Development of a time projection chamber for J-PARC hadron physics program

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Abstract. A time projection chamber (HypTPC) has been newly developed for the various hadron physics experiments at J-PARC. The design of HypTPC was carefully considered to cope with the J-PARC high intensity beam. The triple-layered GEM has been adopted as a signal amplification and the gating grid plane for an ion backflow suppression. The octagonal drift volume is defined by the cathode plane and the field cage structure with the height of 55 cm. A target is located inside the drift volume in order to have a large acceptance. The GET (General Electronic System for TPCs) is utilized for the data acquisition. The HypTPC was first commissioned with 230 MeV proton beam at HIMAC. The obtained position resolution is $400^{-700} \, \mu\text{m}$, which gives the expected resolution of $230^{-300} \, \mu\text{m}$ under a magnetic field of 1 T. We have confirmed the high rate capability of the TPC up to 1 MHz with a good suppression of the ion backflow under the gate operation.

1. Introduction

The J-PARC E42 experiment\cite{1} aims at searching for the H-dibaryon, a 6-quark ($uuddss$) state in $I = J = 0$ channel, via ($K^-, K^+$) reactions. A new spectrometer (Hyperon Spectrometer) has been developed as a primary tracking device of the experiment to detect the decay products of H-dibaryons. The Hyperon Spectrometer is mainly composed of a time projection chamber (HypTPC) and a Helmholtz-type superconducting magnet, as depicted in Fig. 1. Another hadron experiments at J-PARC, such as E45 ($N^*$ baryon spectroscopy)\cite{2} and E72 (New $\Lambda^*$ resonance search near $\eta\Lambda$ mass threshold)\cite{3} were also proposed with this new spectrometer system. The main reactions for each experiment which will be reconstructed in the HypTPC are also summarized in Fig. 1. A special care was taken in the design of the TPC to endure the harsh environment of J-PARC with high intensity beam up to 1 MHz.

2. Hyperon time projection chamber (HypTPC)

The HypTPC has a compact size in the shape of an octagonal prism, as shown in Fig. 2. Both the diameter and the height of the outer gas vessel are approximately 62 cm, which fits in the 80 cm inner diameter of the Helmholtz magnet. The internal structure of the TPC is divided into two main parts: drift volume and amplification readout chamber.
Figure 1. A cross-sectional view of the Hyperon Spectrometer, which mainly consists of a time projection chamber and a superconducting dipole magnet. The main reactions for each hadron experiment proposed at J-PARC hadron hall will be reconstructed using the Hyperon Spectrometer.

2.1. Drift region
The HypTPC drift volume is defined by the cathode plane and the field cage wall with the height of 55 cm, as shown in Fig. 3. The target holder is located inside the drift volume at 143 mm upstream from the TPC center to have a large acceptance. The E42 experiment uses a rectangular shape of the target holder to contain a hexahedral diamond target, whereas the E45/72 experiments need a cylindrical one for a liquid hydrogen target. Each version of the target holder can be assembled with a field cage structure through the hole of the cathode plane at top. The field cage wall and the target holder have the same 2-mm wide copper strips with a pitch of 2.5 mm on the both side of the insulation layer. To avoid the charging up on the

Figure 2. A photograph and an explosion view of the HypTPC. In the octagonal prism shaped gas vessel, a field cage structure with a target holder, a gating grid plane, a triple-layered GEM, and a pad plane are placed from top to bottom.
exposed insulator under the high rate beam condition at J-PARC, we removed the insulator between the field strips to make a beam slit around the beam-through region, as depicted in the left-hand side of Fig. 3.

Figure 3. Photographs of the HypTPC field cage. The field cage structure assembled with the cathode plane, the target holder structure, and the interior of the field cage combined with the rectangular target holder from right to left.

