64 of \( x \) (\( q_{x64} \), top) and in channel 64 of \( y \) (\( q_{y64} \), bottom) for 114.4 \( \mu s \) when \( V_{GEM} \) was set to 20, 260, 300, 340, 380, and 420 V from left to right. The ratios of the mean charges at \( V_{GEM} = 420 \) V to those at \( V_{GEM} = 20 \) V for \( q_{x64} \) and \( q_{y64} \) were 22.7 and 22.2, respectively.

Figure 6 shows the time responses of channel 60 of \( x \) (top) and channel 60 of \( y \) (bottom) for X-rays at \( V_{GEM} = 420 \) V.
IV. TEST OF THE SINGLE-GEM AMPLIFICATION WITH 43-MEV PROTON BEAMS

The single-GEM-loaded detector was tested with 45-MeV proton beams provided by the MC50 cyclotron at the Korea Institute of Radiological and Medical Science (KIRAMS). Firstly, the detector was installed at a distance of 172 cm from the vacuum exit of the proton beam to examine the single-step GEM’s amplification and its spatial uniformity.

Because of energy losses in a 0.5-mm-thick aluminum vacuum window and in the air lying between the beam’s exit and the detectors, the actual most probable energy of the protons delivered to the detector was expected to be 43.0 MeV. The mean flux of a Gaussian-shaped proton beam of 0.5 nA with a full width at half maximum (FWHM) of 4 cm was approximately $2.5 \times 10^8$ Hz cm$^{-2}$. The gas mixture for the operation of the detectors was the same as that for the X-ray test. The maximum sensitivity of the radiation-induced current per channel was adjusted to 384 nA.

Figure 7 shows the distributions of channel responses for a proton beam in the $x$ (top) and the $y$ (bottom) directions, measured at $V_{GEM} = 120$ (dash-dotted), 360 (dot), 400 (dashed), and 440 V (solid) for 5.0 s. The emittances of the beam (defined as standard deviations), measured at the detector’s position, were 1.70 ($x$) and 1.73 cm ($y$). Ratios of the channel responses at $V_{GEM} = 300$ (dash-dotted), 360 (dot), 400 (dashed), and 440 V (solid) to those at $V_{GEM} = 120$ V in the $x$ (left) and the $y$ (right) directions calculated for the region near the beam’s center, are shown in the left and the right figures in Fig. 8, respectively. At $V_{GEM} = 120$, the spatially-inhomogeneous GEM amplification, as well as the magnitude of the gain, is expected to be negligible.

Two calibration functions for the non-uniform channel responses were obtained from the ratios of the smoothed functions of the data at $V_{GEM} = 400$ V to those at $V_{GEM} = 120$ V, where the shape of the beam profile was preserved without deformation. Then, the two calibration functions, one for $x$ and one for $y$, were applied to the other data measured at the neighboring voltages. Figure 9 shows the calibrated channel responses in the $x$ (top) and the $y$ (bottom) directions measured at 360 (dash-dotted), 380 (dotted), 420 (dashed), and 440 V (solid). The central regions (within 2$\sigma$) of the calibrated beam-profile data measured over a wide range of $V_{GEM}$ agreed fairly well with the expected Gaussians. The minimum particle flux to be measured by the present single-GEM-loaded detector is about $10^5$ Hz cm$^{-2}$ when we adjust the maximum $V_{GEM}$ for practically reliable measurements without being hampered by discharges was 420 V, where the expected gain for the gas electrons was about 35.
Radiation Tests for a Single-GEM-Loaded Gaseous Detector – Kyong Sei Lee et al.

Fig. 9. Calibrated channel responses in the $x$ (left) and the $y$ (right) directions measured at 360 (dash-dotted), 380 (dotted), 420 (dashed), and 440 V (solid).

magnitude of the gain to about 20 (obtained at $V_{GEM} = 400$) and apply the proper calibrations for the GEM-amplified channel responses.

Two thin plane detectors composed of just a 3.2-mm-thick induction region and, thus, operating in a pure ionization mode were tested together to demonstrate the detection characteristics of the single-GEM-loaded detector. In order to reconcile the dynamic ranges of detections for the two different type detectors, we set $V_{GEM}$ for the single-GEM-loaded detector at 240 V, where the gain through the GEM is expected to be approximately 2. The voltage applied to the induction region of the thin plane detectors was 800 V.

The single-GEM-loaded and two thin plane detectors were installed at distances of 130.0, 133.6, and 137.2 cm from the vacuum exit of the beams, respectively. The position of the first and the second thin plane detectors in the beam depth were estimated to be $0.658 \pm 0.015$ and $1.300 \pm 0.030$ g cm$^{-2}$, where the specific energy of the 43-MeV protons predicted by using the GEANT4 simulation were 17.4 MeV g$^{-1}$ cm$^{2}$ and 27.5 MeV g$^{-1}$ cm$^{2}$, respectively.

