Time Projection Chambers (TPCs) and applications

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Physics 290E Seminar – Detectors & Experiments
Goals of particle detection & tracking

- Was there a particle(s)?
- What was its trajectory (position)?
- What was its 4-momentum?
- What was its charge?
- With what uncertainty do we know the answer to these questions?
Some historical particle detectors

- **Cloud chamber (1920s-50s)**
  - Discovery of positron, muon, & K meson

- **Spark chamber (1930s-60s)**
  - Layers of parallel plates which can be triggered to spark via HV along ionized tracks through gas

- **Bubble chamber (1952-present)**
  - Invented by Donald A. Glaser (Nobel Prize 1960)
  - Big European Bubble Chamber (BEBC) at CERN in use until 1984
    - Discovery of D meson
  - Used in some modern experimental searches for dark matter / WIMPs

Example cloud chamber
Wire chambers

- Developed by Georges Charpak at CERN in 1968 (Nobel Prize 1992)

Gas ionization detector
- Charged particle (T) traversing gas interacts electromagnetically with gas molecules
- Creation of ion/electron pairs
- Approximately constant applied electric field between wires (W) and grounding plates (P)
- Electron/ions drift to wires, which is amplified and read out as a signal (A)

Second plane of wires can be added in transverse direction to get 2D information
Signal amplification

- Electrons/ions first drift along approximately straight field lines

- Amplification happens in high-gradient area near the wires

- **Electron avalanche**
  - Original $e^{-}$ has enough energy to create additional electron/ion pairs

- Capacitive coupling between nearby wires is largely negated by the positive signal induced on those wires by the avalanche \[^1\]
Drift chamber

- Also utilize the **timing** which is required for the electrons/ions to drift to the nearest wire
- Increases the accuracy of path reconstruction

![Diagram of drift chamber](https://doi.org/10.1017/CBO9781107337701.011)
But how can we create a 3D image?

- Several layers of wire chambers
  - Can be expensive to reproduce the $N$ chambers required for $z$-resolution

- Utilize the **timing of drift** in the $z$-direction

For this particle track, $\Delta t_1 > \Delta t_2 > \cdots > \Delta t_N$
The Time Projection Chamber (TPC)

- First proposed by David R. Nygren at LBNL in 1974 [3]

\[ V_0 \]

\[ e^- A^+ \]

\[ (100 \text{ kV}) \]

\[ e^- A^+ \]

\[ e^- A^+ \]

\[ e^- A^+ \]

\[ e^- A^+ \]

\[ V_0 \text{ can be } O(100 \text{ kV})! \]

[3] https://cds.cern.ch/record/1734475
The Time Projection Chamber (TPC)

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\[ V_0 \]

\[ A^+ \]

\[ V_0 \text{ can be } O(100 \text{ kV})! \]

Easy to symmetrize for collider experiments

How to tell if particle has +/- charge?
How to identify the particle’s momentum?

- Add a **magnetic field** parallel to the electric field direction
  - Charged particles traversing the TPC will have their bend
  - Thinking classically:
    \[
    \vec{F} = q(\vec{v} \times \vec{B}) = m\vec{a} \quad \Rightarrow \quad qvB\sin(\theta) = \frac{mv^2}{r} \quad \Rightarrow \quad r = \frac{p}{qB\sin(\theta)}
    \]
  - **Radius** of curvature is proportional to the **momentum** with known prefactor
  - **Direction** of curvature tells us about the sign of \(q\) versus \(B\)

- **Magnitude** of magnetic field has to be chosen carefully
  - Larger magnetic field increases curvature \(\Rightarrow\) improves resolution for high-momentum tracks, but limits the minimum momentum that can successfully transverse the field
Proportional counter

- Electrical noise in readout electronics can be quite high \[^4\]:
  - = primary ionization (from original atom)
  - = secondary ionization (from $e^{-}$ with $E > 100 \text{ eV}$)

- Equivalent noise charge (ENC) is $O(1000 \, e^{-})$!
- Need a noise-free amplification $\rightarrow$ gas amplification
- TPC has applied voltage high enough that each ionization $e^{-}$ causes a Townsend avalanche
- Amplification $O(10^5)$ for $|\vec{E}| \sim 10 \text{ kV/cm}$
- Pulse height is proportional to the energy deposited ($dE/dx$)

