Techniques developed for the ATLAS Thin Gap Chambers mass production in Japan


Abstract—The Thin Gap Chambers (TGCs) are used for the muon trigger system in the end-cap regions of the ATLAS detector. The TGC mass production phase at High Energy Accelerator Research Organization (KEK) started in January 2001. As the anode-cathode distance is small, 1.4 mm, chamber flatness is essential to achieve a uniform gas gain over the chamber. In order to perform a stable production with high quality we developed a chamber closing system. When we glue two half-chambers together, we sandwich them between a granite table and an aluminum honeycomb panel to keep the chamber flat from both sides. By using silk screens, we control the quantity of epoxy adhesive that affects the chamber thickness. Due to these developments, we can achieve the flatness of less than 100 µm. Uniformity of detection efficiency of the TGC is measured with a cosmic-ray test bench at Kobe University. So far we have tested 300 TGCs. Position dependence of the efficiency is measured with a granularity of 5mm-by-5mm. The average efficiency over the tested chambers is achieved to be 99% excluding the wire supports and spacers.

Index Terms—Gas detectors, Proportional counters, Triggering

I. INTRODUCTION

The Thin Gap Chambers (TGCs) are used for the muon trigger system in the end-cap regions of the ATLAS detector [1]-[3]. The TGC is characterized by fast signal response (99% of the output signals are within 25 ns) for charged particles [4], [5]. This characteristic suits the muon trigger detector of the Large Hadron Collider (LHC), which is required to identify the bunch crossing at 40 MHz. Each TGC has a trapezoidal shape, whose dimensions depend on its location. A typical size is 1.3 m (longer base) × 1.3 m (height). As the anode-cathode distance is small, 1.4 mm (Fig. 1), chamber flatness is essential to achieve a uniform gas gain over the chamber. The parameters of the TGC structure and the operation conditions are summarized in Table I. The TGC is designed to provide a fast signal response for charged particles. The diameter of the wire is 50 µm in order to give a wide range and high electric field. The surface of glass-epoxy laminate (FR-4) in the gas volume is coated with graphite, which serves as the cathode plane. Its nominal surface resistivity is 1 MΩ/square. Pickup read-out strips made of copper foil run perpendicularly to the wire, to give the orthogonal coordinate, on the surface of FR-4 opposite to the gas volume.

Fig. 1. Schematic view of a cross section of the TGC. ASD stands for an amplifier-shaper-discriminator readout channel.

ATLAS TGC chambers are produced in parallel in Japan, Israel and China. Basic performances of materials used in gas volumes were studied at KEK (Japan) in small prototype chambers [6], [7]. Production procedures of real-size TGCs were developed from March 1998 to the end of 2000. The TGC series production started in January 2001. A production
of about 1100 TGCs is to be completed in Japan by the middle of 2004. In order to meet this schedule the KEK production facility was designed to produce two TGCs per day with about twelve workers and three physicists as supervisors.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>CHARACTERISTICS OF THIN GAP CHAMBERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
<td>Nominal value</td>
</tr>
<tr>
<td>Gas gap</td>
<td>2.8 mm</td>
</tr>
<tr>
<td>Anode wire pitch</td>
<td>1.8 mm</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>50 µm</td>
</tr>
<tr>
<td>Wire potential</td>
<td>2900 V</td>
</tr>
<tr>
<td>Gas mixture</td>
<td>CO₂ + n-pentane (55:45)</td>
</tr>
</tbody>
</table>

II. PRODUCTION PROCEDURES

In order to avoid the sag of the anode wire there rows wire supports in the gas volume. In addition, there are zigzag row of small buttons between the supports to keep the anode-cathode gap constant. A TGC with one gas gap is called “singlet” and two or three singlets glued together with honeycomb-panel in-between are called “doublet” or “triplet”, respectively [1]. The TGC production procedures can be roughly divided into nine stages: checking the quality of the materials, graphite spray, FR-4 frame gluing, wire winding, singlet TGC closing, sealing around the singlet, doublets or triplets modules production, mounting read-out boards and assembling CO₂-gas channels around the module. All the procedures except the graphite spraying are performed in parallel. In order to reach the desired high quality the TGC production line is required to keep a precise anode wires spacing (1.8 mm) for a uniform time response, flatness of both anode and cathode planes to obtain a uniform gas gain and cleaness of the detection gas volume to avoid discharges. The main part of the TGC is made of commercially available FR-4 boards.

A. Wire winding

Since more than 700,000 wires are to be soldered in the whole production at KEK, precise and reliable wire winding and soldering technique had to be established. The 50 µm anode wires are strung by using an automatic winding machine, which can control the wire pitch with precision of 1 micron and the wire tension within 3 % error of designed value, 350 gw. The automatic winding machine consists of a linear actuator and a rotating table. Two cathode frames are held on both sides of the table by small fixing pieces around the frame and twelve suction pads at the central part. The linear actuator moves half wire pitch every half turn of the rotating table. The high accuracy in the position of the linear actuator is achieved by a feed back control of the servomotor with a linear encoder. To solder the anode wire we use tin-zinc (80/20) solder. It can hold the wire against higher tension than normally used tin-lead based solder. Since residual of the solder flux causes the ion-migration and weaken the strength by corrosion, we choose a water-soluble flux. We can clean the soldered region with dematerialized water applying supersonic wave before washing the cathode planes.

