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Review on TPC's

Vincent Lepeltier

LAL, Univ Paris-Sud et CNRS/IN2P3, Orsay

lepeltie@lal.in2p3.fr

Abstract The Time-Projection Chamber invented thirty years ago by David Nygren, has been used very successfully for tracking in many particle and ion physics experiments, and is now often developed for rare events physics. After a presentation of the original idea of the TPC, and of the advantages of such a detector, the problems related to its realisation will be developed, then a panorama of TPCs for particle physics will be shown, and finally a survey will be done on potentialities of TPC for rare event detection.

1. Foreword

This review is dedicated to the memory of Mike Ronan, who died on October 18th, 2006. He was at the beginning of the TPC history with David Nygren, and was deeply involved in the development of this detector all along his scientific life. He was a very appreciated colleague and a very good friend.

2. The birth of the TPC.

A big revolution in particle physics arose in 1968 with the invention of multi-wire proportional chambers (MWPC) by Georges Charpak(1), which replaced within a few years spark chambers traditionally used in tracking for many years in target, and then in collider experiments, with many decisive advantages: rapidity, good position accuracy and time resolution, possibility to cover large areas, low material budget, contribution to the particle signature by energy loss measurement (dE/dx). Very soon this new detector was applied in many fields of detection: X-ray, nuclear medicine, crystallography, etc.

A second revolution in charged particle tracking happened in 1974, with the Time-Projection Chamber (TPC) invented by David Nygren(2). The main idea is to replace the pile-up of MWPC planes, with a typical gas thickness of 1 cm by a large volume of gas: applying a constant electric field in this volume, electrons produced by ionising particles drift over a large distance, following the electric field lines, to a single MPWC plane located at one end of the volume (fig.1) and giving the two coordinates on this plane. The third coordinate, z, is obtained from the drift time measurement of the electrons to the anode plane: due to the collisions in the gas mixture, the electron drift velocity is constant for given gas mixture and drift electric field, with a typical value of a few cm/µs. So the TPC is a full 3D-detector, and, consequently, it has a low occupancy, even in a high background environment, and can support high rates. Due to a generally large gas thickness crossed by the ionising particle, it has a large dE/dx capability for particle identification.

As seen on figure 1. showing the first TPC, this detector is well suited for collider physics, with a central cathode plane surrounding the interaction point, and two anode planes at the two ends, with

MWPC for the multiplication and detection of the drifting electrons. This first TPC was designed by the LBNL group led by David Nygren for the e^+-e^- PEP-4 collider at Stanford.

The principle of the TPC is quite simple, but there are many constraints on its realisation, especially for the gas choice, the monitoring, and the mechanical construction.

