Design and construction of a TPC prototype based on GEM detector readout*

LI Yu-Lan(李玉兰)[1;1)] CAO Liang-Jun(曹良俊)[1] QI Hui-Rong(祁辉荣)[1] LI Jin(李金)[1,2]
KANG Ke-Jun(康克军)[1] LI Yuan-Jing(李元景)[1] LAI Yong-Fang(来永芳)[3]
GAO Yuan-Ning(高原宁)[1] YANG Zhen-Wei(杨振伟)[1]

1 (Dept. of Engineering Physics, Tsinghua University, Beijing 100084, China)
2 (Institute of High Energy Physics, CAS, Beijing 100049, China)
3 (Institute of Chemical Defense, Beijing 102205, China)

Abstract A time projection chamber (TPC) readout by gas electron multipliers (GEM) detector is a very promising candidate for the central tracking system of ILC (International Linear Collider). A prototype is designed and set up in our lab and introduced here. The tests during and after the assembly prove that the prototype TPC has been constructed successfully. It is ready for further study.

Key words time projection chamber, gas electron multiplier, endcap readout

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1 Introduction

In international high energy physics community, there is a global consensus that the next accelerator project in particle physics will be an electron-positron linear collider i.e. International Linear Collider, called ILC with the center-of-mass energy up to 1TeV. Its physics goals require a high performance central tracking system, such as excellent momentum resolution, good multi-track separation, precise measurement of $\mathrm{d}E/\mathrm{d}x$ for particle identification, and with minimum thickness of materials. By now, 4 detector concepts have been proposed for the collider, and 3 of them adopt TPC as their main tracking detector[1]. Compared with the previous TPC systems which were installed in other high energy experiment facilities, like ALEPH, ALICE, etc., the new proposed one needs a lot of improvements. Among all the new technologies under study, the most predominant one is a novel readout scheme based on the GEM detector[2, 3]. Compared with the traditional ones readout by MWPC (Multiwire Proportional Counter), the TPC based on GEM detector has many advantages[4]. Collaborations of Europe[5, 6], North America[7, 8] and Japan[9] have been carried out extensive study on this project, and their results are very promising. But further studies are still needed to prove that a TPC system based on GEM readout satisfies the physics requirements of ILC. In our lab, a TPC prototype was designed and constructed successfully, and close study will be carried on soon.

2 Design and construction

2.1 Mechanical structure

Since TPC is a drift gas detector, and any electronegative gases in the chamber may absorb electron greatly, so the contamination of working gas due to air, water and halogen-containing chemical must be constrained to an extremely low level, say, a few ppm. To achieve this, the air tightness of the vessel must be kept in mind during design even when the TPC works in gas-flowing mode. The gas leakage rate should be less than 1 mL/h. Here, the GEM-TPC prototype consists of a gas vessel, a field cage, an end cap readout detector and the following electronics. As shown in Fig. 1, the gas vessel is a PMMA (polymethyl methacrylate) barrel with a flange manufactured from stainless steel, where the gas inlet, high voltage connectors for both field cage and GEM

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1) E-mail: yulanli@mail.tsinghua.edu.cn

are mounted. The total gas volume is $\phi305$ mm × 520 mm with a drift length of 50 cm.

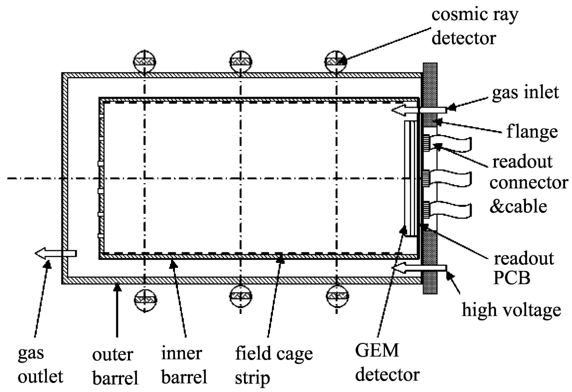

Fig. 1. The scheme of the prototype GEM-TPC.

