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Time projection chambers (TPC) in heavy ion experiments

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Abstract. In this paper the performance of TPCs in heavy ion experiments in terms of tracking and particle identification via dE/dx is reviewed. The principle of operation - drift, readout chambers and front end electronics, is illustrated. A few of the TPCs used are presented, along with a short description of the experiments.

1 TPC working principle

A TPC is a three-dimensional almost continuous tracking detector. It also provides information on the specific energy loss, dE/dx, of the particles traversing the drift volume. A TPC can be divided into three main parts:

- The drift volume
- The readout chambers
- The readout electronics

The charged particles produced in the collision pass through a gas mixture in the drift volume and release electrons from the gas atoms. These electrons drift in an external electric field to the readout chambers. The drifting electrons initiate avalanches in the high fields at the anode wires providing an amplification. The electron cloud disappear immediately. The positive ions created in the avalanche induce a temporary image charge on the readout pads which disappears as the ions move away from the anode wire. The image charge is measured by the readout electronics.

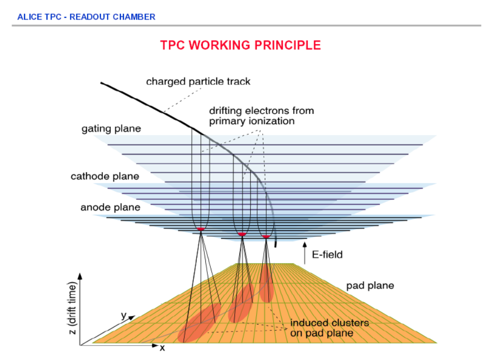

Fig. 1. The working principle of the ALICE TPC. The gating grid, cathode and anode wires are all in the readout chambers (MWPC chambers with pad readout)

2 Drift volume

2.1 Gas mixture

The gas mixture used differs between experiments, see Table 1. The choice of gas [1] is driven by the drift velocity which should be fast and peak at a low electric field. Another property of the gas mixture is its influence on the diffusion of the charge cloud. A dedicated gas system circulates the gas and maintains purity. The main impurities which accumulate in the system are oxygen and water which capture drifting electrons.

Table 1. Gas mixtures of the presented TPCs

Experiment	TPC	Gas mixture
NA49	VTPC	90% Ne and 10% CO_2
	MTPC	90% Ar, 5% CH_4 and 5% CO_2
CERES/NA45	radial	80% Ne and 20% CO_2
STAR central	cylinder	90% Ar and 10% Methane
STAR forward	radial	50% Argon and 50% CO_2
ALICE	cylinder	90% Ne and 10% CO_2

2.2 Electric drift field

In the presence of an electric field, the electrons and ions freed by ionization are accelerated along the field lines towards the anode and cathode respectively. This acceleration is interrupted by collisions with the gas molecules which limit the maximum average velocity which can be attained by the charge along the field direction. The average velocity attained is known as the *drift velocity* of the charge and is superimposed upon its random movement.

2.3 Magnetic field

The curvature of the trajectory of charged particles in the known magnetic field can be used to measure the momentum of the particle. The presence of a magnetic field also influences the drift and diffusion of the ionized electrons [2].

3 Readout chambers

The readout chambers used in heavy ion experiments are based on MWPCs. The chambers consist of a pad plane and three or four wire planes. Drifting electrons originating from the primary ionization by themselves do not induce a sufficiently large signal in the readout pads. The necessary signal amplification is provided by avalanche creation in the vicinity of the anode wires. The induced charge from an avalanche is shared over several adjacent pads (2-3). The outermost wire plane is the gating grid. This grid is a shutter to control entry of electrons from the TPC drift volume into the readout chambers. It also blocks positive ions produced in the readout chamber, keeping them from entering the drift volume where they would distort the drift field.

3.1 Optimalization of the pad and wire layout

The diameter of the wires, their relative position, and the size, shape and positioning of the pads are, along with the choice of drift gas, the main design parameters that are subject to optimization. In a radial TPC (like the forward TPCs of the STAR experiment), the wires are tilted with a small angle so that two or more anode wires cross each pad for the selected pad-wire geometry. This is to avoid the observed periodic shifts in the position measurement that arises when the wire planes are orthogonal to the axial direction of the pads [7]. In linear drift TPCs (i.e. central STAR and ALICE) the wire planes are mounted orthogonal to the pads. The pad size is sometimes different in the outer and inner sectors. The smaller wire spacing and pad size of the inner sectors provides better spatial resolution necessary for tracking resolution near the center of the detector where track density is highest.

4 Readout electronics

The readout electronics generally consists of a chain of amplification, digitalization and transfer to DAQ/permanent storage. In ALICE (see Sect. 9.1) and CERES/NA45 the chain also includes fast digitized pre-processing in the front end electronics, done in a dedicated ASIC. For the other TPCs the amplified signals are stored in analog form in Switched Capacitor Arrays (SCA), which can be regarded as a series of capacitors (512 for NA49 and STAR central) with a sample and hold circuit for each capacitor [3]. After the readout cycle, the stored charges are digitized in ADCs and sent to DAQ. The number of channels to be read out is summarized on Table 2.

