TPC review

D. Attié

DSM/Irfu, CEA/Saclay, F-91191 Gif-sur-Yvette Cédex

Abstract

The Time Projection Chamber (TPC) was invented by David Nygren thirty years ago. TPCs have been used as trackers in many particle and heavy ion physics experiments. There are also TPC projects for non-accelerator experiments such as double-beta decay and dark-matter searches. After a presentation of the original idea of the TPC, and the advantages of such a detector, the R&D for the TPC proposed for the future International Linear Collider will be reviewed. This work is being carried out by the LC-TPC collaboration formed recently by several labs from all over the world.

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1 Introduction

A time projection chamber (TPC) is typically a gas-filled cylindrical chamber (the gas could be at atmospheric pressure, pressurized or liquid) with one or two endplates and a long drift distance (up to a few meters). Proposed in 1974 [1], this detector provides a complete 3D picture of the ionization deposited in the chamber. The density of the ionization, along the track, depends on the momentum and type of the particle. By measuring the arrival, in space and in time t, of electrons moving at constant velocity v to either of the two endplates due to the electric field $\mathbf{E}$ defined by a field cage, the TPC can reconstruct the paths of the original charged particles (x-y are given by the projection and z by $v \times t$). A magnetic field $\mathbf{B}$ parallel to $\mathbf{E}$ could furthermore be added as large as possible to minimize the transverse diffusion which limits the obtainable resolution. The TPC's 3D localization makes it extremely useful in tracking charged particles using approximatively 100 to 200 measurement points along the track and for identifying particles by their ionization energy loss (dE/dx) measurements. In TPCs large track densities are possible due to the low occupancy.

After showing some examples of TPCs which have been used as tracking detectors in high energy physics, and recently for rare event detection, we discuss the new developments using Micro-Pattern Gaseous Detectors and techniques to improve spatial resolution. These R&D are currently being performed by the international LC-TPC collaboration.

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2 TPC in high energy Physics

2.1 Fields using TPC in the past

The first experiment in particle physics using a TPC was designed in 1976 at SLAC for the e^+e^- PEP4 collider [2]. For the same physics, the TOPAZ TPC was proposed at KEK [3] in 1986 and the ALEPH TPC [4] and DELPHI TPC [5], in 1990 and 1992 respectively, for the LEP at CERN. Later, STAR [6] at BNL/RHIC and NA49 [7] at CERN were the first TPCs for heavy ion colliders. Most of the experiments that have used a TPC emphasize the importance of this type of detector for high energy physics.

2.2 Recent and future experiments

The Large Hadron Collider (LHC), currently in its final stages of construction, has one of its detectors designed to search for a quark-gluon plasma of heavy ion collisions named ALICE (A Large Ion Collider Experiment) [8]. Pb-Pb nuclei collisions will be studied with a center of mass energy of 5.5 TeV per nucleon. The main particle tracking device in ALICE is a TPC with a drift cavity measuring two times 2.5 m in length with a diameter of 2.5 m; in total containing 95 m^3 of $Ne/CO_2/N_2$ (90/10/5) of gas mixture. To read out the signal the endplates are equipped with wire planes which perform charge amplification and no less than 560,000 electronics channels for signal detection. Given a maximum sampling frequency of 11 MHz the entire TPC volume comprises of approximatively 6 10^8 pixels in three dimensions.

For the future International Linear Collider (ILC) a TPC is also an excellent candidate for the main tracking detector. A resolution on the momentum of $\sigma_{1/p} \simeq 5\ 10^{-5}$ /GeV is needed to provide precise and model-independent measurement of for instance the Higgs mass in the $Z \rightarrow \mu\bar{\mu}$ recoil reaction. The necessary resolution is 10 times better than the one achieved at LEP. Also a high spatial resolution, better than 100 μm, is necessary differentiate between the high density tracks and final states with more than 6 jets. As such the LC-TPC must have high granularity and good two-track separation in addition to single track identification capability.