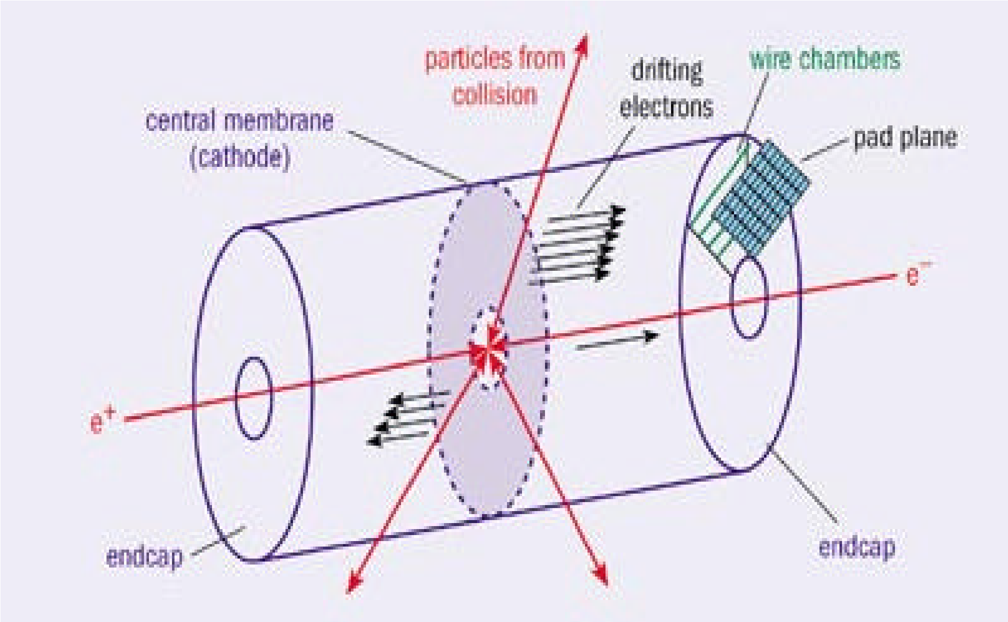

Figure 1. The TPC principle as proposed by David Nygren in 1974

3. Constraints on the realization of a TPC.

Many constraints have to be taken into account for the construction and the operation of a TPC: since one of the main goals for a tracker is the best possible spatial resolution, which is especially limited by the electron production and diffusion, a special care has to be brought on the gas properties before choosing the gas mixture: drift velocity, attachment, diffusion. Also the gas mixture has also to work well for ionisation, and for multiplication near the anode plane. Finally electrons should not be submitted to large distortions coming from the electric field cage of the TPC.

3.1. General considerations on the gas mixture.

This problem is not discussed in details, in the most general case the gas mixture chosen consists in an rare gas, with a low potential ionisation, with an admixture of a few % of a quencher gas, which absorbs UV photons produced in the avalanche process in the rare gas. For spatial resolution and dE/dx considerations, one is interested to produce by ionisation as many as possible primary electrons, so the best choice is in principle a dense and/or noble pressurised gas. But also for many different reasons (multiple scattering, diffusion properties, as explained below, and mechanical constraints in the case of a pressured gas mixture), the most general choice for the gas mixture is Argon with a small admixture of quencher, at the atmospheric pressure (with a small overpressure to avoid pollution from outside).

3.2. Electron drift velocity.

One of the advantages of the choice of a rare gas for the main component of the gas mixture is that the electron drift velocity is increased a lot by the addition of a few % of quencher (CH_4, C_2F_6, CO_2, etc.),

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due to inelastic collisions of electrons on these complex molecules. Moreover, especially for mixtures with Argon, the drift velocity has generally a maximum at relatively low electric field, that is more convenient for the construction of the TPC: on figure 2 is shown the drift velocity as a function of the electric field for Ar-CF_4 mixtures, with a maximum as large as 8-10cm/µs for relatively low electric field values of 200-300V/cm.

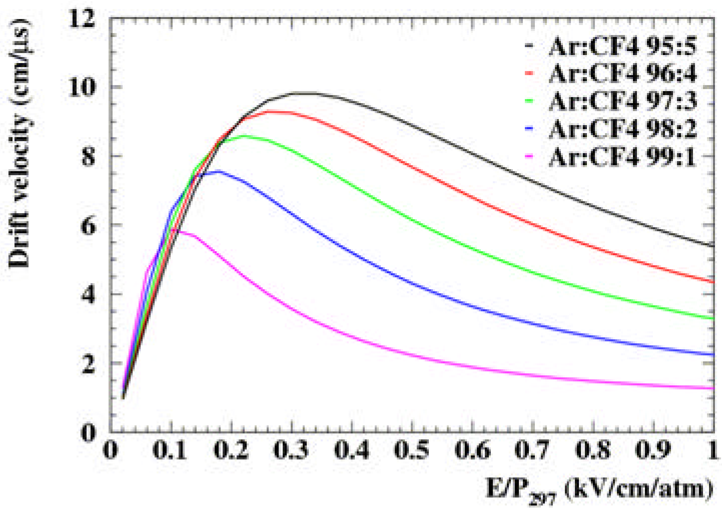

Figure 2. Drift velocity vs electric field in Ar-CF4 mixture.

For the z determination (coordinate along the drift axis), the drift velocity v_e of the electrons in the gas mixture for the chosen drift electric field has to be known very accurately. As an example if you want to know z with an accuracy of 1mm for a drift distance of 1m (10^{-3}), you should know the drift velocity with a better accuracy, about 10^{-4}. It is now possible to calculate very precisely the drift velocity of electrons in most of gas mixtures, at any drift electric field (MAGBOLTZ calculations [(3)]), but the drift velocity may change significantly due to small variation of the pressure, the temperature, or the composit ion of the gas mixture (or the presence of a small amount of impurities inside it), or of the drift high voltage, etc. For these reasons it is crucial to measure permanently the drift velocity during data acquisition of the TPC. On most of the large TPCs, sophisticated laser or UV fibres are used for this velocity monitoring and on fig. 3 is shown an example of the electron drift speed measurement by UV lasers on the DELPHI experiment at LEP during a long period of 3 months (Ar-10% CH_4 at ~200V/cm). Many parameters contributing to the electron drift velocity are also permanently monitored for example the gas mixture composition, the pressure (generally the atmospheric pressure), and the temperature. In order to have a uniform temperature at the level of 0.1K inside the ALICE TPC for the LHC collider, the resistors of the electric field cage are water cooled and the TPC cage is protected by a thermal screen with a $C0_2$ circulation inside.

