Gaseous Detectors

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My Background

- TPC for ALICE @ LHC: hadron identification
- TPC for ILD @ ILC: prototype in electron beam
- HARPO TPC: 10-100MeV gamma polarisation
- NEWS-G SPC: low mass dark matter

Outline

- Applications of gas(eous) detectors
- Principles of gas detectors
- Basics of gas selection
- Examples of detectors

Why gas?

- It is light
  - Does not affect the particles momentum much (low material budget)
    e.g. ALICE TPC at LHC
  - Does not affect particle trajectory much (low scattering)
    e.g HARPO TPC
- It is cheap
  - Allows large size detectors at low cost
    e.g. ATLAS muon trackers, muon tomography
- It is replaceable
  - Good longevity (e.g. radiation hardness), flexibility

Basic principles

- Ionisation
- Drift
- Amplification
- Readout

Ionisation in gas

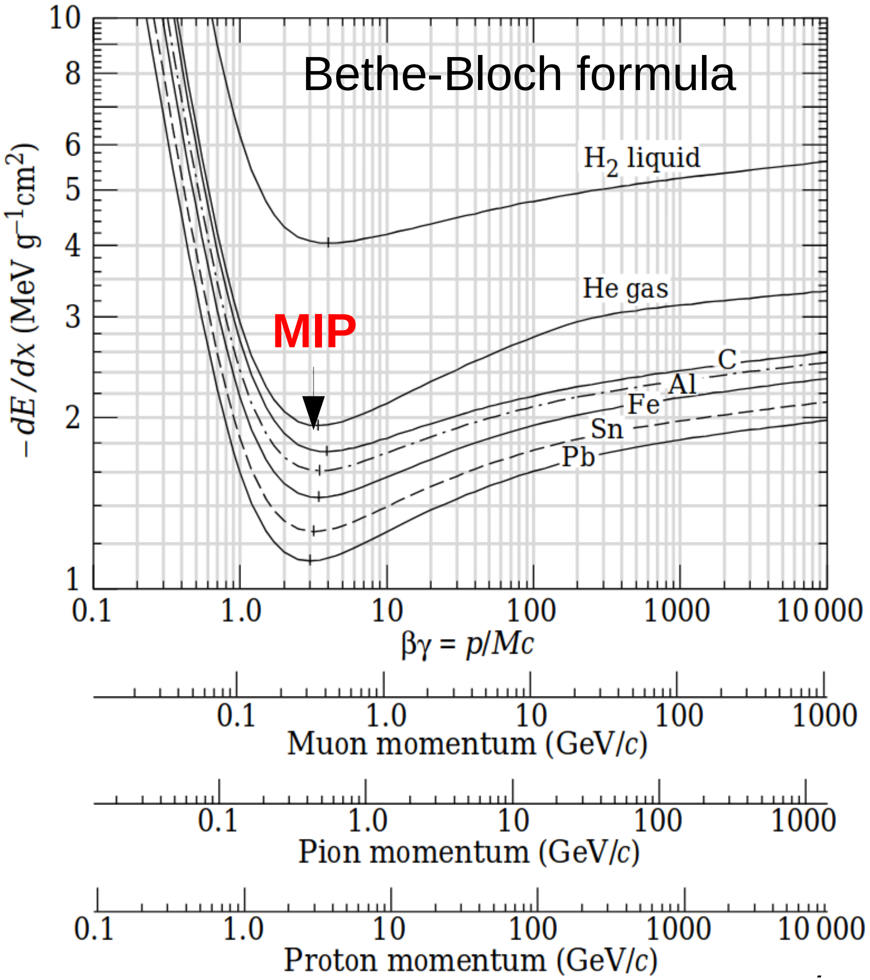
- Main mode of detection
  - Ignoring scintillation here
  - Creation of electron-ion pairs. The electrons will be called “primary electrons”
- Photoelectric effect
  - Photon deposit all their energy in one place
  - Ne- proportional to photon energy $\langle N_e \rangle = \frac{E_{dep}}{W_{er}}$
  - Sub-Poissonian fluctuations: $\sigma_{N_e} = F\sqrt{N_e}$ (F=Fano factor<1)
  - Used for calibrations with radioactive sources

Ionisation in gas

- Nuclear recoil
  - Typically elastic scattering of neutral particle off nucleus
  - Some of the energy in ionisation $\langle N_e \rangle = \frac{E_{dep}}{W_{nr}}$
  - Hard to calibrate. Monoenergetic neutron beam needed
- Charged particle tracks
  - Every charged particle ionises gas along its track
  - Ionisation depends of the particle energy, and its charge

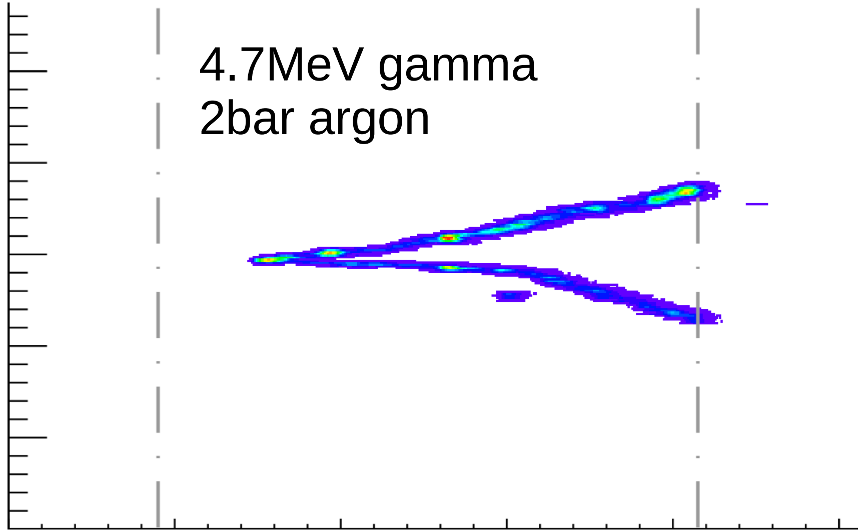
Mean energy deposition along track

- Depends mostly on material density
- Depends on particle speed/energy
- Stronger at low energy
- Mostly independent of energy for ultrarelativistic particles