Figure 10 shows the detector responses in the $x$ (left) and the $y$ (right) directions for 0.5- (dash-dotted), 1.0- (dot), 2.0- (dashed), and 3.0- (solid) nA proton beams measured by using the single-GEM (top), the first thin plane (middle), and the second thin plane detectors (bottom). The detector responses were not clearly proportional to the nominal beam intensities due to the poor accuracy of the beam setup using a Faraday cup. However, as shown in Fig. 10, the ratios of the detector responses for 1.0-, 2.0-, and 3.0-nA beams to those for the 0.5-nA beam measured by the three detectors coincide fairly well. The mean ratio of the total detector responses measured by the first and the second thin plane detectors, averaged over all the beam data, was valued as $1.555 \pm 0.055$, which agrees well with the ratio of the specific energy losses at the given depths, 1.580, predicted by using the GEANT4 simulations.

Fig. 10. Detector responses in the $x$ (left) and the $y$ (right) directions for 0.5 (dash-dotted), 1.0 (dot), 2.0 (dashed), and 3.0 (solid) nA proton beams measured by using the single-GEM (top), the first thin plane (middle), and the second thin plane detectors (bottom).

Fig. 11. Total detector responses of the single-GEM-loaded detector for 0.5-nA, 43-MeV protons (full circles) and X-rays (open circles) measured as a function of $V_{GEM}$.
In Fig. 11, the total detector responses of the single-GEM-loaded detector for 0.5-nA 43-MeV protons (full circles) measured as a function of $V_{GEM}$ are compared with those previously measured for the X-rays (open circles). The estimated mean flux of the 0.5-nA proton beam with a FWHM of 4 cm was $2.5 \times 10^8$ Hz cm$^{-2}$, which was estimated to be about 50 times higher than that for previously measured X-ray data ($\sim 5 \times 10^6$ Hz cm$^{-2}$). As shown in Fig. 11, the trend of the exponential growth of the gain measured for the protons is less steep than that measured for the X-rays because of the higher particle rate. However, the linearity of the detector response to the particle flux was clearly preserved at a particle flux of $2.5 \times 10^8$ Hz cm$^{-2}$, which is still below the expected rate-capability limit ($\sim 10^9$ Hz cm$^{-2}$) for single-step GEM amplification detection.

The position resolution for the single-GEM-loaded detector was measured by placing 20-mm-thick polymethyl-methacrylate (PMMA) collimators with 2-mm-wide holes at 2 cm from the detector window. The single-GEM detector was installed 50 cm from the vacuum exit of a 10-nA proton beam. Figure 12 shows the beam profiles in the $x$ (left) and the $y$ (right) directions collimated by using a collimator with a single hole (top) and by one with a $2 \times 2$ hole matrix with a 20-mm spacing in both directions (bottom). The mean standard deviations of the narrow-beam profiles in the $x$ and the $y$ directions were valued as 0.743 and 0.604 mm, respectively. The intrinsic position uncertainty of measuring a particle track with 1.25-mm-pitch strips is 0.361 mm. Therefore, the effect of the dispersion of the drifting gas electrons in the thin single-GEM-loaded detector on the position resolution was quite insignificant.

Fig. 12. Beam profiles in the $x$ (left) and the $y$ (right) directions collimated by using a collimator with a single hole (top) and by one with a $2 \times 2$ hole matrix with a 20-mm spacing in both directions (bottom).

In the present detector R&D are summarized as follows:

1. The maximum gain obtained by using the single-step GEM amplification without allowing discharges was 35 measured at $V_{GEM} = 420$ V. A maximum gain of about 20 is required to perform statistically qualified measurements for particle-beam profiles with fluxes of less than $10^6$ Hz cm$^{-2}$.

2. The non-uniform GEM-amplified channel responses were properly calibrated by applying the calibration functions obtained by using the ratios of the channel response functions for the sample data measured at $V_{GEM}$ of 120 (unamplified) and 400 V.

3. The quantitative accuracies of the detector responses in space (Fig. 1) and time (Fig. 14) measured by using the single-GEM-loaded detector were confirmed by comparisons with those measured by the two thin plane detectors prepared for the reference detectors.

4. To enhance the rate capability of detector for high particle rates, we reduced the gain of the GEM to about 2. Then, the linearity of the detector’s response to the beam was confirmed for the maximum proton fluxes of about $10^{10}$ Hz cm$^{-2}$, which is a factor of a thousand higher than the rate capability for the typical triple-GEM detectors [7, 8].

5. The intrinsic position resolution for the single-GEM-loaded detector was valued as about 0.5 mm. The dispersion of the drifting gas electrons that affects the position resolution was insignificant.

One of the prospective applications of the detector technology developed in the present research will be for the $x$ (pad arrays) and for $y$ (strips) directions as 0.588 and 0.400 mm, respectively. The intrinsic position uncertainty of measuring a particle track with 1.25-mm-pitch strips is 0.361 mm. Therefore, the effect of the dispersion of the drifting gas electrons in the thin single-GEM-loaded detector on the position resolution was quite insignificant.