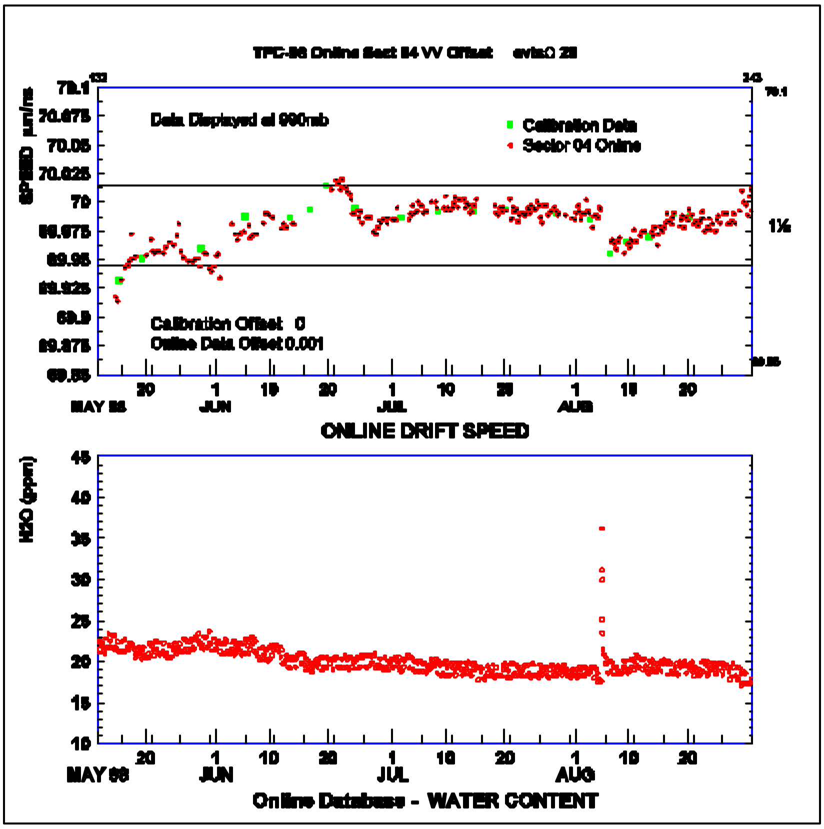

Figure 3. drift velocity and H_20 monitoring on the DELPHI experiment at LEP

3.3. Drift and diffusion properties of the gas mixture.

The spatial resolution for a track is mainly limited by the number of electrons liberated by ionisation , and by the diffusion in the gas mixture.

Electrons liberated by the ionising particle should drift to the anode without being lost during their travel: some molecules should not be present in the gas, even at very low concentration: O_2, H_2O, and more generally electro-negative molecules, on which electrons may attach depending on the drift electric field, giving rise to negative ions. On figure 3 is shown an example of H_2O monitoring of the DELPHI TPC gas mixture.

Due to a large number of collisions in the gas over a long drift distance, electrons experiment a large diffusion, which is a great limitation for the spatial resolution. The typical values for both longitudinal and transverse rms diffusions are ~ 200-500µm/vcm at relatively low electric field applied in the gas, leading to a total rms diffusion ~3 to 8mm for drift distance as long as 200cm. Fortunately, for TPCs developed for tracking experiments, a longitudinal magnetic field B is applied fin order to determine the charge and the momentum of charged particles. The effect of the magnetic field (typically 1-3T) is that between two consecutive collisions, drifting electrons follow a small helix trajectory, so reducing their transverse diffusion, by a factor v(1+?^{2}t^2), where ? is the electron synchrotron frequency (?=e.B/m) and t the mean time between two consecutive collisions. It can be shown that ?t≈(v_e/E)xB, where v_e is the electron drift velocity and E the drift electric field. For a mixture like Ar-CH_4, or Ar-CF_4, as seen on figure 2, v_e/E is equal to ~4-5 T^{-1}, leading for ?t to a value as large as ~16-20 for a magnetic field equal to 4T, so reducing the transverse rms diffusion for a single electron to a fraction of mm for 2m drift distance, and increasing the position accuracy by the same factor.