2.2. Amplification region
The gating grid plane is placed at the boundary between the drift region and the amplification region to navigate the drift electrons generated in the drift volume and to suppress the ion backflow especially in the high rate beam environment at J-PARC. There are 50 µm diameter wires separated by 1 mm each other and the voltages are applied to them alternatively, ±V_{gate}, as described in Fig. 4. When the trigger comes in, the gate opens as the common voltages are applied to all wires (V_{gate} = 0), so that the drift electrons can pass through the plane. The gate closes back again after 16 µs to prevent the ions from flowing up to the drift volume, which can result in the distortion of drift field.

Figure 4. A photograph of a gating grid plane and a diagram describing how the gate operation works.

The drift electrons, which have successfully passed through the gating grid plane, are amplified by an order of 10^4 through the gas avalanche in the triple layered GEM [4, 5]. We adopted the GEMs as a signal amplification to have lower ion backflow rate over the conventional
wires. We utilize two layers of 50-µm thick GEM and one layer of 100-µm thick GEM at bottom to achieve a higher gain with the same potential at the top of the GEM voltage divider with respect to the anode pad plane. The resistor chain setting was optimized to have a higher gain and a lower ion backflow rate [6]. The voltage across 100 µm GEM sheet is applied 1.5 times higher than 50 µm GEM voltage \( V_{\text{GEM}} \). The detailed characteristics for each GEM are summarized in Table 1 with a diagram in Fig. 6. The GEM layers and the pad plane are separated by 2 mm each other and each GEM layer is divided into four sectors. Each quadrant has segmented electrodes on the upper surface to reduce the discharge rate. The sector under the target has a finer segmentation of electrodes as shown in Fig. 5.

![Figure 5. A photograph of GEM installed in HypTPC. There are three layers of GEM with two 50-µm thick GEMs and one 100-µm thick GEM and each layer is divided into 4 sectors.](image)

**Table 1.** Comparison between a 50-µm thick and a 100-µm thick GEM. The insulator material and the hole etching method are different and the 50 µm GEM has smaller hole size. Refer to Fig. 6.

| Property          | 50 µm GEM                | 100 µm GEM               |
|-------------------|--------------------------|--------------------------|
| Manufacturer      | Raytech                  | Raytech                  |
| Insulator material| Polyimide (PI)           | Liquid Crystal Polymer (LCP) |
| Etching method    | Wet                      | Laser                    |
| Cu thickness      | 4 µm                     | 9 µm                     |
| Pitch \((d)\)     | 140 µm                   | 140 µm                   |
| Inner diameter \((r)\) | 25 ± 10 µm            | 35 ± 10 µm              |
| Outer diameter \((R)\) | 55 ± 5 µm              | 65 ± 5 µm               |

![Figure 6. A diagram of GEM sample.](image)

The amplified electron signals from the GEM layers are collected in the pad plane at the bottom of the TPC chamber. There are a total of 5768 readout pads with the concentric configuration around the target, as shown in Fig. 7. The inner 10 layers have smaller pad size with the length of 9 mm while the outer 22 layers with the length of 12.5 mm. On the other side of the pad plane, there is a conversion board which connects the pads to readout electronics.

### 2.3. Data acquisition system

We utilize the GET (General Electronics for TPCs) [7] for the data acquisition of the HypTPC. Fig. 8 describes the TPC signal or data flow in the GET system. The electron signal is first fed into the AsAd (ASIC and ADC) board, and the signal is amplified, shaped, and sampled...
Figure 7. Photographs of the pad plane and the conversion board which connects each pad to each channel of the readout electronics.

with user-selectable parameters by a slow control in the AGET chip and the sampled signals are digitized in the ADC on the board. The multiplexed digital signals are transferred to the CoBo (Concentration Board) where the data processing such as zero suppression and data formatting are done. Finally, the data files are transported to the data storage through the 10 GbE network.

Figure 8. HypTPC data flow chart in the GET system. See text for details.