3 TPC for rare event detection

3.1 Liquid rare gas TPC

The first idea of using a TPC for rare event experiments came from C. Rubbia in 1977 who suggested a 300 t ultra-pure liquid argon TPC [9]. It is based on the fact that in highly pure Argon, ionization tracks can be drifted over distances of the order of meters. Imaging is provided by position-segmented electrodes at the end of the drift path, continuously recording the signals induced. Recently, the experiment known as ICARUS (Imaging Cosmic And Rare

Underground Signals) based at Gran Sasso is aimed at the direct detection of the neutrinos emitted from the Sun [10]. It should start collecting data in 2008. As well, the Giant Liquid Argon Charge Imaging ExpeRiment (GLACIER) is a powerful detector project for uniform and high accuracy imaging of massive active volume (100 kT) [11].

TPCs based on liquefied noble gases have already been proven to work reliably and are being increasingly used and proposed for particle physics experiments, especially for rare event detection. Indeed, the TPC medium can be used for many things at once, it can be used as a large volume target and/or a dense medium with inexpensive price.

All these experiments, generally underground experiments with low activity materials, explore neutrino (double-beta decay) and dark matter (axion, WIMPs) physics.

3.2 T2K long baseline experiment

The T2K long baseline experiment at JPARC (Japan proton accelerator research complex) [12] which will start next year has TPCs using Argon:CF_4:Isobutane (95:3:2) gas mixture at atmospheric pressure. The near detector of T2K at 280 m (ND280) will contain three TPCs segmented in 6 readout planes of 12 modules (34×36 cm^2), for a total of 124 416 pads (6.9×9.7 mm^2 in size) [13]. These bulk detectors are simple and robust. They also have minimal inactive regions and can be produced in large surface area; these demonstrate that larger TPCs using such technologies can be manufactured. The T2K TPCs are under construction and will be operable by the time the neutrino is ready in May 2009.

4 New developments in TPC R&D

4.1 Micro-Pattern Gaseous Detectors

The current R&D for TPC readout focuses on the technology of Micro Pattern Gaseous Detectors (MPGDs); the two new amplification systems replacing wire chambers are Gas Electron Multiplier and Micromegas (see Figure 1).

Gas Electron Multipliers (GEMs) consist of two metal foils (e.g. copper) separated typically by 50 μm of isolated layer (e.g. kapton). GEM has typically bi-conical holes with 70 μm (50 μm) external (internal) diameter with a pitch of 140 μm. Electrons multiplication takes place in holes which are etched through the katpon [14]. The metal foils are charged to a potential difference of a few hundred volts thus creating a strong electric field (a few ten thousand V/cm) in the holes. Electrons drifting into these holes ionize the gas creating an avalanche. They are often cascaded in 2 or 3 stages.

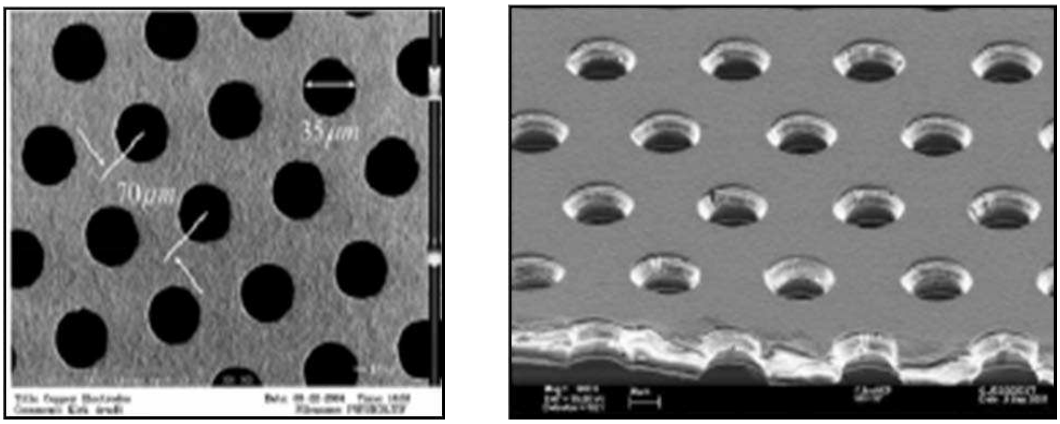

Fig. 1. The two main amplification system of Micro Pattern Gas Detectors MPGD: Micromegas mesh (left picture) ans GEM (right figure).

MICROMEsh GASeous (Micromegas) amplification system use a thin metal mesh held in place by 50-150 μm high pillars. The mesh can be as simple as wire grid. The gas gain occurs between the mesh and the anode due to an applied potential difference where incoming electrons avalanche in the strong electric field. Operating very close to readout pads, the avalanche size is approximatively 15 μm rms [15].