3.4. Electric field distortions

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In order to project perfectly the track into the anode plane, electrons have to drift in a uniform electric field in the TPC volume. This uniform electric field is obtained by two sets of parallel metallic strips deposited on both sides of a kapton sheet , with small width and pitch (a few mm) connected through calibrated resistors. This set of strips links the cathode put at a very high negative voltage (a few ten kV for large TPCs) and the anode connected at the ground. Sometimes a second foil of kapton foil with copper strips is set in order to improve the electric field uniformity, as seen on fig. 4 showing the STAR TPC field cage arrangement. In many cases, for example in the case of TPC designed for a collider, the problem is complicated, since the internal and external electric field cages have to be perfectly aligned: on fig. 5 is shown the inside of the STAR TPC at Brookhaven. To avoid distortions in the electric field, the tolerance was only +/- $2.5\text{x}10^{-5}$ for the resistors equipping the ALICE TPC field cage.

A problem arises when, as it is often the case, a magnetic field B is set: it has to be perfectly aligned with the electric field, with a very small transverse component B_r ($B_r/B_z < 10^{-3}$ or even less) in order to avoid the generation of a ExB force affecting the electron trajectory to the anode plane.

Finally a parasitic electric field may originate from the ion feed inside the TPC volume: in a high density tracks or high background environment, many ions are created in the multiplication process, where the typical gain is $\approx 10^4$. In the case of MWPC, many ions are not collected by the cathode plane or wires and feed back into the TPC volume. Due to their very low mobility, generally about $1\text{cm}^2/(\text{V.s})$, ions drift very slowly to the HV cathode plane (a few hundred ms for 1m drift) so creating an electric field causing distortions on drifting electron trajectories. This problem is generally overcome by putting a wire plane with an alternate low voltage set on two consecutive wires in order to generate a transverse electric field, the negative wires so collecting most of the ions, at a level of more than 99.9%. (fig. 6 illustrates the DELPHI gating system. The problem is less critical with a MPGD (Micro-Pattern Gas Detector) where many ions are naturally stopped by this MPGD device.

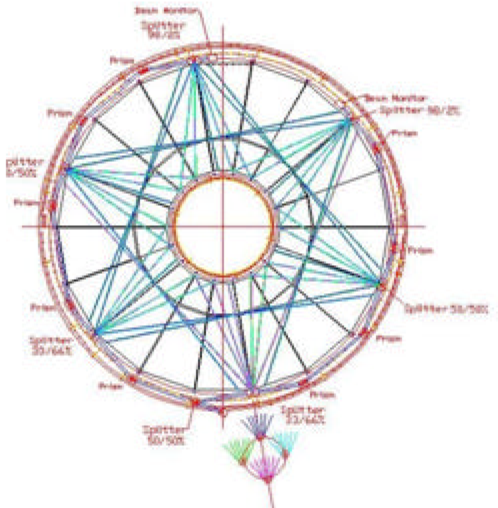

Figure 3. Drift velocity monitoring with lasers on the ALICE TPC at CERN.

4. TPCs for tracking in particle and ion physics

After the idea of TPC developed in 1974 by David Nygren, two TPCs were experimented at the same time, the PEP4 TPC at Berkeley for e^+e^- collisions at SLAC (figures 7a and 7b), with an upgrade into PEP4/9 a few years later, and the Canadian TPC for a target experiment for the study of rare decays at TRIUMF [(4)]. The originality of the first TPC built at Berkeley was its high pressure (8.5 bars) with the main advantage of a very large ionisation by the particles, leading to a better dE/dx capability for particle signature. Nevertheless this idea was not followed, the main disadvantage being the multiple scattering in the thick walls of the TPC and in the gas mixture. Following the PEP4 TPC principle, with a central cathode plane containing the collision point, and a classical read-out with proportional wires and a few ten thousands of pads at the two ends, two groups, ALEPH (fig. 8) and DELPHI (fig. 9), chose in the 80's a TPC for particle tracking on the new e^+e^- LEP collider under construction at CERN.

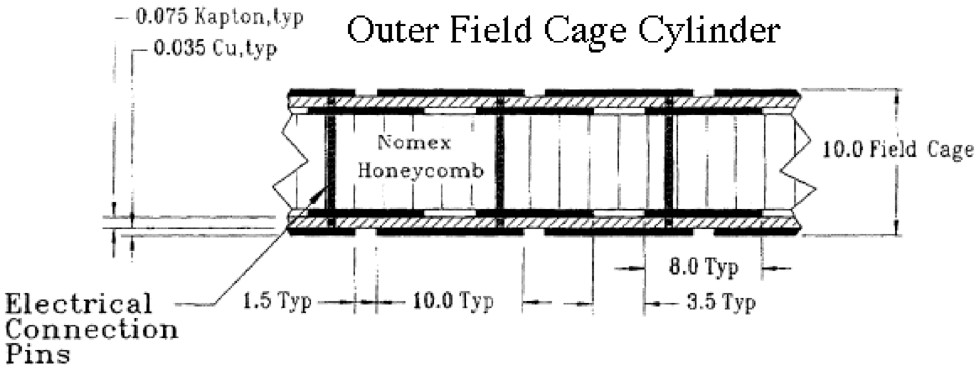

Figure 4. Field cage details of the STAR TPC at RHIC (Brookhaven)