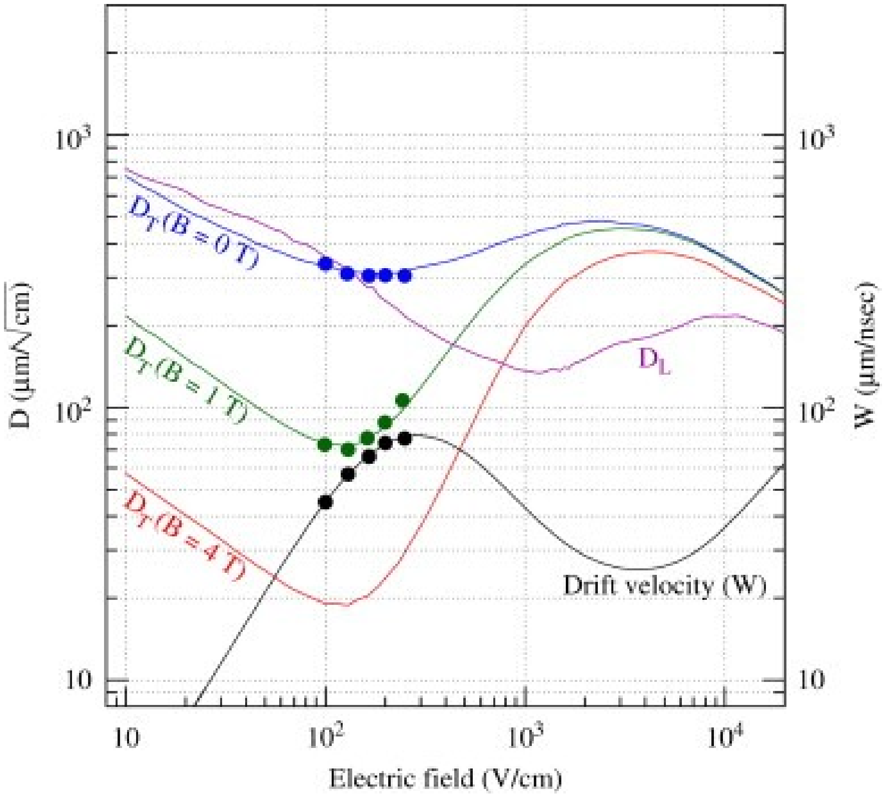
Multiple scattering and δ rays

- Multiple scattering
  - At low energy, charged particles bounce off the gas molecules
  - Tracks are not straight
  - Effect lower at lower density (lower pressure)
- dE/dx fluctuations and Delta rays
  - Energy deposition fluctuates a lot around mean
  - If the energy loss is large enough, an electron is knocked off and creates a short secondary track called delta ray