2.2 Field cage

The ideal electric field in the the drift region of a TPC should be similar to that of an infinitely large parallel-plate capacitor. Generally, it is obtained in a good approximation by covering the inner face of the field cage, whose mass thickness should be as small as possible, with a regular set of conducting strips perpendicular to the electric field. In our design, the drift field is established by a PCB (Printed Circuit Board) drift electrode at the far end and a cylinder of flex PCB (thickness of 0.5 mm) with copper strips located evenly. The specifications of the strips are optimized using Maxwell simulation based on: 1) better uniformity of the electric field; 2) less free charge deposit on the insulators between the strips. Based on our simulation, 99 strips, with a width of 2 mm, and a pitch of 5 mm are used, and each is connected to a resistor chain for voltage supply. The distribution of the electric field is simulated and listed in Table 1. A smaller inner PMMA barrel is used to support the whole field cage. The 130 MΩ resistor is placed at the end of the chain to match the surface voltage of the top GEM foil, as shown in Fig. 2.

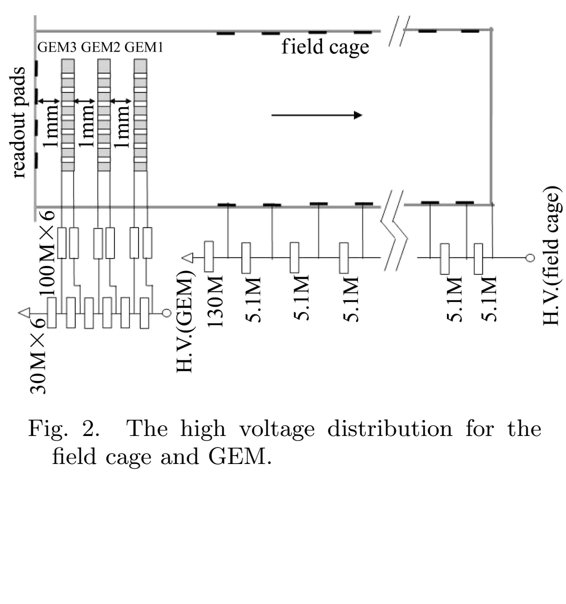

Fig. 2. The high voltage distribution for the field cage and GEM.

Table 1. The distribution of the drift field (normalized to $E_{\max}$=100 V/cm).

distance to the top GEM foil/cm	25	5
average/(V/cm)	99.8	98.3
standard deviation/(V/cm)	0.09	1.60
relative deviation(%)	0.09	1.63

2.3 Readout detector-GEM

The TPC is read out by a triple GEM detector, which is constructed from CERN standard GEM foils[10] with an effective area of 10 cm×10 cm. Since the prototype will work without magnetic field first, the transverse diffusion of drift electron is relatively large; and also for the limitation of available high voltage supplier for the GEM detector at this moment, the gaps between GEM foils, and between the last GEM and the readout board are set to 1 mm, smaller than most of the designs from other groups, but the gaps can be changed easily later for performance optimization. High voltage is applied through another resistor chain (shown in Fig. 2).

The electrons from the GEM detector are collected and read out through pads on the PCB board. If the size of the pads is too big, it is possible for the charge to be collected by one single pad, and a center-of-gravity method yields a bad spatial resolution. If the pad size is too small, the number of channels will increase dramatically; and at the same time, the signal from each pad will be too small for a good $\mathrm{d}E/\mathrm{d}X$ resolution. Another engineering problem that has to be considered in designing pad is the availability of suitable connectors that can connect the readout pad with the front-end electronics. Based on the theoretical analysis and connector available, 620 rectangular staggered pads (area: 1.5 mm × 9.5 mm) are arranged in 10 rows (y direction) by 62 columns (x direction) on a 8-layer PCB board, with the pitches of 10 mm and 1.6 mm accordingly. Connectors of high density and high speed (QTE/QSE-020-01-L-D) from SAMTEC[11] are used to connect the readout pad with the front-end electronics.

2.4 Gas

Working gas is very important to TPCs, almost all the processes in TPC, including ionization, drift and avalanche amplification, take place in the gas. The gas mixture of Ar and CH_4 is widely used in TPC, for example, ALEPH TPC, DELPHI and RHIC STAR, because of its fast drift velocity peak at a low electric field. In order to reduce the neutron cross section of the working gas, TESLA TDR proposed a gas of 93% Ar + 2% CO_2 + 5% CH_4. This three component mixture also has good aging properties, but a poor quenching property.