MPGDs have several advantages over wire chambers: they do not suffer from the $\mathbf{E} \times \mathbf{B}$ effect, they are more robust, easily supported without wire sag and instability and positive ions generated in the avalanche are naturally collected before drifting away from the amplification region thus eliminating the build-up of space charge in the drift region which is known to distort the drift field.

In the last few years, GEMs and Micromegas have begun to replace wire chambers in some experiments and they are prominent in R&D for future colliders and for upgrades of current experiments detectors.

4.2 Gas properties studies

In a TPC, the gas mixture is generally a noble gas, with a low ionization potential, and a few percent of a quencher gas to absorb UV photons produced in the avalanche process in the strong electric field. The spatial resolution is limited by the electron diffusion in the gas which is determined by several properties: drift velocity, attachment, diffusion and multiplication of the electrons. Except for the multiplication (i.e. gain), the other properties can be relatively well simulated by MAGBOLTZ calculations [16].

Thus the gain of the gas mixture used in a TPC has to be studied and tuned to a specified operating state depending on each application.

The gain of a Micromegas-based detector (e.g. 50 μm gap) has been measured at Saclay as a function of the amplification electric field for nearly 50 gas mixtures showing the simulation limitations. To measure the gain the charge deposited by 5.9 keV Xrays was used as a standard for each gas. Using the same detector systematic measurements have been carried out with double mixtures and triple mixtures of gases (Ar, Ne, CO_2, CH_4, C_2H_6, Iso-C_4H_{10}, CF_4, ...) at various concentrations.

Figure 2 shows the gain curves as a function of the amplification field E for many gas mixtures. Three groups of curves can be distinguished. The first group is formed by the Iso-C_4H_{10} mixtures which yield the highest gains, up to 10^5 (50 kV/cm $<$ E $<$ 70 kV/cm). The second group, mainly composed by *cold* gases (CH_4, CO_2), have a maximum gain of a few 10^4 (70 kV/cm $<$ E $<$ 100 kV/cm). Finally, between those two families (60 kV/cm $<$ E $<$ 80 kV/cm) is the C_2H_6 gas mixtures.

4.3 Spatial resolution measurement and techniques

Given that the avalanche charge distribution has a diameter of $\sim 15\mu$m and the pad pitch p limits the resolution to $\sigma_{z=0} \simeq p/\sqrt{12}$, if the pads are to large and collect all the charges on one pad, the spatial resolution must be improved by one of three possibilities. One is to spread the charge using a resistive anode, another is to decrease the pad pitch as much as possible using for example a pixelized readout and we can quiet simply use GEMs by defocusing.

4.3.1 Resistive anode

Recent R&D at Carleton developed a new technique to improve the MPGD-TPC spatial resolution over that achievable with previous techniques. The new concept is based on the phenomenon of charge dispersion by a resistive film, placed on top of the readout anode, which enables one to approach the statistical limit of resolution as defined by the transverse diffusion. The resistive anode allows the dispersion of track avalanche charge over multiple pads to improve the determination of position centroids even with large pads (∼2-3 mm). Recent studies with Micromegas detectors enhanced with a resistive anode are promising as a possible readout option for the LC TPC. Using 2 mm wide pads, they demonstrated better TPC resolution than has been achieved with conventional MPGD TPC readout systems with equally wide pads. The resolution achieved is near the diffusion limit of resolution for a gaseous TPC. In cosmic tests with no magnetic field the measured resolution follows the expectations of transverse diffusion and electron statistics [17,18]. Cosmic tests in a magnet have also demonstrate good resolution for a MPGD instrumented TPC in a magnetic field of 5 T. (Figure 3 in the case of Micromegas-TPC). The spatial resolution resolution is independent of the drift distance over the 16 cm and reaches 50 μm. Extrapolating for the ILC TPC readout using ∼2 mm wide pads and a magnetic field of B=4 T with the same gas mixture, a resolution of ∼80 microns for all tracks (2.5 m drift) ap-