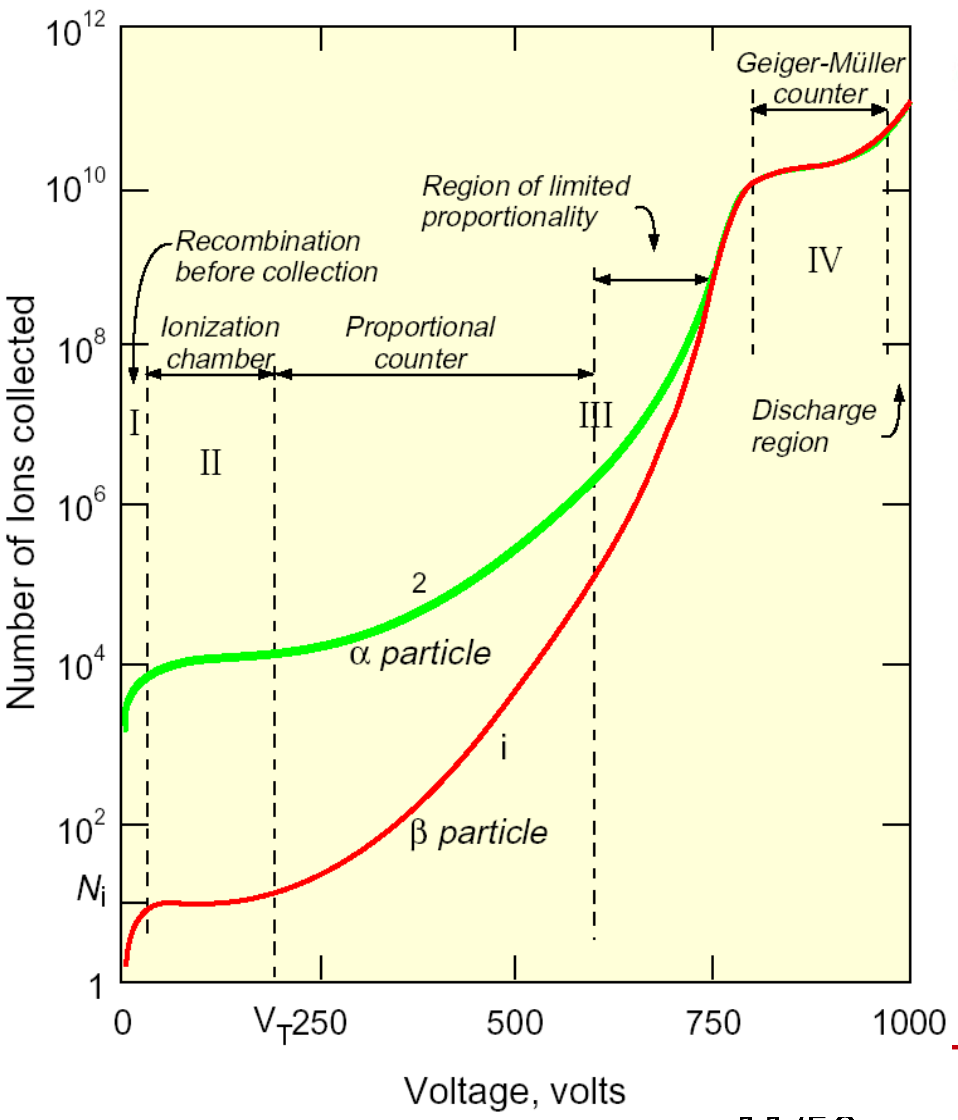
Electron drift

- Primary ionisation electrons drift along electric field
- Velocity depends non-trivially on gas composition and electric field strength
- Diffusion depends non-trivially on gas composition and electric field strength
- Electrons can be captured by electronegative molecules (typically O2)
  - The negative ion will then drift much slower
- Electrons can recombine with positive ions



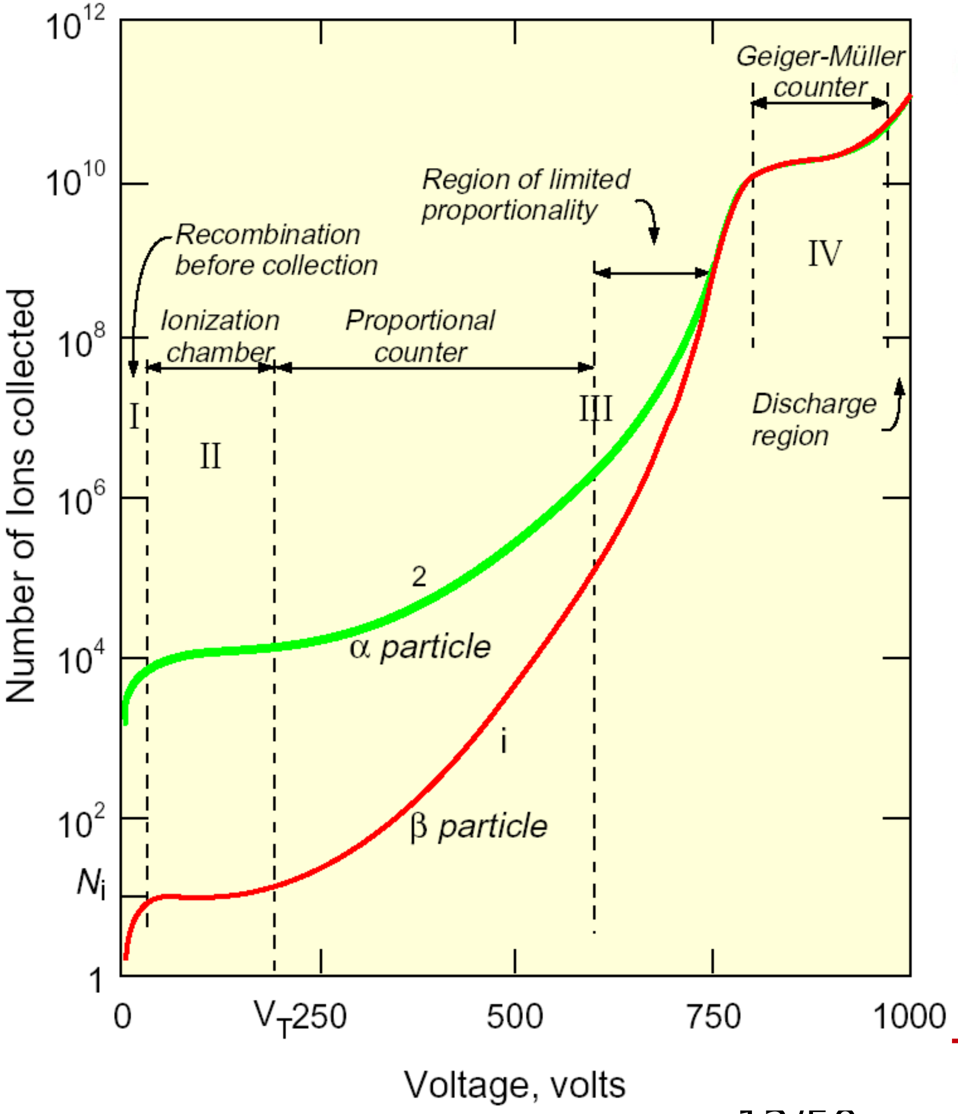
Amplification

- Signal from primary ionisation electrons is usually too low to readout
- In a high electric field, the electrons undergo a Townsend avalanche
  - Electrons ionise the gas, creating more electrons…
- Amplification strongly dependent on field/voltage
- 3 modes depending on strength of field