At the same time, a few ion experiments developed a TPC for tracking: EOS at Bevalac, NA35-36 and later NA49, at CERN for fixed target experiments and more recently very large TPCs for colliders: STAR at RHIC, Brookhaven, in 2000, and ALICE (fig. 10) for the LHC at CERN, operational now. On these new generation TPCs, two innovations appear: a full instrumentation of the anodes in front of the proportional wires (pads "partout"), leading to hundreds of thousands channels, and the implementation of the full electronics on the two endplates, requiring an efficient cooling, as it was previously the case also for DELPHI and ALEPH. On figure 11a is shown a display of a Au-Au heavy ions collision registered on the STAR TPC, and figure 11b illustrates the dE/dx capability of this TPC.

Finally the TPC is a leading candidate as a charged particle tracker for the next e^+e^- collider ILC (International Linear Collider) under study. This collider is not yet appoved and will not be built before 2017. The constraints are very strong especially for the transverse position resolution (typically 100µm for 200 track points for the full 2m drift length, instead of a few hundred for the TPC developed until now). A large magnetic field (3-5T) is planed, reducing the transverse diffusion and improving the spatial resolution, nevertheless the ExB effect expected in the MWPC region is too large, since it is not realistic to build a large MPWC with a wire distance smaller than 1-2mm. For this main reason, it is planed to replace this device by a MPGD (Micro-Pattern Gas Detector), like a GEM (Gaseous Electron Multiplier) or a Micromegas (MICRO-Mesh GASeous detector) developed ten years ago(5),(6). The GEM consists in two copper foils separated by 50µm kapton, in which small holes are drilled (typically with a diameter of 60µm and a pitch of 140µm). A multiplication is obtained in the hole by applying a few hundred volts between the two faces of the device. Generally two or three GEMs are necessary to obtain a large enough gain. For the Micromegas, a metallic micro-mesh at a pitch of 50µm is stretched at a small distance (typically ≈50µm) from the anode plane, and the avalanche takes place in this small gap if a voltage of a few hundred volts is applied. Due to their very small sizes these devices have many advantages: a negligible ExB effect, very fast signals, easy implementation, and low ion backflow. Many tests have been performed since 2000 with various small TPCs on many aspects of these detectors: gas mixtures, electron drift velocity, gain, behaviour in a magnetic field, ion feedback, ageing, and of course spatial resolution. A transverse resolution equal to 50µm at zero drift has been measured, both with cosmic rays and particle beams, and the extrapolated resolution for 2m drift length is less than 100µm(7).

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Recently an industrial production of Micromegas ("bulk"), using commercial woven meshes has been developed, allowing to produce in a short time large surfaces of robust detectors including the mesh and the anode plane. This device will equip the TPCs of the short distance detector of the T2K neutrino experiment in Japan.

An interesting development has appeared since a few years, associating pixel technology to the MPGD; this promising approach allows to detect individually single electrons from the ionising particle in a kind of "electronic bubble chamber"[(8)].

Finally, even if this application is not tracking, but particle identification, it is important to mention TPC devices where the Cerenkov photons emitted along a cone are converted into electrons, then drifting in a classical way into a classical MPWC (CRID Cerenkov Ring Imaging Device on the SLD experiment at SLAC and RICH, Ring Imaging CHerenkov on the DELPHI experiment). After multiplication it is possible to reconstruct the cone aperture and identify the ionising particle, knowing its momentum.

Figure 5. Inside of the STAR TPC field cage at RHIC (Brookhaven)

5. TPCs for rare event detection

For detection of rare events (neutrino, dark matter, double beta decay, WIMPs, etc.) a large and dense volume is necessary in order to increase the interaction probability. So a TPC is naturally well suited for this kind of physics. The main characteristics of such TPCs are quite different from tracking TPCs for particle physics:

- generally a very large volume, with dense medium (pressurized gas or liquid),
- simpler design and construction, for example no need of two concentric electric field cages, often a single anode and no magnetic field,
- quiet TPC (very low occupancy, no need for a gating system for ions),
- very often installed in underground experiments with a need for low activity materials.