[\[^4\] \url{https://www.desy.de/~garutti/LECTURES/ParticleDetectorSS12/L4_gasDetectors.pdf}]

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Neon, 1 atm
$\sim 30 \text{ e-Ion pairs}$
Measuring $dE/dx$

- Energy loss given by Bethe-Bloch formula:

\[
\left(-\frac{dE}{dx}\right) = 4\pi N_A \rho m_e c^2 Z^2 \frac{1}{A} \beta^2 \times
\left[ \frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2}{I^2} - \frac{\beta^2 - \delta(\beta \gamma)}{2} \right]
\]

for $0.1 \leq \beta \gamma \leq 1000$.

- $e^-$ shape is different (dominated by bremsstrahlung)

- With access to the particle speed $\beta$, and its momentum $p$ from the curved tracking, one can find the mass \( \text{can identify the particle type (PID)} \)
Controlling the electric field

- Knowledge of \( \bar{E} \) is required to get an accurate \( dE/dx \) calibration

- Add a **field cage** – several metal rings of \( \Delta V \) between anode & cathode

- Usually must be kept thin to limit the radiation length for incoming/outgoing radiation

- Each ring must be well-insulated from each other and from the outside environment to prevent discharges
  - Must consider charge build-up and breakdown voltages

https://www.lctpc.org/e8/e57671
Gas selection

- Need an **inert gas** which is ionized by the radiation
  - Noble gasses are an obvious choice: Argon, Neon, Xenon [expensive!], …

- $e^{-}$ move much faster than $A^{+}$ → build up a net positive charge in the bulk
  - Distorts the field, and can cause fake secondary pulses when ions reach cathode

- Add **quench gas** to ensure each discharge terminates
  - Hydrocarbons (e.g. methane CH$_4$), carbon dioxide (CO$_2$), carbon tetrafluoride (CF$_4$)
  - Lower affinity to electrons than inert gas; “donates” electrons to positive ions
  - Usually added in a mixture of about ~10% to the inert gas

- This process of adding some small amount of a secondary to a main active bulk is commonly called **doping**
Electron diffusion

- **Diffusion constant** is one of the essential parameters in choice of gas mixture \([4]\).
- Important for separation of tracks & position resolution

\[
|\mathbf{E}| = 0 \rightarrow \text{thermal diffusion} \\
\langle \mathbf{v} \rangle = 0 \\
|\mathbf{E}| > 0 \rightarrow \text{transport & diffusion} \\
\langle \mathbf{v} \rangle = v_o
\]

- Transverse electron motion is limited in part by the magnetic field

\[
\sigma_\parallel = \sqrt{2dt} \\
\sigma_\perp = \frac{\sigma_\parallel^2}{1 + \omega^2\tau^2}
\]

\(\sigma = \text{r.m.s. normal distance}\)
\(d = nl/3 = \text{diffusion coeff.}\)
\(l = e^- \text{ mean free path}\)
\(v = e^- \text{ speed}\)
\(t = \text{total time}\)
\(\omega = eB/m_e = \text{cyclotron frequency}\)
\(\tau = \text{mean collision time}\)

D.R. Nygren’s original paper:
[https://lss.fnal.gov/conf/C740805/p58.pdf](https://lss.fnal.gov/conf/C740805/p58.pdf)
The first major TPC application

- Installed in the PEP-4 experiment at SLAC
- Studied $\sqrt{s} = 24$ GeV $e^+e^-$ collisions in PEP storage ring


David Nygren (LBNL) & Fred Catania (SLAC)
The first major TPC application

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Temperature & pressure stability

- Increased pressure → increased density → higher energy loss \( (dE/dx) \)

- Generally a positive pressure is maintained (> 1 atm), meaning leaks have gas moving out instead of in, though there are low-pressure TPCs

- Front-end electronics use power and generate heat
- Resistors between HV have some dark current that generates heat
- Heat radiation can be absorbed from the surrounding environment
- → need cooling systems to maintain stability

At 8.5 atmospheres, the energy loss rises by about 40% as a function of the momentum from its minimum to its plateau value. In consequence the \( K-\pi \) separation at 3.5 GeV/c, for example, is 14.6% [Figure 3]. If we want a separation of 4 standard deviations, the \( dE/dx \) resolution has to be 3.5% and the systematic errors have to be less than 1%. The challenge is to control the gain of more than 2000 proportional wires, knowing that a 1% change in the sector voltage causes an 18% change in gain, a 1% change in density causes a 9% change in gain, and, most importantly, a 1°C change in temperature makes a 3% change in gain.

