The ALICE Time Projection Chamber

... the World's largest Time Projection Chamber
Outline

- Time Projection Chambers
  - Introduction
  - Coordinate Measurement and Limitations
  - Particle Identification (dE/dx)
  - TPCs for Heavy Ion Experiments
- The ALICE TPC
  - ALICE Experiment
  - Construction
  - Gas Choice
  - Read Out Electronics
  - Calibration
  - Performance
- Summary
Detector Physics for TPCs

1) Gas Ionisation by Charged Particles,
2) Electron Drift and Diffusion in Gases,
3) Ionisation Amplification (at Anode Wires),
4) Signal Creation (Induction),
5) Signal Processing in Readout Electronics,
6) Coordinate Measurement,
7) Ion gates.

All points are described in great detail in e.g. [Blum, Riegler, Rolandi, Particle Detection with Drift Chambers, Second Edition, Springer, 2008]
TPC – The Concept (1)

- Time Projection Chambers (TPCs) are simple but effective particle detectors.
- TPCs consist of:
  1) A large volume filled with a gas (or liquid),
  2) a field cage providing a uniform electric drift field and
  3) at one or two surfaces of the volume readout elements (e.g. wire chambers, GEMs, ...).
TPC – The Concept (2)

1) The track of a charged particle ionises the gas.
2) The electrons drift towards the readout elements.
3) The projected track is detected.
4) The third coordinate is reconstructed from the drift time.
TPC – The Concept (3)

- A magnetic field is applied in order to measure the track curvature and thus the particle momenta.
TPC – The Concept (4)

- A magnetic field is applied in order to measure the track curvature and thus the particle momenta.
- A simple formula: \( p_T = 0.3 \, B \, R \), where
  \( B \) = magnetic field in Tesla;
  \( R \) = radius of particle track.
What is special about TPCs?

- Abilities:
  - **3D coordinate measurement**: Tracking of charged particles in high track density environments and
  - **PID: Particle Identification** through their ionisation energy loss ($dE/dx$).

- Advantages:
  - Low amount of material leads to low *multiple scattering* of particles.
  - Easy *pattern recognition* (continuous tracks).
Coordinate Measurement with TPCs
TPC – 3D Coordinate Measurement

- $z$ coordinate is calculated from drift time $t$ and drift velocity $v_d$. 

![Diagram showing 3D coordinate measurement with a track, projected track, wire plane, and coordinate axes.]
A General Equation of Motion (2)

- \( z \) coordinate is measured via the drift time.
- The drift of electrons in \( E \) and \( B \) fields:

\[
\vec{v}_d = \frac{\mu}{1 + (\omega \tau)^2} \left( \vec{E} + (\omega \tau) \frac{\vec{E} \times \vec{B}}{|\vec{B}|} + (\omega \tau)^2 \frac{(\vec{E} \cdot \vec{B})\vec{B}}{|\vec{B}|^2} \right)
\]

- \( \omega \tau \ll 1 \): Drift along \( E \) field lines.
- \( \omega \tau \gg 1 \): Drift along \( B \) field lines.

\( \tau \) mean drift time between collisions
\( \mu = \frac{e \tau}{m} \) particle mobility
\( \omega = \frac{eB}{mc} \) cyclotron frequency
TPC – 3D Coordinate Measurement

- The z coordinate is calculated from drift time $t$ and drift velocity $v_D$;
- The x and y coordinates are calculated using cathode pads.
TPC – Cathode Pads (1)

- If the cathode pads are small, we measure signals on at least two adjacent pads in $y$ direction (along wires).
- The pulse-height ratio can be used to determine the position of the avalanche with precision much smaller than the pad width $w$. 
Assume an avalanche and the two signal amplitudes: $A_1$ and $A_2$.

Width of pads: $w$.

Then: $\frac{A_1}{A_2} = \frac{P_0(\lambda)}{P_0(\lambda - w)}$, which can be used to get the avalanche position $\lambda$.

$P_0$ is called Pad Response Function and can be measured or calculated.
TPC – Pad Response Function

- Pad Response Function for the ALICE TPC (rectangular 4×7.5mm² pads).
Limitations for Coordinate Measurement

1) **Diffusion** displaces the charge clusters during the long drift.

2) **Attachment** of drifting electrons leads to loss of signal amplitude.

3) **ExB effects**: Small misalignment \( (E \text{ and } B \text{ not perfectly parallel}) \) displaces the charge clusters during the long drift.

4) **Field distortions** due to *space charge* in the drift volume.
Limitation 1: Diffusion (1)

- Electrons are drifting along $z$ and scatter on gas molecules.
- As a consequence, their drift velocity deviates from the average due to the random nature of the collisions.
- The diffusion is Gaussian with $\sigma(z) = D\sqrt{z}$, where
  - $z = \text{drift length}$ and
  - $D = \text{diffusion coefficient [}\mu\text{m/}\sqrt{\text{cm}}\text{]}$.
- Longitudinal (in drift direction) and transverse diffusion can differ.
Limitation 1: Diffusion (2)

- How to reduce diffusion?