In this review only a few examples will be presented:

5.1 Liquid Argon TPCs

An example is the ICARUS TPC, installed in the Gran Sasso tunnel, for neutrino detection in Argon (high energy ? from CERN, or low energy ? from sun or supernovae), following an old idea by Carlo Rubbia in 1977. Argon has many advantages: it is inexpensive, it is not electronegative, so electrons may drift over very long distances, and many electrons are produced ($60000 cm^{-1}$ for a MIP in liquid Ar, and the same amount of photons by scintillation)[9]. On figure 12a is shown the large TPC, filled with 300T of liquid-Ar, and on figure 12b a typical neutrino event. A huge 100kT detector is under study (GLACIER).

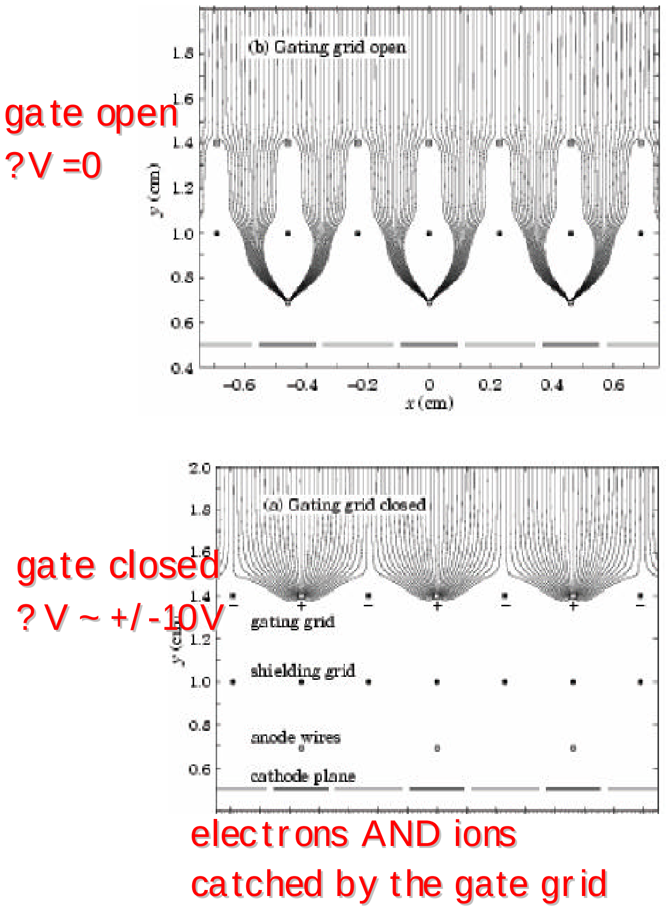

Figure 6. The gating system of the DELPHI TPC at CERN

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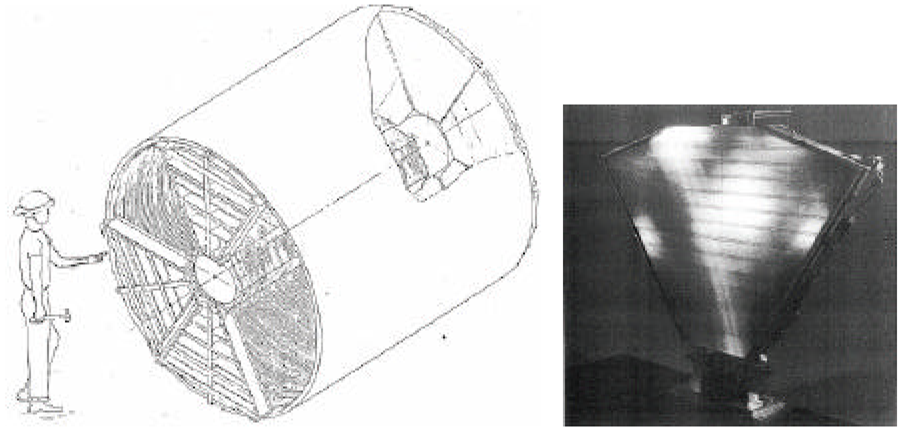