V. CONCLUSION

A single-GEM-loaded detector has been constructed and tested for precision measurements of high-energy hadron beams. The detector’s characteristics have been examined with X-rays and 43-MeV protons with a maximum particle flux of about $10^9$ Hz cm$^{-2}$. The electronics for the signal process and the DAQ with a maximum data-transfer speed of 35 kHz were designed and manufactured for precision time-dependent measurements of hadron-beam profiles. The conclusions of the present detector R&D are summarized as follows:

1. The maximum gain obtained by using the single-step GEM amplification without allowing discharges was 35 measured at $V_{GEM} = 420$ V. A maximum gain of about 20 is required to perform statistically qualified measurements for particle-beam profiles with fluxes of less than $10^6$ Hz cm$^{-2}$.

2. The non-uniform GEM-amplified channel responses were properly calibrated by applying the calibration functions obtained by using the ratios of the channel response functions for the sample data measured at $V_{GEM}$ of 120 (unamplified) and 400 V.

3. The quantitative accuracies of the detector responses in space (Fig. 1) and time (Fig. 14) measured by using the single-GEM-loaded detector were confirmed by comparisons with those measured by the two thin plane detectors prepared for the reference detectors.

4. To enhance the rate capability of detector for high particle rates, we reduced the gain of the GEM to about 2. Then, the linearity of the detector’s response to the beam was confirmed for the maximum proton fluxes of about $10^{10}$ Hz cm$^{-2}$, which is a factor of a thousand higher than the rate capability for the typical triple-GEM detectors [7, 8].

5. The intrinsic position resolution for the single-GEM-loaded detector was valued as about 0.5 mm. The dispersion of the drifting gas electrons that affects the position resolution was insignificant.

One of the prospective applications of the detector technology developed in the present research will be...
dose-verification measurements in proton [9,10] or carbon therapy [11–14]. The small detector thicknesses of the single-GEM-loaded and the thin plane detectors are also advantageous for developing a multilayer detector system, which would dramatically reduce the time and the labor required for executing the dose verification procedure.

Another potential application is large-scale high-energy X-ray inspections for cargo containers and vehicles. The uniform thickness of the cathode material in the planar-type gaseous detectors to produce Compton electrons will guarantee fairly uniform channel responses to gamma- and X-rays. Furthermore, a high resolution for scanned images of better than 300 μm can be reliably achieved by adapting a high-density strip or pad readout with a pitch of narrower than 1 mm, which would be practically difficult to achieve with a detector system composed of scintillator crystals and silicon pindio diode arrays.

**ACKNOWLEDGMENTS**

This study was supported by a Korea University Grant (research fellow program) and by the National Research Foundation of Korea (Grant Numbers NRF-2013R1A1A2060257 and NRF-2013M2B2A9A03050128).

**REFERENCES**

[1] K. S. Lee, B. Hong, K. Lee, S. K. Park and J. Yu, J. Korean Phys. Soc. 64, 958 (2014).
[2] S. Lee, B. Hong, K. S. Lee, B. Mulilo and S. K. Park, Nucl. Instr. Meth. A 724, 6 (2013).
[3] C. Kim et al., J. Korean Phys. Soc. 60, 725 (2012).
[4] K. S. Lee et al., J. Korean Phys. Soc. 59, 2002 (2011).
[5] V. Anferov, Nucl. Instr. Meth. Phys. A 496, 222 (2003).
[6] S. Duarte Pinto, M. Villa, M. Alfonsi, I. Brock, G. Croci, E. David, R. de Oliveira, L. Ropelewski and M. van Stenis, J. Instrumentation 4, P12009 (2009).
[7] S. Bachmann, A. Bressan, S. Kappler, B. Ketzer, M. Deutel, L. Ropelewski, F. Sauli and E. Schulte, CERN-OPEN-2000-299 Sept. 2000.
[8] M. Capeans, B. Ketzer, A. Placci, L. Ropelewski, F. Sauli and M. van Stenis, CERN-EP/TA1-CH-1211 (2000).
[9] T. Bortfeld, Phys. Med. Biol. 51, R363 (2006).
[10] W. Newhauser, K. Myers, S. Rosenthal and A. Smith, Phys. Med. and Biol. 47, 1369 (2006).
[11] M. Kramer, O. Haberer, G. Kraft, D. Schardt and U. Weber, Phys. Med. Biol. 45, 3299 (2000).
[12] B. Schaffner, E. Pedroni and A. Lomax, Phys. Med. Biol. 44, 27 (1999).
[13] T. Inaniwa, T. Furukawa, S. Sato, T. Tomitani, M. Kobayashi, S. Minohara, K. Noda and T. Kanai, Nucl. Instr. Meth. B 266, 2194 (2007).
[14] Y. Futami, T. Kanai, M. Fujita, H. Tomura, A. Higashi, N. Matsufuji, N. Miyahara, M. Endo and K. Kawachi, Nucl. Instr. Meth. A 430, 143 (1999).