B. Washing frames

During the wire soldering, sometimes nebulized flux drops adhere on the cathode plane. Its remaining ion contaminant of the flux might cause discharge in the operation. In order to clean the surface of the cathode plane, we use an automatic washing machine before closing the singlets. The machine showers dematerialized water mist on the whole cathode frame. After the shower, a nozzle mounted on a linear actuator scans the frames and sprays compressed air in order to dry them.

C. Closing singlet TGC

After the wire winding stage, the wire tension causes the frame to arch with a few cm gaps between the wires to the cathode plane. We adopted a combination of vacuum-press and a suction plate technique for gluing to make a singlet TGC as it can apply uniform force on both sides of the TGC.

As shown in Fig.2, the frame with wires places on the granite table and another frame without wires is held under an aluminum honeycomb plate (AL-plate). On the surface of the granite table, a polypropylene sheet (PP sheet) with 30 meshes per inch is attached. A 0.5-mm-thick silicon rubber strip, which its surface is treated with isopropyl alcohol to make the surface sticky, is attached with double-coated tape around the PP sheet for sealing. There are four suction holes for sucking the frame with wire onto it. Since the thicknesses of the PP sheet and silicon rubber are the same and the homogeneous suction force is applied, the frame can be kept flat. Similarly, the frame without wires is sucked onto the AL-plate. To suck the frames, regulated negative pressure (-40 kPa) is applied between the granite table and the frame with wires, as well as between the AL-plate and the frame without wires. The two frames with the AL-plate are covered with a silicon rubber sheet. Inside the volume surrounded by the granite table
and the rubber sheet is then decompressed (-10 kPa Gauge: Pressure1) to press the two frames uniformly. Since the seal of the 0.5-mm-thick silicon rubber strip is not perfect, Pressure1 would become lower and lower and eventually reach the same level as Pressure2 (-40 kPa). In order to avoid such an over pressure on the frames, Pressure1 is maintained by supplying clean air controlled with a pressure sensor and gas ballast.

As for the technique of applying adhesives, a screen-printing method is adopted. We use a polyarylate mesh screen (145 meshes per inch) to apply the epoxy to the wire-supports and frames. The thickness and the width of the adhesive can be uniformly adjusted. The screen is tough enough for multi-use and the residual resin can be easily removed by water. The resulting surface distortions of the singlet TGCs are shown in Fig.3. Almost all the singles reach a flatness of less than 100 µm.

III. QUALITY ASSURANCE

Since the TGCs are assembled with adhesive, once the adhesive is cured it is not possible to return to a previous stage without damaging the chamber. Therefore, it is important to check the quality at each assembly stage before moving to the next one. We have adopted the following quality checks: a measurement of the resistivity of the graphite surface, high voltage tests (HV tests), a pulse test to check the connection of signal routing, and a signal response test with a radioactive source.

A. Cathode surface resistivity control

The surface resistivity of the graphite sprayed should be approximately 1 MΩ/square in order to reduce cross talk between strip channels while still avoiding voltage drop [1]. To realize the uniform surface resistivity, we use an automatic sprayer composed of a two-dimensional linear actuator and a spray gun with pneumatic control. The sprayer can uniformly paint the whole cathode plane with a thickness of about 10 µm. The surface resistivity is measured at about 66 sampling points on a plane. If they are smaller than 0.5 MΩ/square, then the plane is cleaned up and is sprayed again. If it exceeds 1.5 MΩ/square, the area is polished with soft paper until it reaches 1.5 MΩ/square.

B. High voltage tests

We apply high voltage at three stages and check leak current in the course of the whole assembly: before closing the singlet TGC, after the closure, and the assembly of adaptor boards which bring signals from wires or strips to the ASDs. The purpose of the HV test is to verify that there is no serious problem up to this stage: no broken or slack wires, and no fine dusts or chemicals inside the gas volume which would cause problems later on. The acceptance criterion of all these tests is that the chamber current should be less than 100 nA at the applied voltage of 2.8 kV with CO₂ gas.

Before closing singlet the HV test is a particularly important feature in the production. The setup is the same as closing singlet TGC, except for feeding CO₂ gas into the silicon rubber. If we find steady high leak current or some discharges, we reopen the frames and wash the inside of the frames. Then we do the HV test again. We repeat this procedure until the leak current satisfies the criterion. Since the pressure in the gas
volume is -10 kPa, the HV of 2.8 kV corresponds to 3.1 kV at
the standard atmospheric pressure. Fig.5 shows a distribution
of the leak current measured at the first cycle of the tests. From
this distribution, one can see majority of the singlet TGCs pass
this test at its first attempt.

![Leak current distribution at 2.8 kV with CO₂ gas before closing singlet TGC.](image)

**C. Pulse test**

After the doublet or triplet assembly, we attach the so called adaptor boards which bring signals from the wires or strips to
the ASDs. After the attachment, we check the correctness of
the connections and verify there is no shortage between the
adjacent signal lines or to the ground. A pulse test is adopted
for this purpose. A rectangle pulse is applied to the TGC HV
supply line. The output pulse through the RC-CR circuit from
each channel is recorded with a digital oscilloscope. Fig. 6
shows a schematic diagram of the electrical circuit of TGC [8].
If a channel is shorted to the adjacent one, its output pulse
becomes approximately twice larger than the nominal; if its
signal path is broken or is shorted to the ground, no output
pulse is observed.

