

# Development of Thick-GEMs for a GEM-TPC Tracker

Fuminori Sakuma<sup>1</sup> and Makoto Tokuda<sup>2</sup>

<sup>1</sup> RIKEN Nishina Center, RIKEN, Saitama 351 0198, Japan

<sup>2</sup> Department of Physics, Tokyo Institute of Technology, Tokyo 152 8551, Japan

E-mail: sakuma@ribf.riken.jp

**Abstract.** A Time Projection Chamber (TPC) with Thick Gas Electron Multipliers (TGEMs) has been developed for an inner tracker of the J-PARC E15 experiment, a deeply-bound kaonic nuclear states search experiment. The TPC has a cylindrical design with an inner diameter of 170 mm, an outer diameter of 280 mm, and a drift length of 300 mm filled with P10 gas (90:10 argon-methane) at atmospheric pressure. A TGEM is used for the amplification of the TPC in order to realize a self-supporting structure in a limited space. We use a double TGEM structure and the maximal effective gain of more than  $10^4$  is achieved with  $100 \times 100$  mm TGEM prototypes. Moreover, we have been developing a resistive-electrode TGEM (RETGEM) with graphite electrodes, which has the advantage of being fully spark-protected. The results of our recent studies on the TGEM prototypes with conventional copper electrodes, the RETGEM with graphite electrodes, and the newly developed hybrid-RETGEM with copper and graphite electrodes are discussed.

## 1. Introduction

The purpose of the J-PARC E15 experiment is to search for the simplest kaonic nuclear bound state,  $K^-pp$  cluster, by using an in-flight  ${}^3\text{He}(K^-,n)$  reaction [1]. The produced  $K^-pp$  cluster will be identified with missing mass spectroscopy using a forward-going neutron with an invariant mass analysis of the expected decay particles from the  $K^-pp$  cluster, such as  $p\Lambda/p\Sigma^0$  and  $p\pi\Sigma$ . The baseline detector for the E15 experiment consists of a high-precision beam line spectrometer, a Cylindrical Detector System that surrounds a target to detect the decay particles from the  $K^-pp$  cluster and a neutron TOF counter that is located 15 m away from the target position. The detector has been designed to focus on the  $K^-pp \rightarrow p\Lambda$  channel, which is expected to be the main decay branch of the  $K^-pp$  cluster. Therefore, the interaction vertex position resolution is limited to  $\sim 6$  mm along the beam direction ( $z$ -direction). However, recent theoretical progresses on the  $K^-pp$  cluster indicate the importance of another decay mode, i.e.,  $p\pi\Sigma$ , in reaching an informed conclusion about the  $K^-pp$  cluster. In order to realize an efficient measurement of the decay mode  $K^-pp \rightarrow p\pi\Sigma$ , we need to install a new detector in our baseline detector system. The requirements of the new detector system are as follows:

- interaction position resolution in the  $z$ -direction must be less than 1mm,
- the new detector system must be compact because of the limited space availability around the target, and

- the material budget of the new detector must be minimized because the detector will be installed as the innermost detector of the tracking system for the experiment.

After a detailed investigation, we chose the Time Projection Chamber (TPC) as the technology for the innermost tracking detector. Moreover, in order to realize the compactness and robustness of the detector, we selected a recently developed technology, a Thick Gas Electron Multiplier (TGEM), for the signal amplification stage of the TPC.

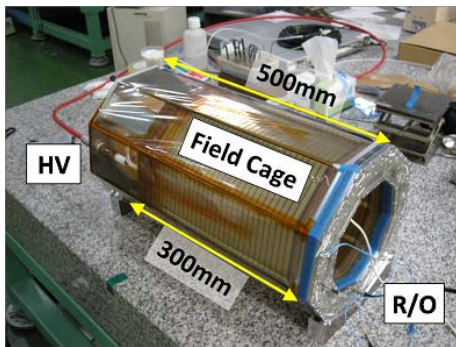
The TGEM is made from a double-sided copper cladding FR4 plate using standard PCB techniques with mechanically drilled holes, and if necessary, with chemically etched rims around the holes [2][3]. The typical parameters of our TGEM prototype are a thickness of 400  $\mu\text{m}$ , hole-diameter of 300  $\mu\text{m}$ , rim of 30  $\mu\text{m}$ , and pitch of 600  $\mu\text{m}$ . Because of the rigidity of the TGEM, it is comparatively easy to construct a self-supporting structure in a limited space. Further, the TGEM has the following advantages: robustness, cost-effective fabrication, high-gain multiplication, and ease of handling. In the recent years, a resistive-electrode TGEM (RETGEM), whose electrodes have been replaced by the resistive electrodes of graphite paint [4] or resistive Kapton [5] has attracted considerable attention as a more robust version of the TGEM. The resistive electrodes protect the detector and the readout electronics from damage by any occasional discharge. We have developed conventional TGEMs with copper electrodes, RETGEMs with graphite-paint electrodes, and newly constructed hybrid-RETGEMs which have copper and graphite electrodes on each side. In this article, we first describe the design of the TGEM-TPC for the J-PARC E15 upgrade and then discuss the results of our recent studies on the TGEM prototypes.