1) Certain additions to the gas mixture (like e.g. CO₂) help reduce the diffusion.
Limitation 1: Diffusion (2)

- How to reduce diffusion?

1) Certain additions to the gas mixture (like e.g. CO\(_2\)) help reduce the diffusion.

2) Assume \(E || B\) and \(\omega \tau >> 1\): Transverse Diffusion is suppressed by a large factor:

\[
\frac{D(B)}{D(0)} = \frac{1}{1 + \omega^2 \tau^2}
\]
Limitation 2: Attachment

- The drifting electrons can be absorbed in the gas by the formation of negative ions.
- Need to keep $O_2$ content low!
- $<1$ ppm of $O_2$ keeps signal loss below 10% for 250 cm drift.
Limitation 3: ExB Effects

- $ExB$ distortions arise from **nonparallel $E$ and $B$ fields**.
- It is difficult to build a very big detector (~5m) such that $E$ and $B$ fields are always perfectly parallel.
- Remaining effects must be corrected for in data.
- In ALICE we use a Laser system to calibrate $ExB$ distortions.
Limitation 4: Space Charge

- In high-rate environments charges distort the electric field.
Limitation 4: Space Charge

- In high-rate environments charges distort the electric drift field.
- The gating grid allows electrons to enter anode region only for interesting events and keeps ions produced in avalanches out of the drift region.
Particle Identification with TPCs
Particle Identification by $dE/dx$ (1)

- Charged particles loose energy in the gas volume.

\[
\frac{dE}{dx} = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \ln \frac{2m v^2}{J (1 - \beta^2)} - \beta^2 - \frac{\delta}{2} \right]
\]

- $m$ mass of electron
- $z, \nu$ charge and velocity of incident particle
- $J$ mean ionization energy
- $\delta$ density effect term
Particle Identification by $dE/dx$ (2)

- Energy loss distributions as function of particle momentum.
- Different particle species can be identified in certain regions.
- Image: Measurements with PEP4 TPC.
Particle Identification by $dE/dx$ (3)

- Energy loss distributions as function of particle momentum.
- For ALICE TPC we have so far only cosmic particles that make it through ~50m of rock (muons) and some secondary electrons and protons.
TPCs for Heavy Ion Experiments
TPCs for Heavy Ion Experiments

- Events in $e^+ - e^-$ collisions have rather low densities of charged tracks.
TPCs for Heavy Ion Experiments

- Events in $e^+e^-$ collisions have rather low densities of charged tracks.
- In heavy ion collisions we need much smaller pad sizes and a large number of pads (ALICE TPC: 570 000).
The ALICE TPC

A rapid 3-dimensional tracking device for ultra-high multiplicity events.
The ALICE Experiment

THE ALICE DETECTOR

1. ITS
2. FMD, T0, V0
3. TPC
4. TRD
5. TOF
6. HMPID
7. EMCAL
8. PHOS CPV
9. MAGNET
10. ACORDE
11. ABSORBER
12. MUON TRACKING
13. MUON WALL
14. MUON TRIGGER
15. DIPOLE
16. PMD
17. ZDC

a. ITS SPD Pixel
b. ITS SDD Drift
c. ITS SSD Strip
d. V0 and T0
e. FMD
A Large Ion Collider Experiment

- Search for evidence of quark-gluon plasma in Pb-Pb collisions at the LHC (5.5 TeV per nucleon pair).
- Study properties of p-p collisions (14 TeV).

- Trajectories of thousands of particles (~20,000) produced in central collisions have to be measured and the particles have to be identified.
- To serve these tasks, the largest TPC in the world was built.
Pb-Pb collisions in ALICE

- Pb-Pb collisions at 5.5TeV per nucleon pair.
- Simulated event with **cut in theta** 60-62 deg.
- If all tracks would be shown, the image would be yellow ...
The ALICE TPC: Tasks

- Track finding,
- momentum measurement and
- particle identification

at transverse momenta $0.1 < p_T < 100\text{GeV/c}$.

Rate capability:
- 200 Hz for central Pb-Pb collisions and
- 1 kHz for p-p collisions.
The ALICE TPC Collaboration

Bergen  Bratislava
CERN    Copenhagen
Darmstadt TU Frankfurt
GSI Darmstadt Heidelberg KIP
Heidelberg PI Krakow
Lund
ALICE TPC: Overview

- Central High Voltage electrode (100 kV)
- Field cage
- Readout chambers
- Inner and Outer Containment Vessels (150 mm, CO₂)
- Endplates housing 2 x 2 x 18 MWPC
- Suspended field defining strips 400 V / cm
- 557568 readout channels
- Beam path
- Dimension: 510 cm
**ALICE TPC: Low-Mass Field Cage**

- Light composite materials for all four cylinders.
Field Cage Construction (2002-04)
ALICE TPC: Central Drift Electrode

- Aluminized mylar on 100kV potential.