![The schematic view of the electrical circuit inside the TGC.](image)

The results are shown in Fig. 7. The maximum fluctuations of
the pulse height are about ±6 % for the wire and ±12 % for
the strip. They are both much less than two. Using the SPICE
program [1] we simulated the pulse height dependence on the
cathode surface resistivity and the anode-cathode distance. The
results are given in Table II. It shows a strip deviation could be
on the order of 10 % due to the deviation in the surface resistivity. In addition, the quoted errors of the coupling capacitor for the wire (C_{HV}) and the decoupling resistor at the
HV input (R_{HV}) are 10 % and 5 %, respectively. These errors
could cause pulse height fluctuations of up to 3 % for the
resistor or 6 % for the capacitor. The distributions of the signal
output pulse height are therefore consistent with these errors
and the surface resistivity criterion.

![The relative pulse height distribution for anode wire and pickup strip read-out on the pulse test.](image)

**TABLE II**

<table>
<thead>
<tr>
<th>Gas Gap</th>
<th>0.5M Ω</th>
<th>1.0M Ω</th>
<th>2.0M Ω</th>
<th>3.0M Ω</th>
</tr>
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<tbody>
<tr>
<td>Wire</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2 mm</td>
<td>-3</td>
<td>-1.8</td>
<td>1.2</td>
<td>4.2</td>
</tr>
<tr>
<td>1.4 mm</td>
<td>-1.2</td>
<td>0.0</td>
<td>2.4</td>
<td>4.8</td>
</tr>
<tr>
<td>1.6 mm</td>
<td>0.6</td>
<td>1.8</td>
<td>3.6</td>
<td>6.0</td>
</tr>
<tr>
<td>Strip</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.2 mm</td>
<td>-10.4</td>
<td>4.5</td>
<td>18.6</td>
<td>23.6</td>
</tr>
<tr>
<td>1.4 mm</td>
<td>-14.1</td>
<td>0.0</td>
<td>12.4</td>
<td>19.1</td>
</tr>
<tr>
<td>1.6 mm</td>
<td>-16.4</td>
<td>-2.1</td>
<td>10.1</td>
<td>15.7</td>
</tr>
</tbody>
</table>

[UNIT: %]

**D. β-ray test**

After the pulse test, we check the basic functionality of the
TGCs with using a β-ray radioactive source. The chambers are
operated with CO₂ at 2.8 kV. We investigate the signal output
rate searching for noisy channels. We also check for
oscillations caused by grounding problems.

**IV. DETECTOR PERFORMANCE**

The last quality assurance stage is a measurement of the
detection efficiency uniformity of all the produced TGC in a
dedicated test bench at Kobe University. We set the operating
point of the TGC just above the shoulder of the HV curve to
emphasize the non-uniformity, if it exists, while keeping high
detection efficiency for the normal TGCs. The Kobe cosmic ray test bench can test 24 singlets at a time. Up to now 100 triplets (or equivalently TGC 300 singlets) have been tested.

Fig. 8. Example of detection efficiency maps. White dots show better than 99 %, deep gray less than 60 %. (a) A Typical chamber showing good uniformity. Five vertical lines correspond to the wire supports. Small zigzag points in-between correspond to the button spacers. (b) Bad chamber having several inefficient regions.

Position dependence of the efficiency was measured with a granularity of 5mm-by-5mm. It takes about two weeks for data-taking to get one full map. Fig. 8 shows two examples of the detection efficiency maps. Fig. 8(a) is a typical example. Excluding the wire-supports and spacers, the average efficiency is achieved to be better than 99 %. Fig. 8(b) is a bad example of a chamber with some inefficient regions. There are seven chambers showing similar non-uniformity in total. These chambers were produced in relatively early period of the series production. The reason could be a gluing-off or applying thicker glue during the triplet assembly. This could be a result of failure in the viscosity control of the epoxy adhesive.

![Image](image.png)

Fig. 9. Mean detection efficiency distribution for each chamber

We summarize the mean detection efficiencies in Fig. 9. There are 8 TGCs having less than 98 % detection efficiency. Excluding the above-mentioned 6 TGCs with the epoxy problem, there are only two additional TGCs which show a poor quality than the average. There is a correlation between the non-uniformity or lower efficiency and the flatness of the triplet, but little correlation with the flatness of the singlet. This indicates that the flatness of singlet might have been damaged during the doublet (or triplet) assembly. We continue to study the problems and trying to reduce the number of poor performance TGCs. All the other produced TGCs demonstrated a good uniformity with high detection efficiency.

V. REFERENCES

Neutron sensitivity of thin gap chambers

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Abstract

Thin gap chambers (TGC) will be used for triggering forward muons in the ATLAS detector for the LHC at CERN. A large amount of neutron background is foreseen in the ATLAS experiment. This paper describes the measurements of the neutron sensitivities (detection efficiencies) of the TGCs. The sensitivities of both small and real size TGCs to 2.5 and 14 MeV mono-energetic neutrons were measured. For a small size TGC, sensitivities of 0.032% and 0.10% were measured to 2.5 and 14 MeV neutrons, respectively, whereas for a real size TGC, sensitivities of 0.048% and 0.13% were measured. These measured values were in reasonably good agreement with the simulations based on the Geant4.