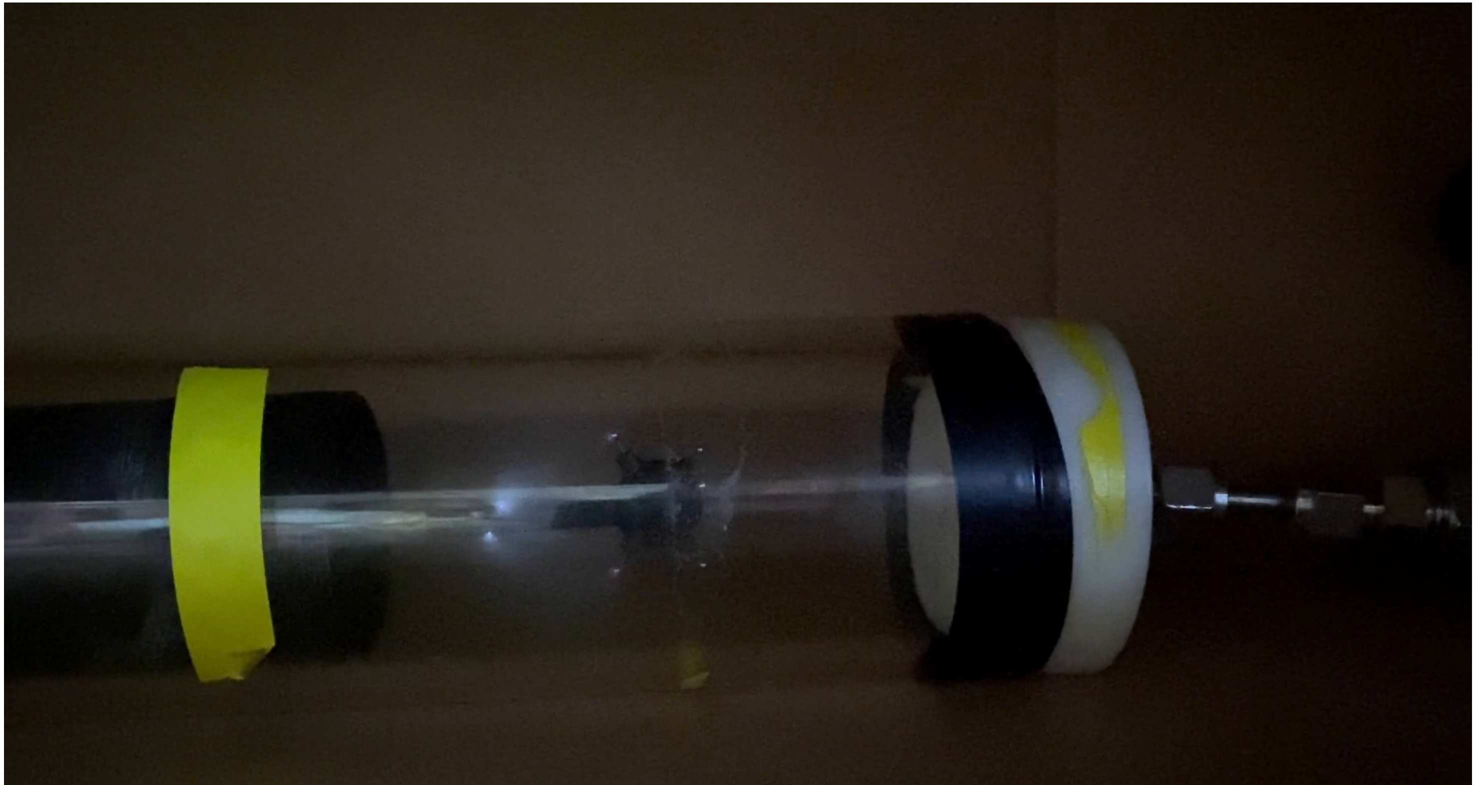
Amplification

- Ionisation chamber mode
  - No gain
  - Works for strong signal (e.g. alpha particles)
- Proportional mode
  - Signal proportional to number of primary electons
  - Fluctuations around the mean
- Geiger-Müller mode
  - Signal same regardless of number of primary electrons



Discharges

- Even in proportional mode, discharge events can happen
  - Highly ionising event, field fluctuation, operation error
- Discharges contribute to aging and can be destructive
  - Burning material, creating molecular compounds in gas, ...
- Discharges will temporarily affect amplification
  - Lowered voltage (while recharging capacitance)
  - Screening from residual charges (while they drift)
- Spark reduction often needed



http://sphere.phy.queensu.ca:8321/share/IMG_4405.MOV

Resistivity

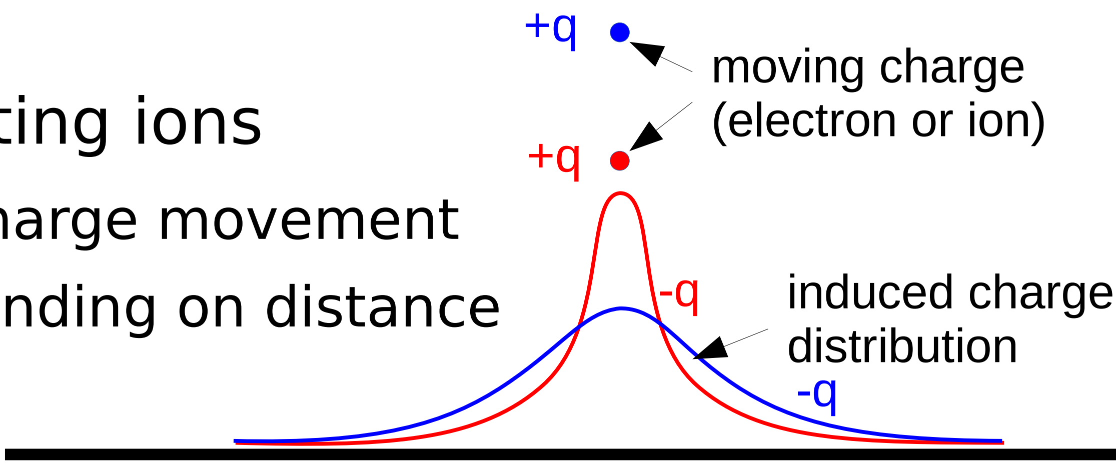
- Sparks can be mitigated thanks to resistive materials
- When a streamer forms (plasma precursor to a spark), it induces charges that counteract the amplification field
  - If all materials are conductive, the charge are evacuated, and a spark will happen
  - If the material has a high resistance, the charge accumulate, and the streamer gets quenched
  - If the material is an insulator, the charges remain, and the field is permanently reduced