## 2. Design of the TGEM-TPC

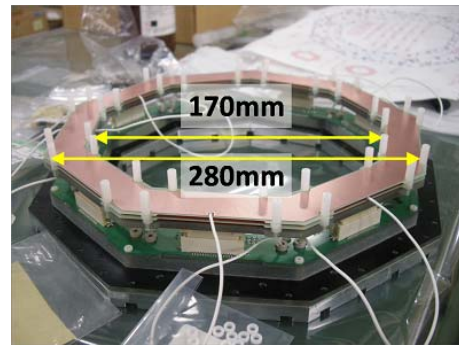
The TPC has a cylindrical design with an inner diameter of 170 mm, an outer diameter of 280 mm, and a drift length of 300 mm filled with P10 gas (90:10 argon-methane) at atmospheric pressure. A photograph of the TPC is shown in Fig. 1. The TPC consists of an end-cap TGEM chamber, an inner field cage and an outer field cage, which are made from double-sided Flexible Printed Circuits (FPC) with staggered strip electrodes having a width of 8 mm and pitch of 10 mm and connected with 1 M $\Omega$  resistors. A drift field of 150 V/cm is applied to the field cages. For amplification, a double-TGEM structure is used as shown in Fig. 2. The TGEM has a nonagonal shape whose one side is subdivided into three sectors and separately connected externally to the voltage supply through high-value resistors in order to reduce both the energy and the propagation probability of the discharge. High voltages are applied to the double-TGEM through connectors penetrating the end cap with a resistor chain. The layout of the readout system is also nonagonal and is divided into 4  $\times$  4 pads on each side with 4 mm-long and 20 mm-wide pads printed on a standard PCB (the number of total readout channels is 144). For the TPC front-end electronics, preamplifier cards with amplifier-shaper-discriminator ASICs developed for the ATLAS experiment [6] are used, i.e., we obtain only the Z-direction information from the TPC.

## 3. Results of TGEM prototypes

In order to study the performances of the TGEM, we used 13 types of prototype TGEMs with an active area of 10  $\times$  10 cm<sup>2</sup>; these TGEMs were produced by REPIC Corp., Japan. The TGEM electrodes were made of copper (TGEM#1 - 7), graphite (TGEM#8 - 12), and copper/graphite (TGEM#13). Table 1 summarizes the geometrical parameters of the TGEMs studied in the present work. Measurements were carried out with a double-TGEM configuration using a test bench that consisted of a gas chamber housing, a voltage divider with a resistor chain, and the read out pad with a charge sensitive preamplifier. Figure 3 shows the gas chamber for the TGEM prototypes, and Fig. 4 shows the experimental setup for testing the TGEMs. The effective gain



**Figure 1.** Photograph of the TPC.



**Figure 2.** Photograph of the TPC readout with a double-TGEM configuration.

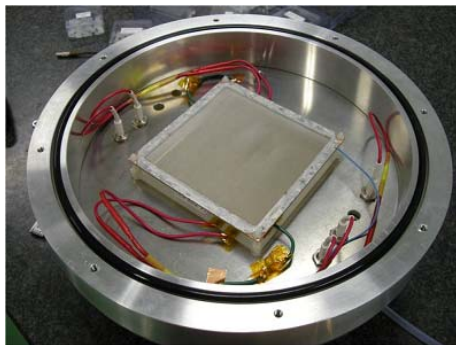
is required to be more than  $10^4$ , and the stability of the gain and the energy resolution should be within 10% per day as per the requirements of the TPC stable operation.