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Keywords: LHC; ATLAS; Trigger; Thin gap chamber; TGC; Neutron; Geant4

1. Introduction

The ATLAS detector [1] is one of the major detectors for the future 14 TeV proton collider, the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN). The event rate of the ATLAS experiment is expected to be 1 GHz [2] for the designed luminosity of the LHC-10^{34} cm^{-2} s^{-1}. The event trigger is one of the important issues for the experiment. Thin gap chambers (TGC) [3] will be used for triggering forward muons in the ATLAS detector. The structure of TGCs is similar to that of multi-wire proportional chambers and their detection efficiency for minimum ionizing particles (MIP) is more than 99% within a 25 ns time gate [4] (time duration of this time gate is referred to as “time jitter”), that satisfies the requirements of the ATLAS muon triggering.

A large amount of background radiation is predicted in the ATLAS experiment. In the
installation area of the TGCs, neutrons and photons are the primary components of the background. This may induce a high counting rate in the TGCs, thereby affecting stable operation and causing false muon triggers or the chamber aging. In order to estimate such effects, the sensitivities of TGCs to such background particles must be measured.

The primary energy range in the case of the photon background ranges from 10 keV to 10 MeV according to simulation [5], where photons are primarily generated through the capture of thermal neutrons. The sensitivity was measured in the energy range from 20 keV to 1.8 MeV and was found to be less than 1% [6].

In the case of the neutron background, it originates from the interaction of primary hadrons with the materials of the ATLAS detector and accelerator elements. Its energy spectra ranges primarily from 0.025 eV to 1 GeV with a gentle peak around the 500 keV region obtained from the simulation [5]. Recoil nuclei or fragments from neutron reactions can produce hits in the TGC. Photons generated through neutron reactions can produce electrons that can also be the cause of hits in the TGC.

We performed the first measurements on the neutron sensitivity (detection efficiency) of TGCs for mono-energetic neutrons of 2.5 and 14 MeV. The results of the measurements were evaluated with a Monte Carlo simulation that was based on the Geant4 [7] and a good understanding of the TGC response to neutrons was obtained.

2. Real size TGC and small size TGC

In this measurement, two types of the TGCs were used to get a better understanding through comparing both results. One was a real size TGC, the structure and materials of which were identical to that of the TGCs that will be used in the ATLAS experiment. The other was a small size TGC that had a smaller and a simpler structure than the real size TGC. The structure of the real size TGC is described in Ref. [8]. The cross-sections of both real and small size TGCs are shown in Fig. 1. The anodes are gold-plated tungsten wires—50 μm in diameter—uniformly spaced at 1.8 mm. The gap between the anodes and the cathode is 1.4 mm. The cathode surface is made of a conductive layer of approximately 10 μm in thickness, which primarily comprises graphite and acrylic resin in order to achieve a surface resistivity of approximately 1 MΩ/square.

The real size TGC is trapezoidal in shape—with a height of 1250 mm and a base length of 1529 mm. Approximately 20 wires are grouped together in order to obtain 32 channels for the anode readouts. There are 32 rows of copper strips, each with the thickness of 30 μm on the FR4 boards, which are perpendicular to the wires. Two chambers compose a double layer module (doublet) with a 20-mm thick paper honeycomb between them to maintain mechanical rigidness. In addition, 5-mm thick paper honeycombs with 500-μm thick FR4 skins are glued on both the outer surfaces for protection and rigidness.

The small size TGC is 10 cm in width and 12 cm in length. It is a single layer chamber without cathode strip readouts. Its wire spacing, the wire diameter and the gap between the wire and the cathode are identical to that of the real size TGC. The thickness of one side of the chamber wall is 1.6 mm and that of the other side is 0.2 mm. The thickness of the copper cladding on the wall is 10 μm. There are 16 anode wires, each of which is 8 cm in length. The signals generated at each wire are individually read. The two edge wires are not used in order to eliminate the effect of a higher electric field and a larger drift space corresponding to the edge wires. Accordingly, the sensitive area was 8 cm in length and 2.52 cm in width.

3. Experimental setups

The geometrical and electrical setups for the measurements with both 2.5 and 14 MeV neutrons are described in this section.

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2 Flame retardant glass fabric base epoxy-resin laminate.
3.1. Experimental setup for the measurements of the sensitivities to 2.5 MeV neutrons

Mono-energetic neutrons with energies of approximately 2.5 MeV were produced through \( d + D \) reactions\(^3\). A Cockcroft–Walton type accelerator in the Rikkyo University\(^4\) was used to generate 97.5 keV \( d^+ \) ions. The ions were transported to a TiD\(^3\) target, 0.5 mm in thickness, through a collimator (a 150-\( \mu \)m thick aluminum with a hole, the diameter of which was 6 mm). At the target, the mono-energetic neutrons with an energy of approximately 2.5 MeV were produced through a D(\( d, n \))^3He reaction,

\[
d + D \rightarrow n^+ + ^3He + 3.27 \text{ MeV}.
\]

\(^3\)D and d represent deuterium and deuteron, respectively.
\(^4\)Rikkyo University 3-34-1 Nishi-Ikebukuro, Toshima, Tokyo 171-8501, Japan.

\(^5\)Deuterium storage titanium.
Neutrons can be tagged with $^3$He nuclei generated at the same time. The geometrical setup around the target is shown in Fig. 2, where the $x$, $y$, and $z$ coordinates are indicated. A Si PIN photodiode of 1 cm$^2$, S3590-02, fabricated by Hamamatsu Photonics, was placed at an angle of 90° with respect to the d$^+$ beam axis and at a distance of 14.5 cm from the target to detect $^3$He nuclei. A collimator of 500-µm thick aluminum with a hole 6 mm in diameter were placed in front of the photodiode. The collimator was positioned in order to define the direction of the $^3$He nuclei. A 0.8-µm thick aluminum foil was also positioned in front of the photodiode to stop deuterons coming from the target through Rutherford scattering in the target. All the apparatuses mentioned above were placed inside a vacuum chamber connected to the beam line.