CE reflects images of Readout Chambers
ALICE TPC: Read Out Chambers

- MWPCs with 2 (3)mm wire spacing,
- 3 different pad sizes.
Read Out Chamber Installation (2005)
The gas mixture for the ALICE TPC
ALICE TPC - Choosing a Gas

- Basic components could be Ar, Ne, CO$_2$, CH$_4$, N$_2$.
- Different (competing) requirements:
  - Low **multiple scattering** ($\Rightarrow$ low $Z$),
  - Low **gas gain** ($\Rightarrow$ high primary ionisation $\Rightarrow$ high $Z$),
  - Low space charge distortions ($\Rightarrow$ low **primary ionisation** $\Rightarrow$ low $Z$),
  - Low event overlap ($\Rightarrow$ high **drift velocity**),
  - Low **sensitivity to variations** in gas composition or ambient conditions.
ALICE TPC Gas: Ne-CO$_2$-N$_2$

- ALICE TPC uses Ne-CO$_2$-N$_2$ [90%-10%-5%].

- **Advantage**: Low diffusion, fast drift, low space charge by primary ionisation.

- **Drawback**: High gain needed, sensitive to variations of pressure, temperature and to exact composition;

- **But**: Addition of N$_2$ reduces this sensitivity.
The ALICE TPC Read Out Electronics
ALICE TPC Electronics (1)

- In Pb-Pb collisions the high occupancy (many consecutive signals per read out pad) is challenging.

Signals on one read out channel = one pad

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- Input Signal

- ZS=5ADC
ALICE TPC Electronics (2)

- **ALICE TPC Read Out Chip (ALTRO):**
  - 2 baseline correction circuits, Signal tail cancellation and Zero Suppression (to reduce data size save only interesting signals) for 16 channels.
ALICE TPC Electronics (3)

- After signal correction in the ALTRO the baseline is nicely restored.

Signals on one read out channel = one pad

Amplitude in ADC counts

After ALTRO Correction

Input Signal

ZS=5ADC

time [a.u.]
Front End Cards hold 8 ALTRO chips each.
128 read out channels per FEC.
Install. of Read Out Electronics (2006)
Descent of the TPC into Cavern (2007)

2 hours for descent
The TPC in the ALICE Cavern (2007)
TPC in ALICE (2007-08)
Calibration of the ALICE TPC
ALICE TPC - Gain Calibration

- **Gain**: How large are the signals on the pads for given charge?
- $^{83}$Kr isotopes released into the gas.
- Relative resolution of main peak: $\sim$5%.
- Pad to pad calibration.

![Gain Calibration Diagram](image)
ALICE TPC - Laser Calibration (1)

- Can inject 168 laser beams into the drift volume on both sides.
- Can calibrate distortions ($E \times B$, Space Charge).
ALICE TPC - Laser Calibration (2)

- Stray laser light extracts electrons from central electrode.
- Used to calibrate $v_d$ ($\sim 2.65\text{cm/\mu s}$, pressure dependent, precision $10^{-4}$) and analyse pad-by-pad variations.
ALICE TPC: Cosmics Event
Performance (Preliminary)

- Systematic effects on position resolution before (after) calibration:
  - ExB Effects: $\Delta y < 3\text{mm} (<0.3\text{mm})$
  - Drift velocity: $\Delta z \sim 50\text{mm} (1\text{mm})$
  - Alignment: $\sigma_y = \sigma_z = 0.15\text{mm} (0.1\text{mm})$
- Momentum resolution (from cosmic tracks):
  - $\sigma(p_T) = 3\%$ at $2\text{GeV/c}$
  - $\sigma(p_T) = 10\%$ at $10\text{GeV/c}$
- $dE/dx$ Resolution (from cosmic tracks):
  - $\sigma(dE/dx) = 6\%$
Summary

- TPCs are quite simple constructions which allow to take “3D photographs” of particle tracks.
- It also allows particle identification via the characteristic energy loss.
- A strong magnetic field is used to bend the particle tracks (spectrometer) and on top reduces the diffusion over the long drift paths.
- The largest existing TPC is installed into the ALICE experiment.
- A lot of calibration data (Kryton, Laser, Cosmics) was taken in dedicated run periods in 2007 and 08.
- The start of LHC is now delayed until summer 2009.
- The ALICE TPC is ready for collisions.