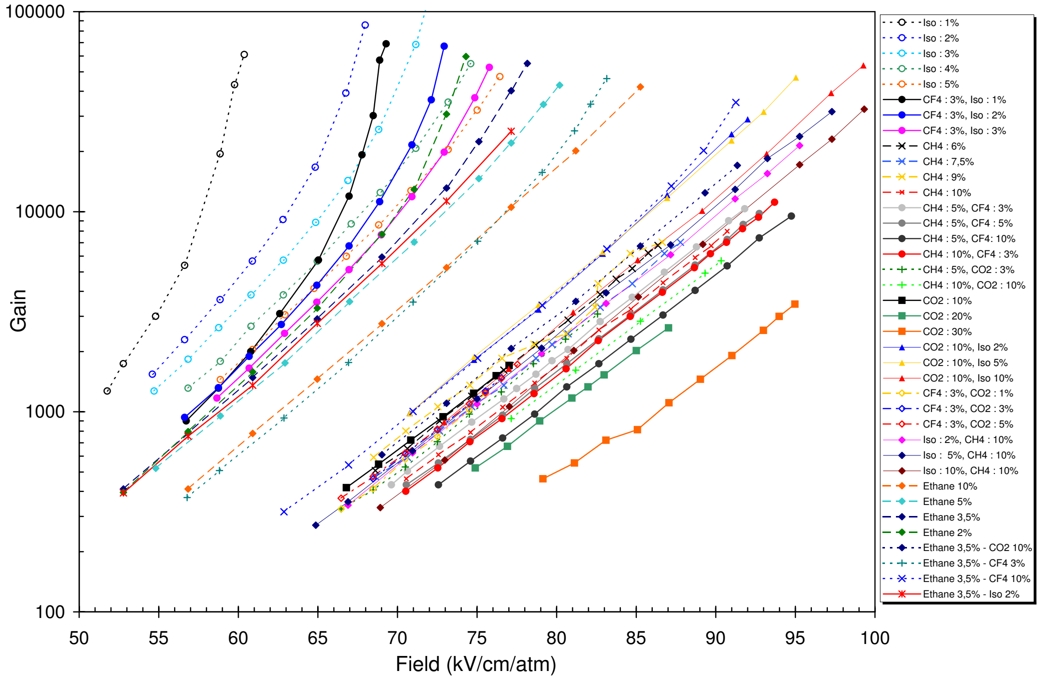

Fig. 2. Gain measurements as a fucntion of the amplification electric field provided by a 50 μm gap Micromegas detector using gas mixtures containing Argon and a few percent of other constituents (CO_2, CH_4, C_2H_6, Iso-C_4H_{10}, CF_4, ...).

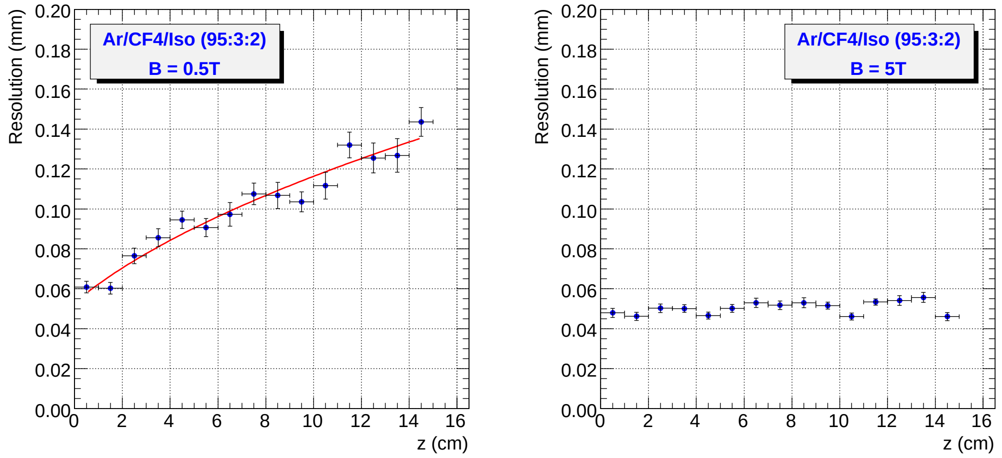

Fig. 3. Measured transverse resolution as a function of drift distance z for 2 mm pitch pads using the Ar/CF_4/iC_4H_{10} (95/3/2) gas mixture for magnetic field of 0.5 T (left figure) and 5 T (right figure). The data with charge dispersion (left figure) is fitted to the resolution σ expected from diffusion in the TPC gas and electron statistics using the formula $\sigma(z) = \sqrt{\sigma_0^2 + \frac{\mathrm{D}^2}{N_{\mathrm{eff}}} z}$ (where σ is the resolution at $z = 0$, D is the transverse diffusion and N_{eff} is the effective number of electrons)

pears achievable thanks to the possibility of using a resistive anode [19].