When a $^3$He nucleon was detected at an angle of 90°, the energy of $^3$He nucleon was 800 keV and the corresponding neutron was emitted at an angle of 78° with its energy of 2.57 MeV in agreement with the two-body kinematics. Due to the energy loss of the deuteron in the target and the geometrical acceptance, the energy of the neutron ranged from 2.45 to 2.62 MeV at most. The full energy spread of the neutron was less than 7% and the emitting angle of the neutron in the $x$–$z$ plane ranged from 93° to 65° at most.

There was a D(d,p)t reaction\textsuperscript{6} besides D(d,$^3$He), d + D → p + t + 4.03 MeV.

According to the two-body kinematics, the proton energy was approximately 3.1 MeV whereas the triton energy was approximately 990 keV. Such protons and tritons could be rejected by applying cuts on the energy distribution measured with the photodiode. The photodiode energy calibration was performed using three types of $\alpha$ sources—$^{239}$Pu, $^{241}$Am, and $^{244}$Cm. The energy resolution of 0.2% around 5 MeV with a good linearity of 0.1% was obtained.

On the opposite side of the photodiode, a small size TGC was placed outside the vacuum chamber at a distance of 9 cm from the target, whereas a real size TGC was placed at a distance of 40 cm from the target. The wall of the vacuum chamber was made of stainless steel (SUS) and was 8 mm in thickness. There was a 0.5-mm thick SUS neutron window at the side of the wall facing the TGC. From all the particles produced in the d + D reactions, only neutrons could enter the TGC, whereas the other particles were stopped at the vacuum chamber wall or the neutron window. The loss of the neutrons at the TiD target or the neutron window was negligible according to the

\textsuperscript{6}t represents triton.
Geant4 simulation and the loss was less than 5% according to the total cross-sections. The TGC was set as its wires ran parallel to the z-axis and were spaced along the y-axis. The position of the TGC was designed such that it covered the cone of the neutrons corresponding to the $^3$He nuclei detected by the photodiode. Events due to the neutron incidence on the TGC (this implies that the neutron was emitted toward the TGC sensitive volume) could be selected with a $^3$He hit on the photodiode. Events due to the neutron hit on the TGC (this implies that the neutron generated the hit signals of the TGC) could be distinguished with the coincidence of a $^3$He hit at the photodiode and a hit on the TGC.

The electrical setup was designed to measure both the energy deposited in the photodiode with an peak hold ADC and time interval between the signal of the photodiode and that of the TGC with a TDC. The signal from the TGC was digitized with Amplifier-Shaper-Discriminators (ASD) [9] to supply the stop timing of the TDC. The signal from the photodiode was used for serving its charge, making the gate of the ADC and making the start timing of the TDC. In order to serve these functions, two amplifiers—shaping amplifier (SA) and timing filter amplifier (TFA)—were used after a pre-amplifier. The energy deposited in the photodiode was measured with the ADC using the signal from the SA. The coincidence timing was measured with the TDC which began by the signal from the TFA and halted by the signals from the TGC.

### 3.2. Experimental setup for the measurements of the sensitivities to 14 MeV neutron

In the case of 14 MeV neutrons, mono-energetic neutrons were produced through the T(d,n)$^4$He reaction,

$$
d + T \rightarrow n + ^4He + 17.5 \text{ MeV}.
$$

There were no other d + T reactions except for the Rutherford scattering. The electrical setup was identical to that for the 2.5 MeV neutrons. The geometrical setup was slightly modified. A TiT$^7$ target, instead of a TiD target, was used. The T emitted 18.6 keV electron through beta decay. In order to avoid a high counting rate and pileups due to the beta rays, a 1-μm thick gold foil, instead of the 0.8-μm thick aluminum foil, was placed in front of the photodiode. It also stopped deuterons that were produced through Rutherford scattering. The 3.5-MeV$^4$He nuclei (α particles) were detected using the photodiode. The energy of the neutrons ranged from 14.0 to 14.2 MeV and the emitting angle of the neutrons ranged from 78° to 91° at most. The full energy spread was less than 2%.

### 4. Experimental results

Using the experimental setups described in the previous section, the measurements of the detection efficiencies to both 2.5 and 14 MeV neutrons were performed for both the small size TGC and the real size TGC. The analyses of the data are described separately for 2.5 and 14 MeV neutrons with the small size TGC, followed by the analysis with the real size TGC. The systematic uncertainties of the measurements are described in the last subsection.

#### 4.1. Sensitivity of the small size TGC to 2.5 MeV neutrons

The analysis for the sensitivity of the small size TGC to 2.5 MeV neutrons is described in this subsection. The energy distribution measured with the photodiode is shown in Fig. 3. Three peaks that corresponded to the 800 keV $^3$He nuclei, 990 keV triton, and 3.1 MeV proton are clearly seen. The decrease in their energy was primarily due to the energy loss in the 0.8-μm aluminum foil placed in front of the photodiode. Deuterons scattered in the target through Rutherford scattering were well stopped in the aluminum foil. In this energy distribution, events in the region from 100 to 700 keV were selected to obtain events with $^3$He detected by the photodiode. This selection was referred to as “loose $^3$He selection.”