Resistivity

- Good materials
  - Keep the charges on the time scale of signal formation (typically ~1μs)
  - Evacuates the charges before the next event (easy for low rate experiments)

Readout

- Direct electron collection on conductor
  - fast signal, localised
- Induced charge from drifting ions
  - signal shape related to charge movement
  - spatially distributed depending on distance



- Induced charge from electrons collected on resistive surface

Effects of gas composition

What do we want?

- On ionisation
  - Optimise interaction probability, scattering
  - Maximise mean number of primary electrons
  - Gas composition has a minor effect
- On drift
  - Maximise velocity (fast), minimise diffusion (accurate)
  - Avoid electron attachment/capture
- On amplification
  - High gain at low voltage
  - stability

Primary ionisation

- Gas composition has a minor effect on the mean number of primary electron per eV $W_{er} \approx 30\, eV / e^-$

- Gas will affect the energy loss of the ionising particle
  - dE/dx proportional pressure
  - Photon cross section proportional to Z^2
  - Energy transfer from elastic scattering depends on mass of target nucleus
  - ...

Drift

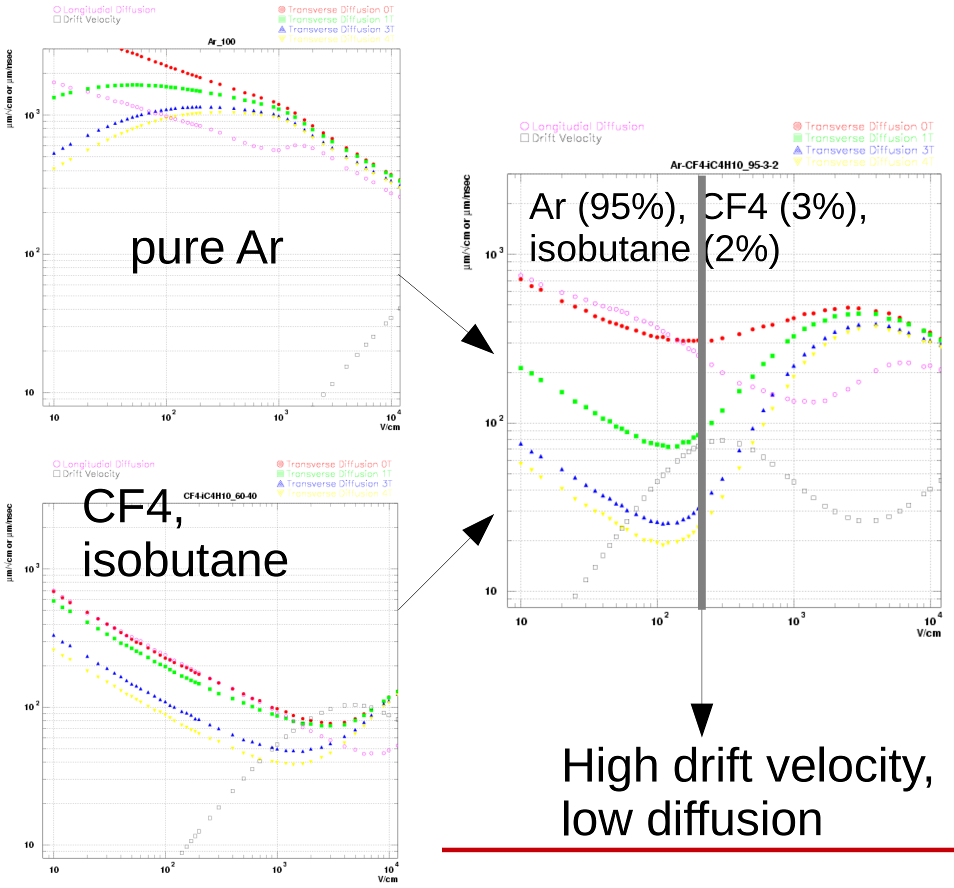
- Maximise drift field
  - Can be challenging because of very high voltages
  - Can interfere with amplification region (see MPGD later)
- Minimise scattering of ionisation electron
  - Absorb electron momentum: “soft” molecules
  - Use “cooling” gas, with many vibrational modes to absorb momentum
  - CO_2, isobutane, CF_4

Aside: Drift in magnetic field

- If there is a magnetic field parallel to the drift field
  - Common situation in trackers (momentum measurement)
  - The drifting electrons' trajectory will coil around the field lines, reducing the transverse diffusion
  - Longitudinal diffusion and drift velocity are less affected
- If the magnetic field is transverse to the electric field
  - Will always happen at the transition between drift and amplification
  - Trajectories will be distorted (ExB effect)