Figure 7.a and b. View of the PEP4-TPC at SLAC

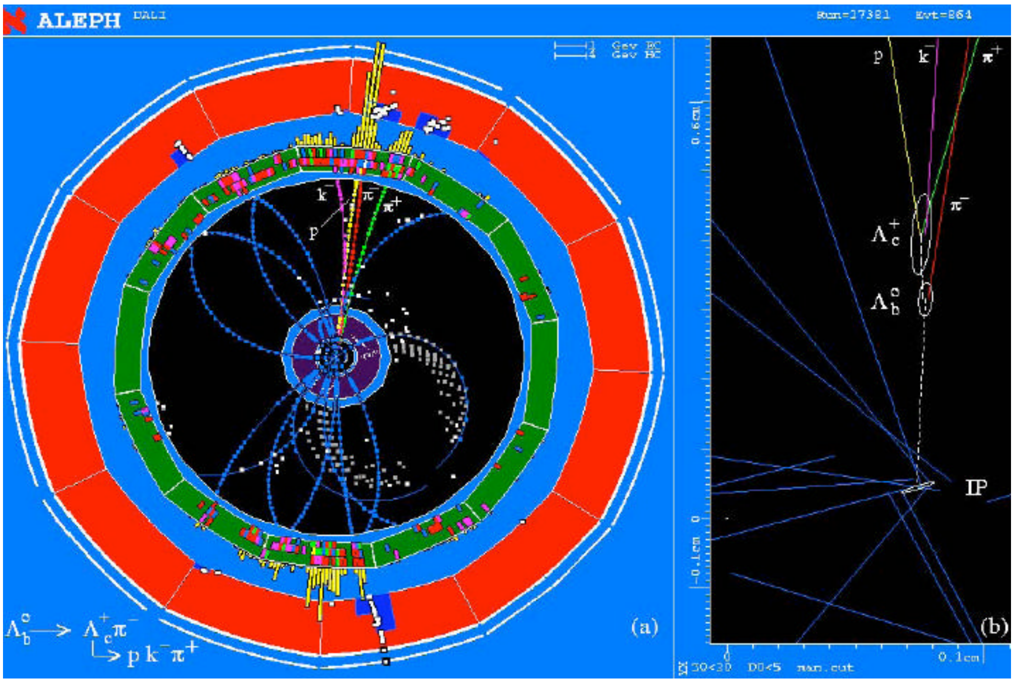

Figure 8. An ALEPH display event

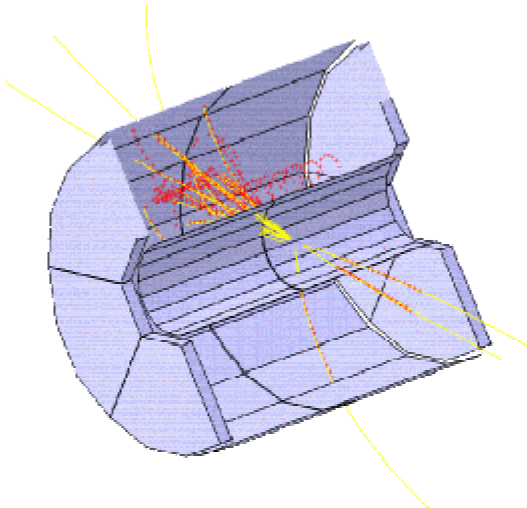

Figure 9. The DELPHI TPC at CERN

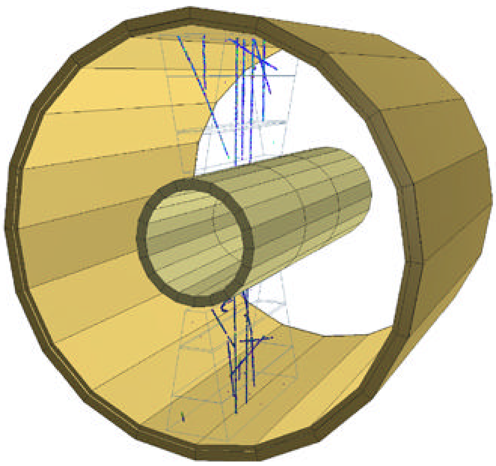

Figure 10. The ALICE TPC at CERN and the first cosmic rays tracks (2006)