Table 2. Number of channels of the presented TPCs

Experiment	Pads	Pad size (mm^2)
NA49	182000	16x3.5, 28x3.5, 40x5.5
CERES/NA45	15360	chevron (w=10.3 mm, l=6 mm)
STAR central	136608	2.85x11.5, 6.20x19.5
STAR forward	9600	1.6x20
ALICE	570000	4x7.5, 6x10, 6x15

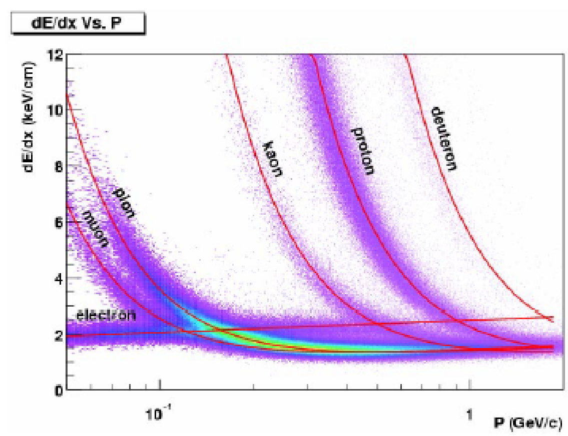

Fig. 2. The energy loss distribution for primary and secondary particles in the STAR TPC as a function of the momentum p of the primary particle. The magnetic field was 0.25 T

5 The NA49 TPCs

The NA49 detector [4] is a wide acceptance spectrometer for the study of hadron production in p+p, p+A, and A+A collisions at the CERN SPS (fixed target). The main components are 4 large volume TPCs for tracking and particle identification via dE/dx. The TPC system deploys two "Vertex" chambers (VTPC) inside the magnets and two "Main" chambers (MTPC) on both sides of the beam behind the magnets.The VTPCs measures 2.0 x 2.5 x .98 m^3. These are used to derive the particle momentum. The MTPCs have a length of 3.9 m and a height of 1.8 m. They are placed behind the magnets to measure the ionization energy loss in the relativistic rise in order to meet the requirements of the dE/dx resolution.

6 The CERES/NA45 TPC

CERES (Cherenkov-Ring Electron Spectrometer) [5] is a dilepton experiment at the CERN SPS (fixed target). The CERES TPC is a cylindrical drift chamber with the drift field in radial direction and segmented pad readout. The sensitive volume is about 9 m^3 and the length 2 m. It is used to determine the momentum of the particles produced in the collision and was added to increase the mass resolution of the experiment.

7 The STAR central TPC

The STAR detector at RHIC uses the TPC [6] inside a solenoidal magnetic field as its primary tracking device. The TPC records the tracks of particles, measures their momenta, and identifies the particles by measuring their ionization energy loss (dE/dx) with a resolution of 8%. This is the first big cylindrical TPC in a heavy ion collider experiment. The central TPC is 4.2 m long and 4 m in diameter. The central cathode, the inner and outer field cage cylinders and the readout end caps, defines the electronic drift field. More than 3000 tracks per event are routinely reconstructed.

8 The STAR forward TPC

The main argument to chose a TPC with a radial drift field is the improved two-track resolution in the transverse direction. The transverse separation of two charge clouds increases linearly with increasing r, but the width of the charge distribution of the cloud only increases by $\sqrt{r}$. The Forward Time Projection Chambers (FTPC) [7] were constructed to extend the acceptance of the STAR experiment. The FTPC has a cylindrical structure, 75 cm in diameter and 120 cm long. The field cage is formed by the inner HV-electrode, a thin metalized plastic tube, and the outer cylinder wall at ground potential. Drift length at maximum is only 23 cm. A two-track resolution of 1-2 mm and a position resolution of 100 μm is expected.

9 The ALICE TPC

The ALICE TPC [8] is the main tracking detector of the central barrel of the ALICE experiment at LHC. It provides charged particle momentum measurement with sufficient momentum resolution, particle identification by dE/dx and by decay topology analysis and vertex determination in the region $p_t < 10$ GeV/c and pseudorapidities $|\eta| < 0.9$. In addition, the TPC will provide - standalone or in combination with the other central barrel detectors (e.g. TRD and ITS) - the input for the High Level Trigger [9] in order to select low cross section signals and rare processes.

The TPC is a 88 m^3 cylinder (5.1 m long and 5.56 m in diameter) divided in two drift regions by the central electrode located at its axial center. It is being constructed based upon the aggregated experience from previous TPCs, and is very similar to the STAR central TPC.

9.1 Front end electronics

One of the challenges in designing the TPC for ALICE is the design of front end electronics to cope with the data rates and the channel occupancy. For this purpose a custom chip has been designed. The ALTRO (ALice Tpc ReadOut) chip [10] contains 16 times the TSA1001 ADC from ST Microelectronics in the form of two 8-ADC IP blocks. This ADC has differential inputs and can work up to 20 MS/sec with a resolution of 10 bits, while consuming as little as 12 mW. After digitization, a Baseline Correction Unit is able to remove systematic perturbations of the baseline by subtracting a pattern stored in a memory. The tail cancellation filter is a 3-stage IIR digital filter that removes the long complex tail of the detector signal. This narrows the clusters to improve their identification. The filter can also remove undershoot that typically distorts the amplitude of the clusters when pile-up occurs. A second correction of the baseline is performed based on the moving average of the samples that fall within a certain acceptance window. Eventually, the Zero Suppression procedure removes all data that is below a certain threshold, except for a specified number of pre- and post-samples around each peak. An example of data processing with the ALTRO chip is shown in Fig. 3.

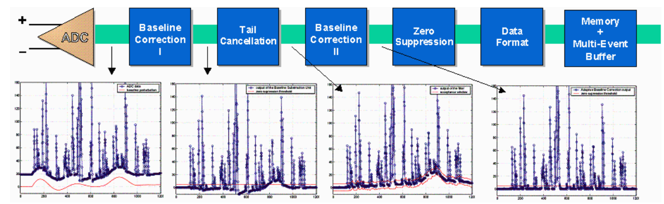

Fig. 3. The data processing stages of the ALTRO chip

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