**Table 1.** A summary of the geometrical parameters of TGEMs studied in this work.

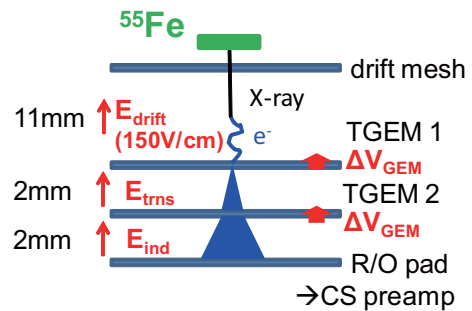
TGEM#	electrode	insulator (mm)	thickness (mm)	hole diameter (mm)	pitch (mm)	rim size (mm)
1	Cu	FR4	0.2	300	0.6	0.05
2	Cu	FR4	0.2	500	0.6	-
3	Cu	FR4	0.4	300	0.6	-
4	Cu	FR4	0.4	300	0.6	0.03
5	Cu	FR4	0.4	300	0.6	0.05
6	Cu	FR4	0.4	300	0.7	0.1
7	Cu	FR4	0.4	500	0.6	-
8	C	FR4	0.4	300	0.7	-
9	C	FR4	0.4	300	0.6	-
10	C	G10	0.4	300	0.6	-
11	C	CEM3	0.4	300	0.6	-
12	C	FR4	0.6	300	0.7	-
13	C/Cu	FR4	0.4	300	0.6	-

### 3.1. TGEM with copper electrodes

Figure 5 shows the effective gain of the double TGEM measured with  $^{55}\text{Fe}$  with four types of the rim configuration (TGEM#3 - 6). Further, the stability of the gain and the energy resolution for a day under the same configurations are shown in Fig. 6. The effective gains shown in Fig. 6 are corrected with the ratio  $P/T$  of the absolute temperature and the pressure: a function of the form  $f(P/T) = \alpha \exp(\beta P/T)$ , where  $\alpha$  and  $\beta$  are the fitting parameters. All types of TGEMs achieve the maximal effective gain of more than  $10^4$ , but TGEMs with larger rims require a higher voltage. In the stability plots, the gains of all TGEMs decrease for a few hours after a high voltage is turned on, and the energy resolutions of TGEMs with rims (TGEM#4 - 6) fluctuate during the measurement. Although thus far, such behaviors of the TGEM are not

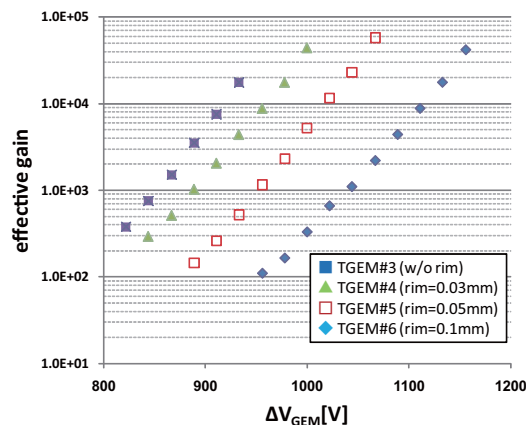


**Figure 3.** Photograph of the gas chamber for the TGM prototypes.



**Figure 4.** Schematic representation of measurement setup.

understood well, the initial drop effect of the gain is likely to be caused by the charge-up (or polarization) of the overall insulator, and the instability of the TGM with rims is possibly caused by the charge-up of insulator that is not metalized.