The timing distribution of the coincidence for the selected events is shown in Fig. 4 as an open

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$^7$Tritium storage titanium.
the “time jitter” of the TGC is 25 ns. In particular, the broadening of the peak in the 0–50 ns region in Fig. 4 was due to the time walk of the signals from the photodiode to start the TDC.

In Fig. 5, the energy distribution measured with the photodiode corresponding to the “loose $^3$He selection” is shown as an open histogram. The energy distribution for the events with a coincidence TDC from 0 to 400 ns is also shown as the hatched histogram. The ratio between them (coinidence ratio) is also plotted at the bottom. The decrease in the coincidence ratio in an energy region around 250 keV was due to the large time walk corresponding to the small $^3$He signals, which delayed the TDC start and the coincidence between the photodiode and the TGC was missed. In order to avoid such an effect, an energy region from 275 to 475 keV was selected for further analysis. This selection was referred to as “tight $^3$He selection.” The number of events within the energy region for the open histogram was also referred to as $N_{\text{neutron}}$, which implied the number of neutrons generated due to $^3$He nuclei detected with the photodiode.

The timing distribution for the events obtained with the “tight $^3$He selection” is shown as a hatched histogram in Fig. 4. The effect of the time walk was reduced with the tight energy selection. The number of events within the region from 50 to 200 ns (coincidence region) in the distribution was referred to as $N_{\text{coincidence}}$. The side bands for the distribution (the region of the former 50 ns and the latter 200 ns in Fig. 4) were used to evaluate the accidental coincidence and the events in the side bands were fitted with a constant value. The fitted value was multiplied by the total bin number in the coincidence region to obtain the number of the accidental coincidences, $N_{\text{accidental}}$.

The detection efficiency was evaluated as follows:

\[
\text{Efficiency} = \frac{(N_{\text{coincidence}} - N_{\text{accidental}}) \times (1 - \xi \text{contamination})}{N_{\text{neutron}}/(1 - \phi_{\text{loss}}) \times \eta_{\text{coverage}}}
\]

where $\phi_{\text{loss}}$ was defined as the loss of the neutron flux at the target or the neutron window, $\eta_{\text{coverage}}$
was defined as the TGC coverage for the neutron flux and \( \zeta \)\text{contamination} was defined as the contamination of the hits of gammas in the coincidence region, which were produced through the reactions of the incident neutrons in the surrounding materials (the target chambers and concrete walls of the experimental area).

The \( \phi_{\text{loss}} \) was set to 0, as such loss was estimated to be negligible, as previously mentioned in Subsection 3.1.

The hit wire distribution of the TGC was used for the estimation of \( \eta_{\text{coverage}} \). The hit wire distribution, which corresponds to the events in the coincidence region is shown in Fig. 6. The distribution was well restricted in the sensitive region which was 2.52 cm in width. This was confirmed by an analysis of other runs where the TGC was shifted to approximately \( \pm 1 \) cm in the \( y \) direction as shown in Fig. 2. The distribution was

![Figure 5](image1.png)

**Fig. 5.** The energy distributions measured with the photodiode for the events with the “loose \( ^3 \)He selection” (open histogram) and further with the coincidence within 400 ns (hatched one) are shown at the top. The coincidence ratio is also shown at the bottom. The energy range corresponding to the “tight \( ^3 \)He selection” is indicated.

![Figure 6](image2.png)

**Fig. 6.** The hit wire distribution of the TGC is shown. The distribution was fitted with Gaussian plus a constant value calculated from the event number of accidental coincidence. The width of sensitive area that corresponded to the 14 channels was 2.52 cm.
fitted with a Gaussian plus constant value that was fixed at the value calculated from the number of accidental coincidences mentioned above. Subsequently, the coverage was estimated as being 99.4%. The other dimension of the sensitive area was 8 cm, which was wide enough to cover the entire neutron flux.

The contamination was estimated at 1.5% with the Geant4 simulation, where all materials (the target, target chamber, and concrete walls, where the concrete walls surrounding the experimental area were placed at a distance of approximately 1.5 m from the target) were treated in addition to the TGC itself. The systematic uncertainties are discussed later in Subsection 4.4.

The detection efficiency was calculated according to Eq. (1) and the result is shown in Table 1.

### 4.2. Sensitivity of the small size TGC to 14 MeV neutron

The sensitivity of the small size TGC to 14 MeV neutrons was analyzed. The energy distribution measured with the photodiode corresponding to the d + T reaction is shown in Fig. 7. The peak corresponding to the 3.5 MeV \(^{4}\)He nuclei (\(\alpha\) particles) is clearly seen. The decrease in the energy is primarily due to the energy loss in QJ; the 1-\(\mu\)m thick gold foil placed in front of the photodiode. Electrons from the tritium target through beta decay and deuterons scattered in the target through Rutherford scattering were well suppressed in the gold foil. The event selection in the case of 14 MeV neutrons was similar to that in the case of the 2.5 MeV neutrons. An event selection referred to as “loose \(^{4}\)He selection” entailed selecting the range of the energy distribution measured with the photodiode from 2.2 to 3.6 MeV, which is indicated in Fig. 7.