A gas mixture machine with mass flow control and four inlets of different kinds of gas (Ar, CH_4, CO_2, and CF_4) is used to supply working gas for the prototype. CF_4 is included here for its very small diffusion coefficient and fast drift velocity. The specifications of different mixtures are studied using Garfield . Based on our simulation, a three-component mixture of 90% Ar + 7% CH_4 +3% CF_4 may be a good candidate for its fast drift velocity and other reasonable performances (shown in Table 2).

Table 2. The properties of working gas proposed for the prototype.

Transv. Diff./ (μm/$\sqrt{\text{cm}}$)	Long. Diff./ (μm/$\sqrt{\text{cm}}$)	drift field/ (V/cm)	drift velocity/ (cm/μs)	Attach. Coeff./ (1/cm)	dE/dx/ (eV/cm)	ω_i/ eV
317.7	222.1	250	8.8	0	2466.5	8.9

2.5 Testing

The prototype has been set up recently, see Fig. 3 for its photograph. The supporting systems, such as the gas supply system, the high voltage suppliers and the cosmic ray telescope system are tested and confirmed to work well. From our test, the gas leakage rate is less than 0.2 mL/h at pressure of 1 atm + 20 cm-high water column. The currents of the two high voltage supplied are monitored.

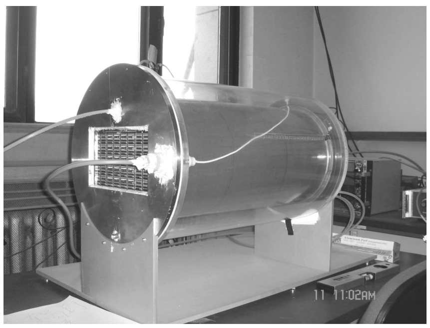

Fig. 3. The photograph of the constructed prototype TPC (electronics is not shown here).

2.5.1 GEM detector testing

To test the readout GEM detector and PCB board, an extra drift electrode is added temporarily over the first GEM foil with a drift distance of 5 mm, and a triple-GEM is set-up. Then it is tested by measuring the energy spectrum of ^{55}Fe in the working gas proposed for the TPC, Ar:CH_4:CF_4 = 90:7:3. A high voltage of 2500 V is applied to the whole detector, which is distributed around 357 V to each gap and each GEM foil. Fig. 4 shows the spectra when 7 adjacent pads, 3 adjacent pads and 1 pad are connected to the preamplifier (Ortec 142PC) respectively.

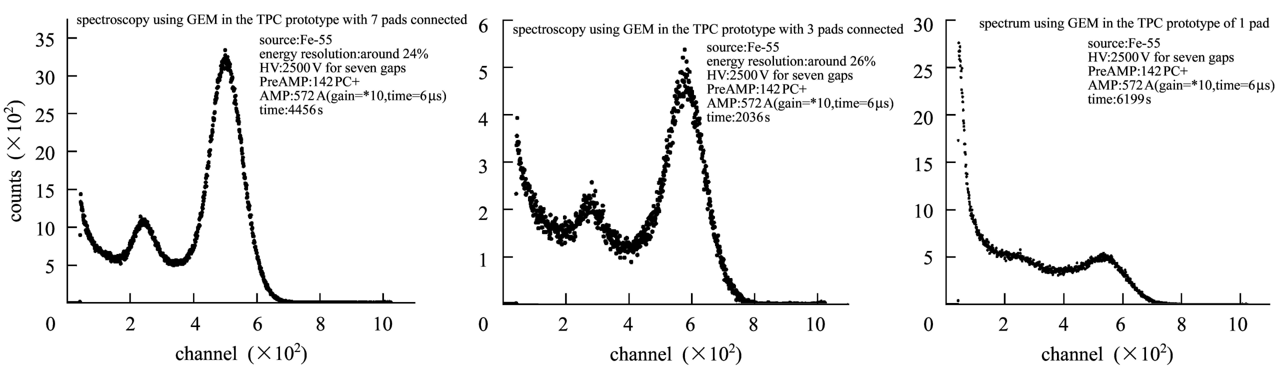

Fig. 4. ^{55}Fe spectra of GEM used in GEM-TPC prototype with different output pad number.