Drift

- Dependence is not trivial
- Simulations are used to optimise
  - Magboltz (FORTRAN)
    - https://cern.ch/magboltz
    - Velocity, diffusion and attachment
  - Garfield++ (c++)
    - https://gitlab.cern.ch/garfield/garfieldpp
    - Electron transport in electric field



Drift: attachment/capture

- Electronegative molecules can capture electrons
- Most common contaminant: oxygen
  - Few ppm become a problem
- Purify gas to maximize electron “lifetime”
  - Drift distance before ½ of the electrons are captured
- Negative ions will drift slowly
  - Will release their electron near the amplification region
  - Problem only when sensitive to single electron signals

Amplification

- Minimise voltage for amplification
  - Few non-ionising energy loss modes → noble gases
  - Longer free path for electron acceleration → low pressure
- Stability
  - Gas scintillates UV during avalanche
    - Can re-ionise the gas, or extract photoelectrons from metal surfaces
  - Small amount of quencher gas will suppress UV
    - CH_4, CO_2, isobutane (C_4H_{10}), N_2, ...

Penning effect

- First ionisation energy strongly affects amplification
- The introduction of a gas molecule with lower ionisation energy allows for process of the type

$$A^{*}+B\rightarrow A+B^{+*}+e^{-}$$

- Typical example, adding Argon (first ionisation 15eV) to Neon (21eV)
- A very small amount (~0.1%) can make a big difference

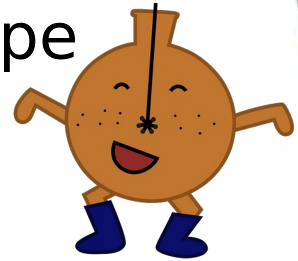
Other concerns with gas choice

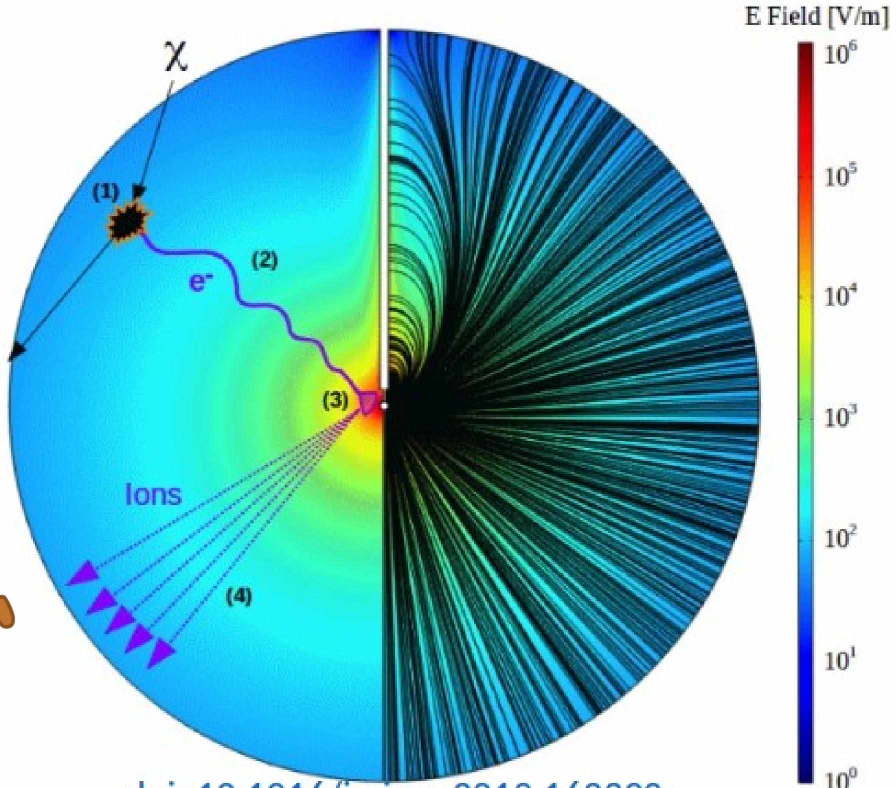
- Cost
  - Argon is common and cheap (~1% in air)
  - Neon is expensive, xenon very expensive
- Safety
  - Toxicity, flammability, pressure
- Environmental impact
  - Greenhouse gases
  - e.g. CF_4 is 6,500 stronger than CO_2
  - Gases recycling

Examples of detectors

Spherical Proportional Counter

- A radial field get stronger close to the center ($1/r^2$)
  - Small ball at center of a sphere
- Challenge: support for the ball messes up the field
- Limitation: sphere shape is not very flexible