The energy distributions of events both after the “loose \(^{4}\)He selection” and with coincidence TDC from 0 to 400 ns is shown in Fig. 8. The ratio between them (coincidence ratio) is also shown at the bottom of the figure. The energy region from 2.9 to 3.2 MeV, where the coincidence ratio was stable was set as “tight \(^{4}\)He selection,” which is indicated in Fig. 8.

The timing distributions of the coincidence after the “loose \(^{4}\)He selection” and the “tight \(^{4}\)He selection” are shown in Fig. 9. The regions from 0 to 150 ns and 250 to 400 ns were referred to as “side bands.” The points with error bars that corresponded to events after the “tight \(^{4}\)He selection” in the “side bands” were fitted with a constant value and the amount of accidental coincidence was evaluated.

<table>
<thead>
<tr>
<th></th>
<th>Measurement (%)</th>
<th>Simulation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small size 2.5 MeV</td>
<td>0.032 ± 0.001(stat)(^{+0.002}_{-0.001})(sys)</td>
<td>0.035</td>
</tr>
<tr>
<td>Real size 2.5 MeV</td>
<td>0.048 ± 0.001(stat)(^{+0.002}_{-0.001})(sys)</td>
<td>0.039</td>
</tr>
<tr>
<td>Small size 14 MeV</td>
<td>0.10 ± 0.002(stat)(^{+0.001}_{-0.001})(sys)</td>
<td>0.11</td>
</tr>
<tr>
<td>Real size 14 MeV</td>
<td>0.13 ± 0.002(stat)(^{+0.002}_{-0.002})(sys)</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Table 1
The measured sensitivities and the results of the simulation are summarized.
The TGC coverage for the neutron flux ($\eta_{\text{coverage}}$) was evaluated as 99.9% in a manner similar to that of the 2.5 MeV neutrons. The contamination of the hits of gammas in the coincidence region ($\xi_{\text{contamination}}$) was evaluated as being 4% with the Geant4 simulation.

The result of the sensitivity for 14 MeV neutrons is also shown in Table 1. The evaluation of systematic errors was performed in Subsection 4.4.

### 4.3. Sensitivity of the real size TGC

The event selection for the analysis with the real size TGC was performed in a manner similar to that of the small size TGC except for the following three points:

The first is that a coincidence of the hits of the cathode strips was required in addition to that of the hits of the anode wires.
The second is that the TGC hits within the area, 27 cm × 30 cm (7 channels in anode readouts × 7 channels in cathode readouts) were used as the neutron hits. This area was large enough to cover the neutron flux. The TGC coverage for the neutron flux was set to 100% for the real size TGC. This condition reduced the contamination of the hits by gammas produced in the surrounding materials.

The third is that the contamination of such gammas were evaluated with the data. The evaluation of the contamination for the case of 14 MeV neutrons is described below in detail. The measurement was performed with 15 anode readouts and 16 cathode readouts. The hit channel distribution after the “tight 4He selection” with TDC coincidence is shown in Fig. 10. With regard for the hit channel distribution, three regions were selected as follows. The first region was referred to as the “central region,” which was a single bin with the largest bin contents. This is indicated as a region inside the dotted line in Fig. 10. The second region was referred to as the “inner region,” where anode readouts from the 2nd to the 8th channel and cathode readouts from the 5th to the 12th channel were selected. This is indicated as a region inside the dashed line in Fig. 10. This region was used to calculate the center value of the neutron detection efficiency. The third region was referred to as the “outer region,” which was outside the inner region. The contamination of gamma hits from the surrounding materials was smaller at the “central region” and was dominant at the “outer region” because the neutron flux was concentrated around the “central region.” The timing distribution corresponding to the “inner region” was fitted with the shape of the two histograms, one corresponding to the “central region” and the other corresponding to the “outer region.” The accidental coincidence, which was calculated in a similar manner as indicated in Fig. 4 was subtracted beforehand from each histogram. The result of the fitting is shown in Fig. 11, where the contributions of both the central region and the outer region were indicated. The delay of the coincidence timing for the events in the “outer region” was primarily due to the time of flight of neutron to the concrete wall behind the TGC and the time for which the neutron existed in the wall. The gamma contamination in the timing distribution corresponding to the “inner region” was evaluated to as being 11% ± 1% according to the ratio of the contents of the two histograms used in the fit. With regard to this estimation, no contamination of such gamma hits in the “central region” and no contamination of neutron hits in the “outer region” were assumed and the possible contaminations were considered in the evaluation.

Fig. 10. The hit channel distribution after the “tight energy selection” with the TDC coincidence was plotted with boxes. A region inside the dotted line was referred to as “central region” and a region inside the dashed line was referred to as “inner region” and a region outside the “inner region” was referred to as “outer region.”

Fig. 11. The timing distribution after the “tight energy selection.” The accidental coincidence was subtracted.
of the systematic errors in Subsection 4.4. The estimation of the contamination according to the Geant4 simulation was 9%, where the target chambers and the concrete walls surrounding the experimental area were simulated. The gamma contamination for 2.5 MeV neutrons was evaluated in a similar manner as being 3% ± 3% and the estimation with the Geant4 simulation was 1%.

The sensitivities of the real size TGC to 2.5 and 14 MeV neutrons were similarly calculated and the results are shown in Table 1.

4.4. Systematic uncertainties

The systematic uncertainties for the sensitivities of both the small size and real size TGCs were evaluated in this subsection. As for Eq. (1), the systematic errors corresponding to the evaluations of \( N_{\text{coincidence}}, N_{\text{accidental}}, \xi_{\text{contamination}}, \phi_{\text{loss}}, \) and \( \eta_{\text{coverage}} \) were considered.