The test shows that the GEM detector used in the TPC prototype keeps its basic performance as a detector alone. When 7 pads are connected, the signals' energy resolution can reach 24%@5.9 keV. As the number of connected pads gets less, the energy resolution gets worse. This shows that most of the electron clouds cover about 3 pads at the readout plane.

We have also noticed that the peak position for the 7-pads' spectrum is little smaller than the ones for 3-pads and 1-pad. This may be caused by the small gain increasing due to charging-up in GEM detector during irradiation since the activity of the ^{55}Fe source used in the test is very high, and the test is done in the order of 7 pads readout, 3 pads readout and 1 pads readout. This phenomenon also happens in other group's study, like the one in COMPASS[12]. Further study is needed.

2.5.2 Cosmic ray testing of the prototype

After 32 channels of the electronics is ready, the TPC prototype is tested to track the cosmic ray events. As shown in Fig. 5(a), the outputs from 8 pads in the upper row are connected together and used as the trigger signal; once there is a trigger signal, the current outputs of the lower 4 rows × 8 columns are measured and displayed. Fig. 5(b) shows the outputs from the pads in the left 4 columns. From this, we can predict that there is a muon event with its track projected in readout plane as shown in Fig. 5(a).

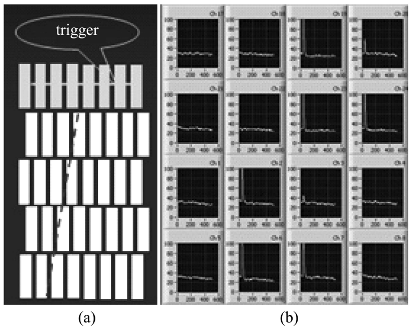

Fig. 5. Current outputs of pads from a cosmic ray event and the possible track reconstructed.

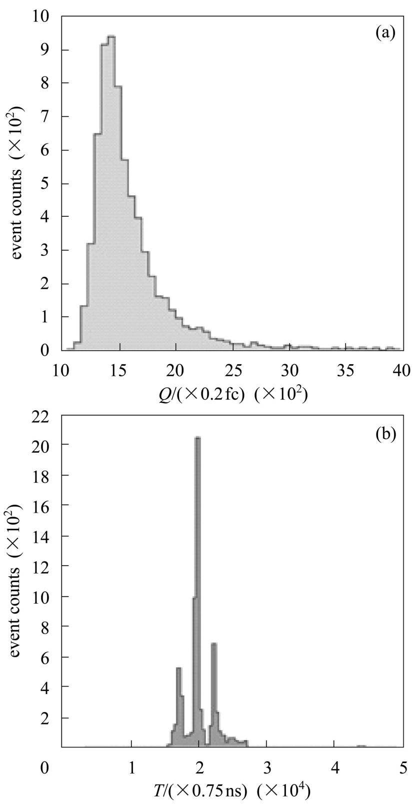

Fig. 6. Q and T spectra of the prototype from cosmic ray events.

Recently, all 320 channel electronics have been set up. The trigger signals from three sets of cosmic ray telescope, which are located at three different positions along the drift direction, are ORed and used as the trigger signal of the prototype. Then the charge distribution and drift time distribution of all 320 channels are recorded, see Fig. 6(a) for Q spectrum and Fig. 6(b) for T spectrum accordingly. It is very clear that the charge or $\mathrm{d}E/\mathrm{d}X$ distribution is close to Labdau distribution; and the three peaks on T spectrum corresponds to the three different positions of the cosmic ray telescope. All these preliminary test results prove that the drift field, the GEM detector and the DAQ system works.

3 Conclusion and discussion

A prototype GEM-TPC is designed and set up in our lab. Its main chamber and supporting system are tested by different means. From the test result, we can conclude that the system has been designed successfully, the prototype has achieved it basic function, and is ready for more close study.

For the time being, the specifications of the prototype, such as the gaps between GEM foils, are optimized for the test condition without magnetic field, but they can be adjusted once the magnet is accessible. In the meantime, by designing the DAQ system with the ability of multi-hit event processing, the TPC also has the potential to work with high event rate and under high multiplicity condition. We will join the international cooperation and have our system tested using the facilities from other countries.

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