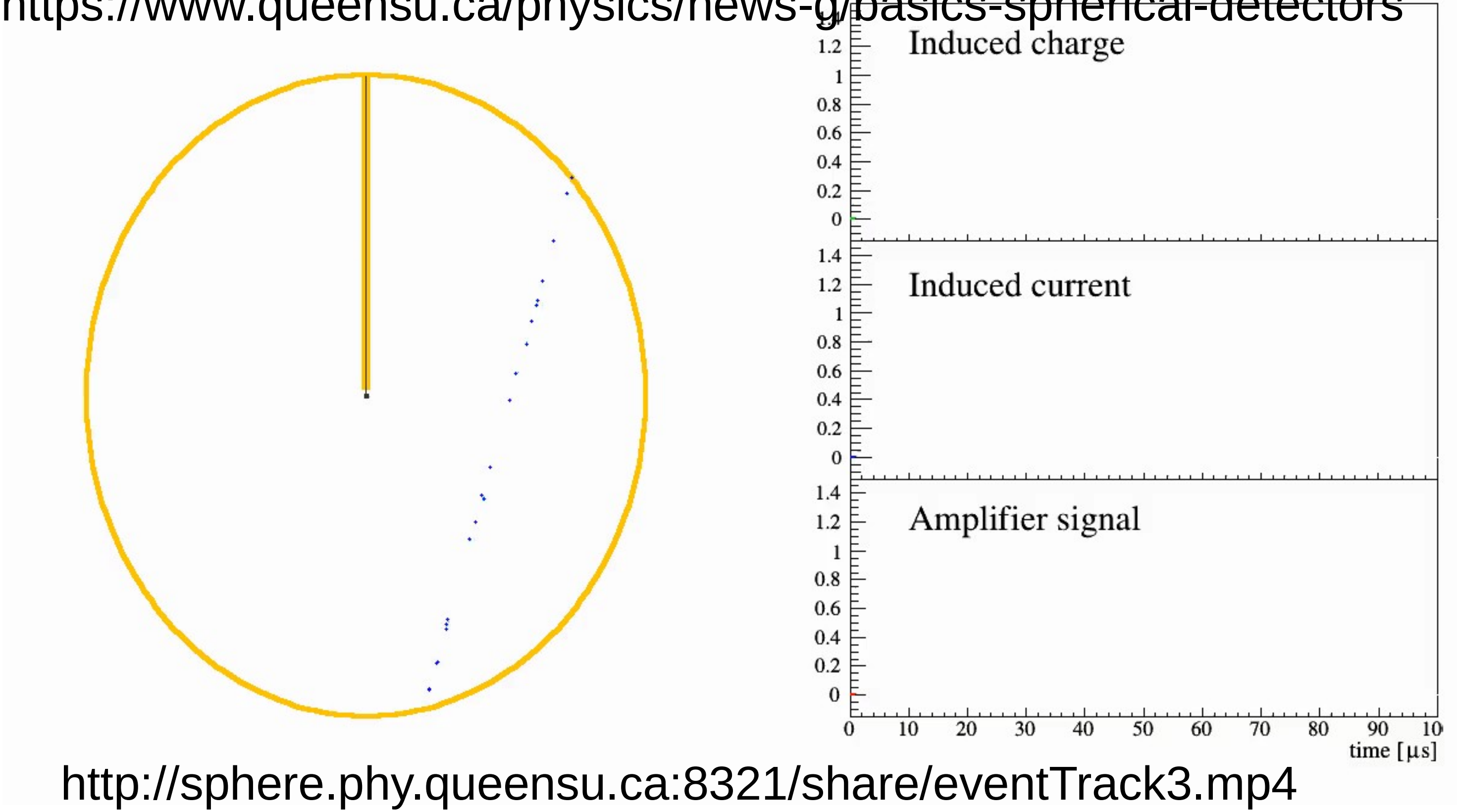




doi: 10.1016/j.nima.2019.162390

SPC

https://www.queensu.ca/physics/news-g/basics-spherical-detectors



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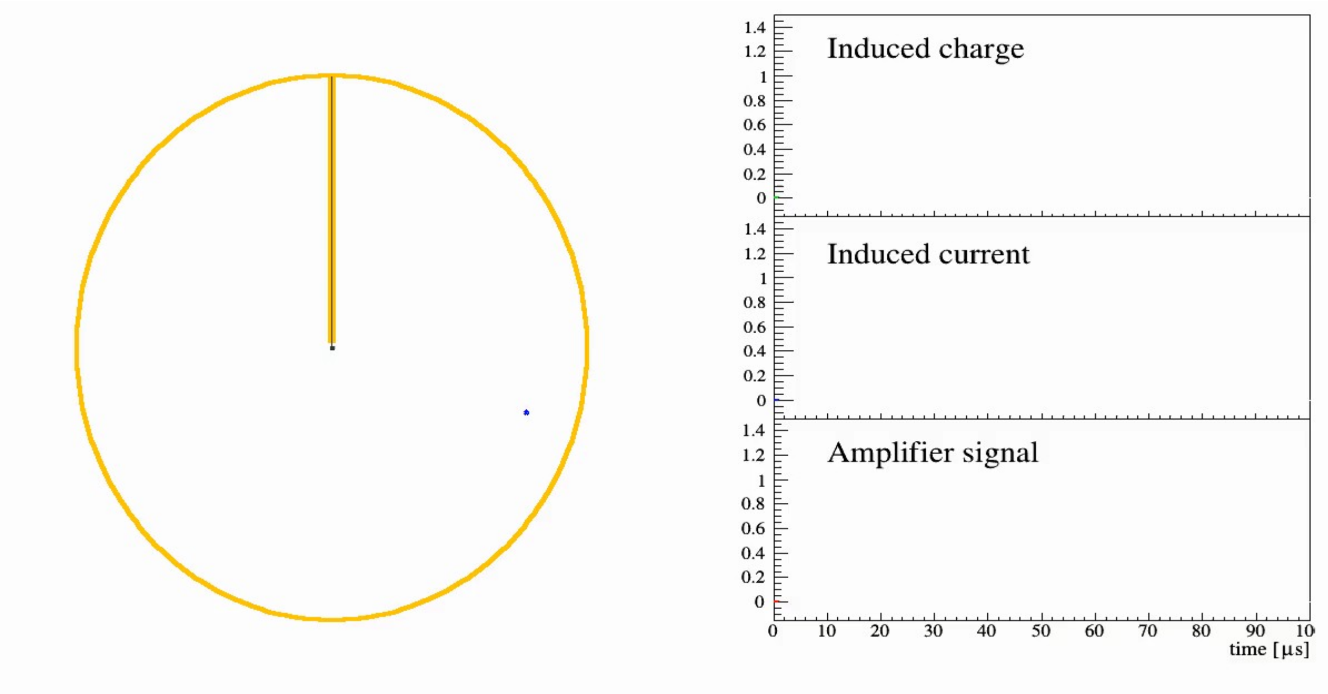