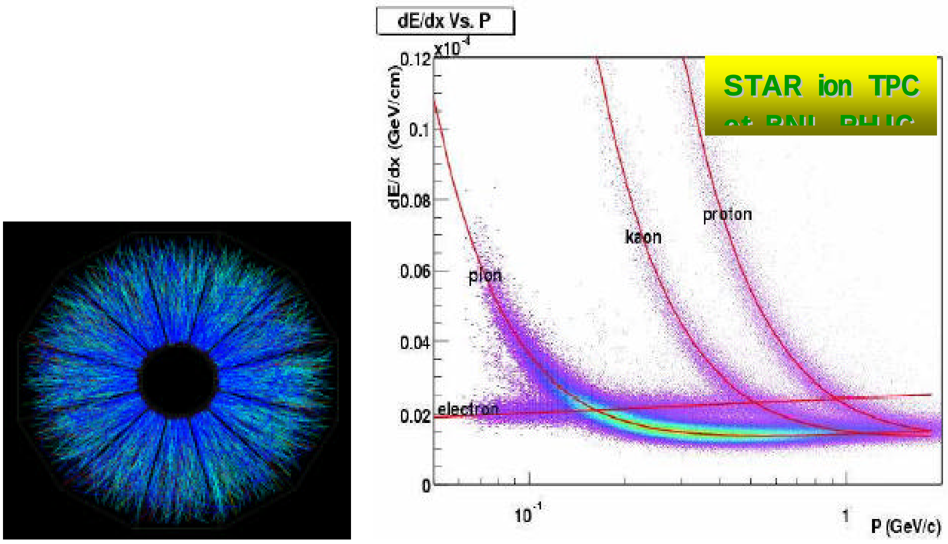

Figure 11a and 11b Au-Au collision in the STAR TPC and dE/dx separation

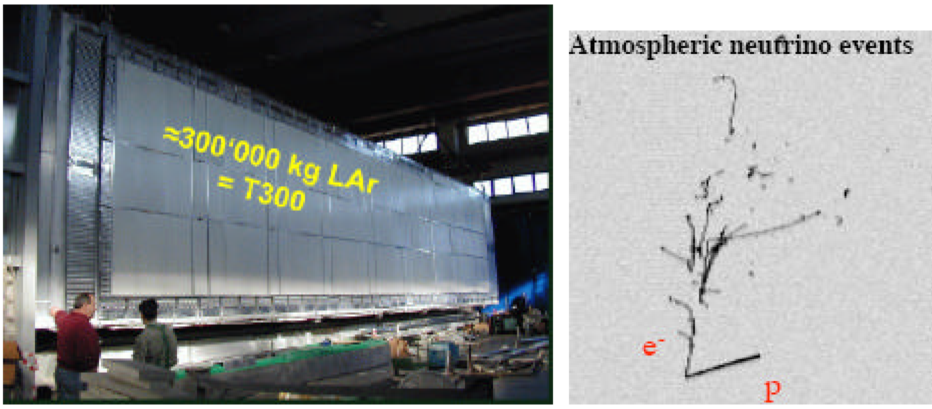

Figure 12a and 12b The ICARUS TPC in the Gran Sasso tunnel and a typical event.

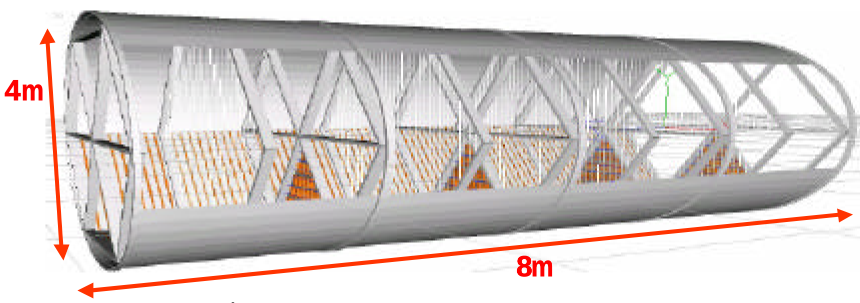

Figure 13. Negative ion TPC project

5.2 Negative ion TPC

In a TPC, electrons may drift over large distance, but with a large diffusion, except if a large magnetic field is applied, which is not always possible, but ions drift with a very small diffusion. The original idea, from B.Martoff[10] is to fill the TPC with a gas mixture containing a very electro-negative molecule, so electrons produced by ionisation are attached on these molecules and create negative ions. These ions drift very slowly and with a small diffusion to the end plate anode, where, in presence of a high magnetic field, they dissociate, and release the electrons, which are classically multiplied in the MPWC or MPGD. This concept has been successfully tested by the author, with CS_2 as electro-negative molecule (DRIFT experiment, Directional Recoil Identification From Tracks). A large detector is under study (figure 13.) for rare low energy events, like WIMPs, axions, etc

6. Conclusion

The gaseous detectors have a long history behind them, they have also, especially TPCs a promising future. The new MPGD technologies are now mature, in association with TPCs, they will permit a large development in many fields, not only in tracking for particle and ion physics, but also in rare event detection.The first paragraph after a heading is not indented (Bodytext style).

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