The “tight \(^3\text{He}/^4\text{He}\) selection” and the “side band” regions were altered to evaluate the systematic errors corresponding to \( N_{\text{coincidence}} \) and \( N_{\text{accidental}} \).

As for the evaluation of \( \phi_{\text{loss}} \), the maximum loss of the neutron flux according to the total cross-sections of the target and the neutron window was evaluated as being 5% and it was attributed to the systematic error.

The systematic error in the evaluation of \( \eta_{\text{coverage}} \) was considered only for the small size TGC. The amount of hits on the edge wires that were not included in the active area was used to estimate the maximum leak of the neutron flux and it was attributed to the systematic error.

Finally, the systematic uncertainties in evaluating \( \xi_{\text{contamination}} \) was considered. For the analysis with the real size TGC, \( \xi_{\text{contamination}} \) was evaluated with the assumption of the absence of the contamination of gamma hits in the “central region.” The possible contamination of such gamma hits in the “central region” was estimated as being 10% using both the number of events in the “outer region” and a simulated distribution of the hit position of such gammas. The upper limit of \( \xi_{\text{contamination}} \) was set to 10% larger than the center value. The fluctuations of the sensitivities in modifying \( \xi_{\text{contamination}} \) from 0 to the upper limit was used at the systematic errors. The errors of the fitting to evaluate \( \xi_{\text{contamination}} \) were also considered.

For the analysis with the small size TGC, the sensitive area was approximately 1/100 as compared with that of the real size TGC, and the distance from the walls of the experimental area was greater than for the real size TGC. Accordingly, the effect of the contamination was considered to be smaller. However, an identical upper limit for the contamination as that for the real size TGC was conservatively assigned.

Among all the systematic errors, the systematic error due to the contamination of the coincident hits of gammas from surrounding materials had a major contribution. The experimental results with the systematic errors are shown in Table 1 and in Fig. 12.

5. Simulation and discussion

In order to understand the above results, a Monte Carlo simulation based on the Geant4 was performed. For this simulation, all the geometrical configurations and materials of the TGC were implemented. The real size and small size TGCs were modeled separately and each anode wire was
implemented. The incident angle of the neutron was set to 0° (perpendicular to the TGC plane) and the incident position was uniformly distributed from a wire to its neighboring wire.

The hits on the TGC were created when charged particles moved in the gas and their energy deposited in the gas was more than 50 eV. A single electron in the gas is sufficient to register a hit for the TGC operated in the limited proportional mode. Accordingly, the latter condition was introduced to simulate the threshold of ionization. When the threshold value was varied from 0 to 200 eV, it did not change the results of the simulation in the energy range of neutrons from 1 to 20 MeV.

The measured sensitivities and the results of the simulations are summarized in Table 1 and shown in Fig. 12. As regard to the results of the simulation, there was an uncertainty of approximately 10–20% due to the limited knowledge of the ratio of the components of the cathode surface and the variations of both the thickness and the density of the material used in the cathode surface.

The measured values were found to be in reasonably good agreement with the simulation. The lower sensitivities of the small size TGC were due to its smaller volume and thinner wall. The neutrons scattered in the small size TGC could escape from its volume more easily than the neutrons scattered in the real size TGC.

Furthermore, the contributions of each material to the sensitivities were studied with the simulation. Over 75% of the hits were produced by hydrogen nuclei for the neutron energy from 2.5 to 20 MeV. (The contribution of the hydrogen nuclei for a 1 MeV neutron was 65%.) The remaining hits were primarily produced by carbon and oxygen nuclei. Such nuclei entered in the gas volume of the TGC through nuclear recoil by elastic scattering of the neutrons in each material. The contributions of each material to the sensitivity of the small size TGC are shown in Fig. 13, where the contributions from the copper and the wire are negligible and their markers are overlapped.

Finally the dependence of the sensitivity on the incident angle of the neutron was studied with the simulation, which was important to estimate the rate of the neutron hits of the ATLAS experiment. The sensitivity increased as the incident angle θ (the angle between a line perpendicular to the TGC plane and the direction of the incident neutron) increased. For the neutron energy of approximately 1 MeV, the sensitivity was approximately 1.1 times higher for θ = 30°, and approximately 1.4 times higher for θ = 45°, where the factor was approximately 1 / cos θ. The gas made a major contribution to the sensitivity for such neutron energies, and the increase in the thickness of the gas due to the increase of the incident angle made a linear contribution to the increase in the sensitivity. As regards the neutron energy above 1 MeV, the sensitivities were 1–1.1 times higher for θ = 30°, and approximately 1.1 times higher for θ = 45°, where the decrease in the factor
was due to the fact that the contributions of the FR4 wall and the cathode surface increased and the increase in the thickness for these materials did not make a linear contribution to the sensitivity. The thickness of the FR4 or the cathode surface beyond the range of the recoil nuclei did not contribute to the sensitivity.

6. Summary

The sensitivities of the TGC for 2.5 and 14 MeV mono-energetic neutrons were measured for both small and real size TGC. The Monte Carlo simulations based on the Geant4 were performed and the measured values were found to be in reasonably good agreement with those obtained from the simulation. Further studies with the simulations were performed and good understanding of the TGC response to neutrons was obtained.

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References