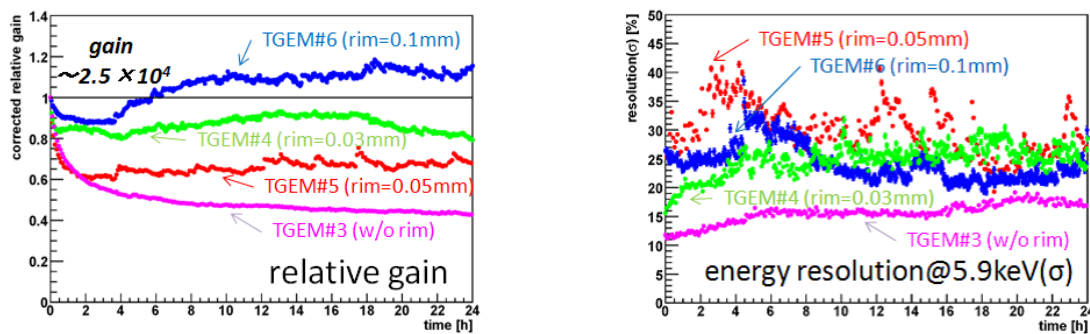


**Figure 5.** Effective gains measured with double-TGEMs of different geometries.

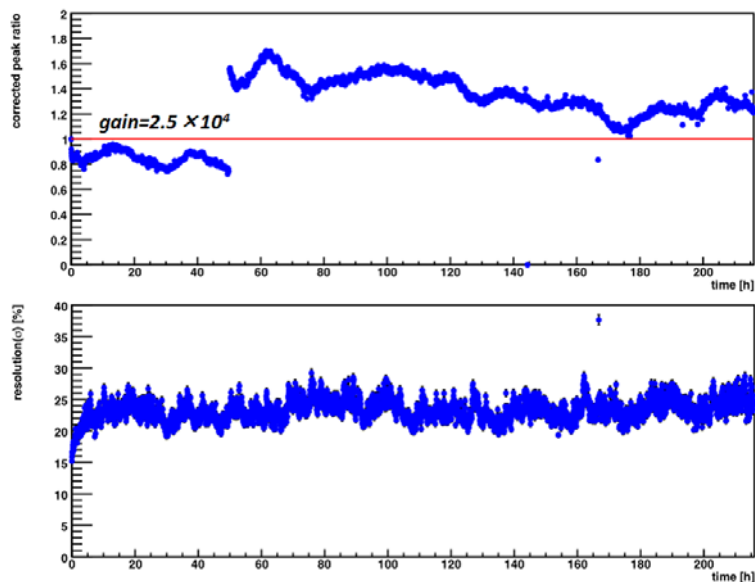
In order to further investigate the long-term stability of TGM, we applied a high voltage to TGM#4 with an  $^{55}\text{Fe}$  X-ray irradiation continuously for approximately 10 days. Figure 7 shows the effective gain corrected with the P/T and the energy resolution. It should be noted that the high voltage for the TGM is turned up manually at interval of around 50 h in order to maintain a high gain of more than  $10^4$ . In the figures, the effective gain is maintained at more than  $10^4$ , but the gain fluctuation is approximately 30% per day. A possible reason for this instability is the charge-up of the insulator that is not metalized.

### 3.2. TGM with graphite electrodes

In order to avoid the effects of the rims, we have developed a resistive-electrode TGM (RETGEM), which has electrodes coated with graphite paint. The RETGEMs have the advantage of being fully spark-protected. We have fabricated and tested several types of TGEMs (TGM#8 - 12); However, RETGEMs with an FR4 insulator (TGM#8, 9) were not produced stably because of the discharge from the graphite attachment inside the holes caused by the knot of the glass fiber on the cross section of FR4. Another problem related to the fabrication



**Figure 6.** Stability of effective gains (left) and energy resolution (right) measured with double-TGEMs of different geometries for a day. The gains are corrected with the ratio  $P/T$ , and unity of the relative gain corresponds to the effective gain of  $2.5 \times 10^4$ .



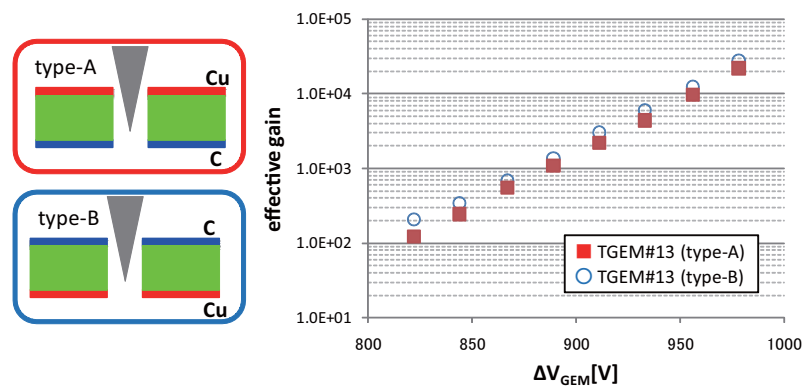
**Figure 7.** Effective gain corrected with the ratio  $P/T$  (up) and energy resolution (down) of double-TGEM#4 for approximately 10 days. Unity of the relative gain corresponds to an effective gain of  $2.5 \times 10^4$ . The high voltage for the TGEM is turned up manually at interval of around 50 h in order to maintain a high gain of more than  $10^4$ .

of the RETGEM with graphite electrodes was the discharge from the burrs arising from the drilling process, but this discharge could be removed by using an antistatic brush. The problem of the graphite attachment could not be solved by improving the drilling procedure. In fact, only the first 2 out of the 11 samples of the RETGEMs (TGEM#8, 9) worked. Now, we have been studying the RETGEM with a CEM3 insulator, which contains less glass fiber than FR4.