ALICE TPC [4] [5]

- Dimensions: 5 m length, 2.5 m radius → 88 m³ of Ne/CO₂/N₂ (90-10-5) gas mixture
- High voltage: −100 kV at a central electrode (400 V/cm throughout)
- Total drift time: 92 μs
- End-cap detectors: 32 m² with 557 568 readout pads
- Gain: >10⁴
- Diffusion: σ⊥ = 250 μm
- Resolution: σₓ ≈ 0.2 mm; σₚ/ₚ ≈ 1% p; σdE/dx / (dE/dx) ≈ 5%
- Magnetic field: |B| = 0.5 T
- Temperature control: dT < 0.1 K

ALICE TPC \cite{4} \cite{5}

- \(dE/dx\) resolution depends on the number of space points (159 radial pads)
1209 positively-charged (darker tracks) and 1197 negatively-charged (lighter tracks) particles are produced, about 80 percent are $\pi$ mesons.
Pros/cons of using a TPC for tracking [4]

Advantages:
- Reconstruct complete tracks with a single detector
  - Almost the whole volume is active detector region
- Good momentum resolution (many space points)
- Minimal radiation length (field cage + gas)
- Proportional counter, so gives \( \frac{dE}{dx} \rightarrow \) good particle identification
- Excellent for track reconstruction in high-density environments (e.g. heavy-ions)

Challenges:
- Long drift time \( \rightarrow \) limited rate capabilities
- Large volume \( \rightarrow \) precision
- Large \( \Delta V \) gradient \( \rightarrow \) discharges
- High data rates
- Extreme load at high luminosity
  - Need to apply gating to select on specific, triggered events
Liquid scintillator TPCs

- Liquid Argon (LAr) TPC proposed by Carlo Rubbia in 1977
  - In addition to ionization electrons, excited Argon will scintillate at $\lambda_{\text{peak}} = 127 \text{ nm}$
    - Quartz glass only transparent to $\sim 170 \text{ nm}$ → require wavelength shifter
      - Tetraphenyl butadiene (TPB) is often used (peak at 430 nm)
    - Liquid Xenon (LXe) is also used (expensive!) → $\lambda_{\text{peak}} = 178 \text{ nm}$
  - Light collection improves energy resolution and can be used as a trigger
  - Much higher density (order $\sim 1000x$) → useful for detecting neutral particles
    - Neutral particle (e.g. neutron or neutrino) must scatter off of a charged particle (e.g. Argon nucleus) which then ionizes / excites the LAr
Scintillation light

- **Prompt ("S1")** scintillation signal
  - Light emitted from atoms excited by the original ionizing particle

- **Secondary ("S2")** scintillation signal
  - Light emitted from atoms excited by the electron avalanche

$^{57}$Co ($\gamma$ source)
dual-phase Ar detector

https://doi.org/10.1016/j.phpro.2012.02.465

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Large Underground Xenon (LUX) experiment

- 370 kg LXe (!) TPC for searching for WIMP dark matter candidates
- Began running April 2013 → decommissioned 2016
  - Detector now on display at Sanford Underground Research Facility (SURF) in SD
- White material seen in the photo is PTFE (Teflon), which is used to reflect scintillation light and thus improve light yield
- Detector was submerged in 71600 gallons (271 kL) of de-ionized water; 4850 ft (1480 m) underground
ZEPLIN-III experiment

- Third generation of ZonEd Proportional scintillation in LIquid Noble gases
- 12 kg LXe TPC for searching for WIMP dark matter, based in UK
- ZEPLIN-II was the very first dual-phase TPC (both gas & liquid)
- Ran in 2008, 2010-2011

LUX-ZEPLIN (LZ) experiment

- “Next generation” dark matter search using 7000 kg (!!!) LXe TPC