3. Commissioning of the HypTPC
The beam test with 230 MeV protons at HIMAC was carried out to study the basic characteristics and high rate capability of the HypTPC. We installed the silicon strip detectors (SSD) sandwiching the HypTPC and the trigger counters along the beam axis. The 1 atm P-10 gas (Ar 90%+CH$_4$ 10%) was flowing the TPC at the rate of 470 mL/min. The drift field was fixed at 130 V/cm. The two independent DAQ systems, GET for HypTPC and HDDAQ [8] for other detectors, were operated. The trigger and busy signals were shared via a master trigger module (MTM) in the HDDAQ system. The pad signal was sampled 200 times at the sampling frequency of 12.5 MHz, which allows a 16 µs time window. The full readout mode was used and the data size per CoBo for each event was 426 kB. The pre-scaled trigger rate was set as around 230 Hz with nearly 100% DAQ efficiency.
3.1. Basic performance

We utilized the 1 kHz beam events to study the basic properties of the HypTPC. The height of the HypTPC stand was adjusted to inject the beam at the drift length of 15, 30 (target center), and 45 cm. An event display of the typical beam event is presented in Fig. 9. The neighboring hits in each TPC pad layer were clusterized and the weighted mean of the hits in a cluster was used to reconstruct the beam track.

![Figure 9](image)

The drift velocity was obtained as 5.0 cm/µs from the drift time distributions at each drift length. The transverse diffusion coefficient \(D_T\) was also measured to be 0.57±0.02 mm/√cm. The pad efficiency which is defined by the ratio of the number of clusters on the corresponding pad layer to the number of reconstructed tracks is shown as a function of the GEM voltage \(V_{GEM}\) in Fig. 10. We chose 305 V as a GEM operation voltage for this beam test. The horizontal spatial resolution was calculated in the range of 400 – 700 µm, and the vertical resolution of 500 – 800 µm, as shown in Fig. 11. The transverse resolution is expected to be improved to 230 – 300 µm under a magnetic field of 1 T with \(D_T=0.18\) mm/√cm [9].

![Figure 10](image)

Figure 10. Efficiency trend with respect to the GEM voltage. The operation voltage was set as 305 V throughout the beam test.
3.2. High-rate performance

The high-rate capability of the HypTPC was studied with beam rate up to 1 MHz. At high beam rate, the pad signals from a bunch of beam events were recorded in a 16 µs time window of a single event, as depicted in Fig. 12. However, the triggered beam event is well separated from the accidental events with the help of the tracking information of SSD.

![Figure 11. The transverse (left) and vertical (right) spatial resolutions as a function of the drift length of the reconstructed tracks.](image)

![Figure 12. An event display of 1 MHz beam event. The triggered event is well separated from non-triggered events at earlier and later times.](image)

The residual of the TPC cluster point with respect to the reconstructed track from SSD is calculated as a function of the cluster coordinate. Due to the vertically distributed high density ions along the beam centroid built up by the ion backflow at the high beam rate, the drift electrons generated along the off-center track are attracted toward the positive ions, which leads to the position distortion. When the gate operation was turned off, this distortion was clearly observed as shown in the rightmost histogram in Fig. 13. The slope parameters from a linear fitting in each residual distribution are plotted as a function of the beam rate and compared depending on the gate operation in Fig. 14. The position distortion is barely observed under the gate operation with $V_{gate}=50$ V.
Figure 13. The x residual ($x_{TPC} - x_{SSD}$) graphs with respect to $x_{TPC}$ without the gate operation at the beam rate of 1 kHz, 5 kHz, and 10 kHz from left to right.

Figure 14. The slope parameters from a linear fitting in Fig. 13 with respect to the beam rate from the x residual (left) and y residual (right) distributions.

4. Summary
A GEM-based TPC has been developed for the J-PARC hadron experiments. The HypTPC was commissioned using 230 MeV protons with beam rate up to 1 MHz, and we have confirmed its basic operation and high-rate capability. This powerful tool, HypTPC, with high statistics data thanks to the high intensity beam at J-PARC will give a lot of opportunities to deepen the understanding of the hadron physics in near future.

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