### 3.3. TGEM with copper and graphite electrodes

Because of the difficulty in producing graphite RETGEMs, we attempted to fabricate a new type of RETGEM with copper and graphite electrodes on each side (hybrid-RETGEM, TGEM#13). The resistivity of one side of the electrodes would be spark-protected in principle. Further, the

hybrid-RETGEM would have a possibility of a reduction of the graphite attachment inside the holes by an alignment of the drilling process. We fabricated the hybrid-RETGEM with two drilling directions: drilling into the hybrid-RETGEM form the copper to the graphite electrode and vice versa. We found that the two fabrication methods work almost similarly with respect to the gain (and resolution) as shown in Fig. 8, which shows the obtained effective gain of the two double hybrid-RETGEMs. Figure 9 shows the long-term stability of a double hybrid-RETGEM for approximately 25 days with  $^{55}\text{Fe}$  X-ray irradiation. The upper figure in Fig. 9 shows the effective gain corrected with the P/T, and the lower figure shows the energy resolution. It should be noted that high voltage for the TGEM is turned up manually at interval of around 40 h in order to maintain a high gain of more than  $10^4$ , and blanks in the plots are absent of the  $^{55}\text{Fe}$  source but are kept for turning on the high voltage. The effective gain is maintained more than  $10^4$ , and a gain fluctuation of approximately 5% per day is achieved.

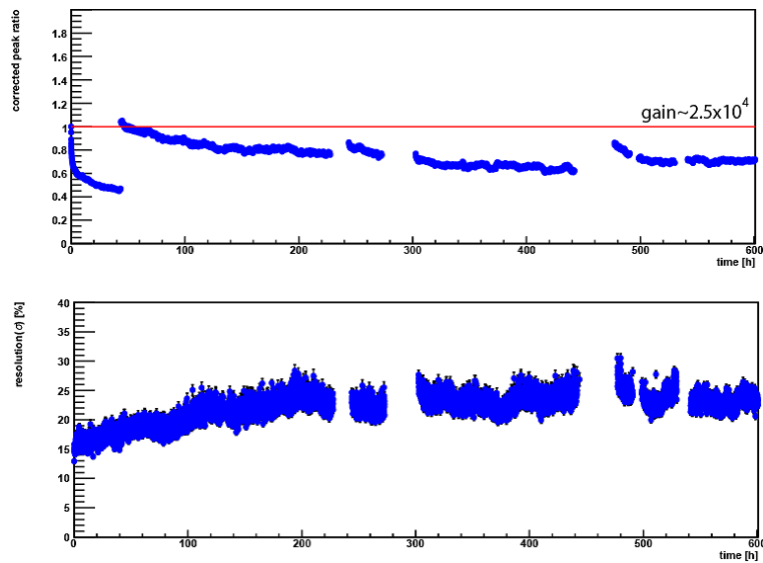


**Figure 8.** Effective gains of double-TGEM#13s with two different fabrication methods. Type-A indicates drilling into the hybrid-RETGEM form the copper to the graphite electrode, and type-B indicates the opposite.

#### 4. Summary

A TPC with TGEM has been developed for an inner tracker of the J-PARC E15 experiment, a deeply-bound kaonic nuclear states search experiment. The TPC has a cylindrical design with an inner diameter of 170 mm, an outer diameter of 280 mm, and a drift length of 300 mm filled with P10 gas at atmospheric pressure. The TGEM is used for the amplification of the TPC in order to realize a self-supporting structure in a limited space. We have used a double TGEM structure. Further, a maximal effective gain of more than  $10^4$  is achieved with  $100 \times 100$  mm TGEM prototypes with conventional copper electrodes. Moreover, we have developed RETGEMs with graphite electrodes and with copper and graphite electrodes; these RETGEMs have the advantage of being fully spark-protected. Although further investigation is required for a stable production of the RETGEM with graphite electrodes, the newly developed hybrid-RETGEM with copper and graphite electrodes exhibits with good performance: the effective gain is maintained more than  $10^4$  in the long term, and a gain fluctuation of approximately 5% per day is achieved.

The next challenge will be to establish a stable production method of the RETGEM with graphite electrodes and insulators other than the FR4 insulator.



**Figure 9.** Effective gain corrected with the ratio P/T (up) and energy resolution (down) of double-TGEM#13 for approximately 25 days. Unity of the relative gain corresponds to the effective gain of  $2.5 \times 10^4$ . The high voltage for the TGEM is turned up manually at interval of around 40 h in order to maintain a high gain of more than  $10^4$ , and blanks in the plots are absent the  $^{55}\text{Fe}$  source but are kept for turning on the high voltage.

#### 4.1. Acknowledgments

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