4.3.2 Digital TPC

A completly new approach for the readout of a TPC is to use a pixelized CMOS chip, such as the TimePix chip, combined with a MPGD. This chip contains a square matrix of 256 × 256 pixels as described in Llopart 2007 [20]. Due to the fine granularity (55 μm pitch) this system could be used to count primary clusters and primary electrons (see Figure 4). Additionally the pixelized chips are useful for δ-ray recognition and suppression and also are sensitive to 3D directionality for other physics topics: nuclear recoils in WIMP or neutrino interactions, two electrons from double beta decay and X-ray polarimetry using low-energy electron.

4.3.3 GEM defocusing effect

Generally GEMs (two or three) are stacked one above the other at 1-2 mm distance (the transfer gaps) and positioned 1 mm above the readout pads (the induction gap). Due to the transverse diffusion in the gaps and to the electric field lines which are more compressed inside the holes than outside in the transfer gap, GEM create a defocusing effect. This intrinsic effect is tuned to spread charges over the readout pads. This result is that good resolution is possible with pads as small width as 1 mm.

5 LC-TPC collaboration

In order to unify the effort on the ILC TPC prototyping and design R&D a collaboration of about 40 groups was formed in October 2007 from three geographic regions (North America, Asia and Europe). The next goal of this collaboration is to setup a 60 cm × 80 cm TPC in a test beam at DESY as a technological demonstrator. This collaboration always is open to new members.

6 Summary

Over the last few decades large volume TPCs have been operated as the main tracking detectors in a wide range of physics experiments. With the recents R&D on MPGDs, gas properties studies and spatial resolution techniques, we expect that this tracking detector will continue to be very useful in the present and future of particle physics, heavy ion colliders and rare event experiments.

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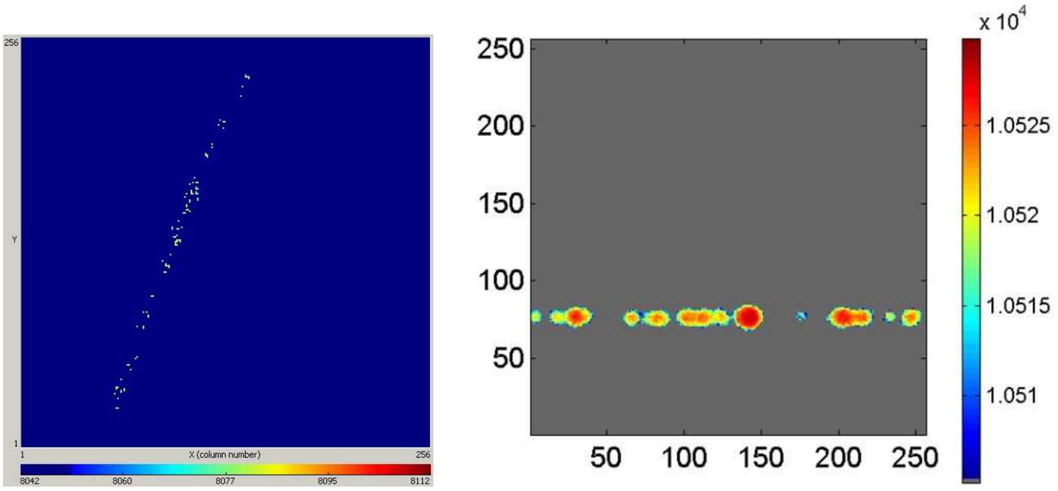

Fig. 4. Cosmic ray tack from a Micromegas-based TPC from Saclay in Ar/Iso-C_4H_{10} 95:5 (left figure) and 5 GeV/c e^- beam from a Triple GEMs-based TPC in He/CO2 70:30 by Freiburg/Bonn (right figure, see also [21]). Both was taken using a TimePix chip readout which is was protected by amorphous-Si in the case of Micromegas.

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