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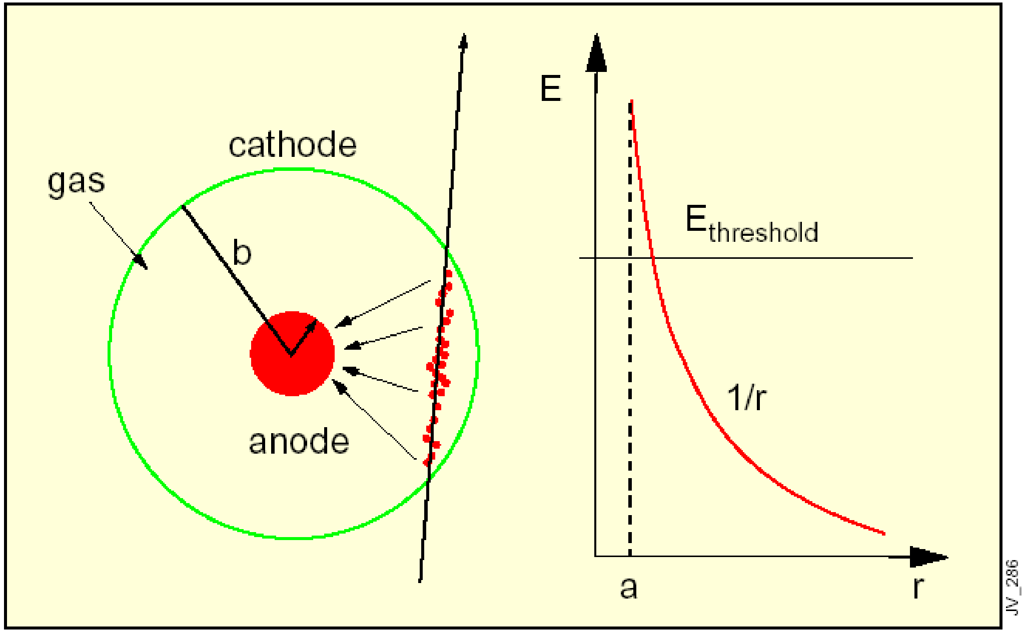
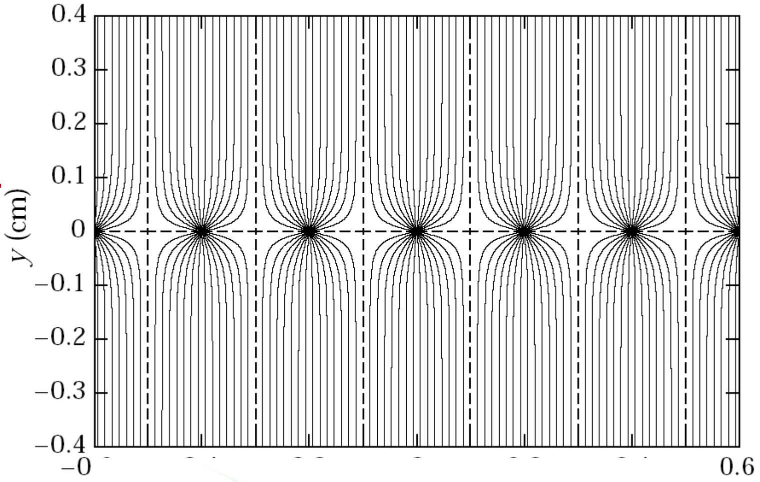
Wire chamber

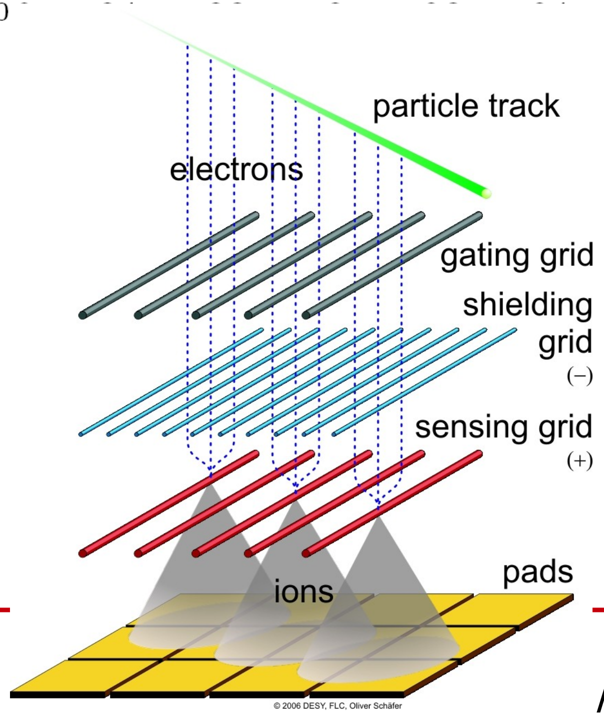
- Thin wire in a cylinder
- Field in 1/r
- Ideal field away for support at the end of the wires
- Tubes can be long, can be stacked
- Challenge:
  - very thin straight and smooth wire
  - vibrations



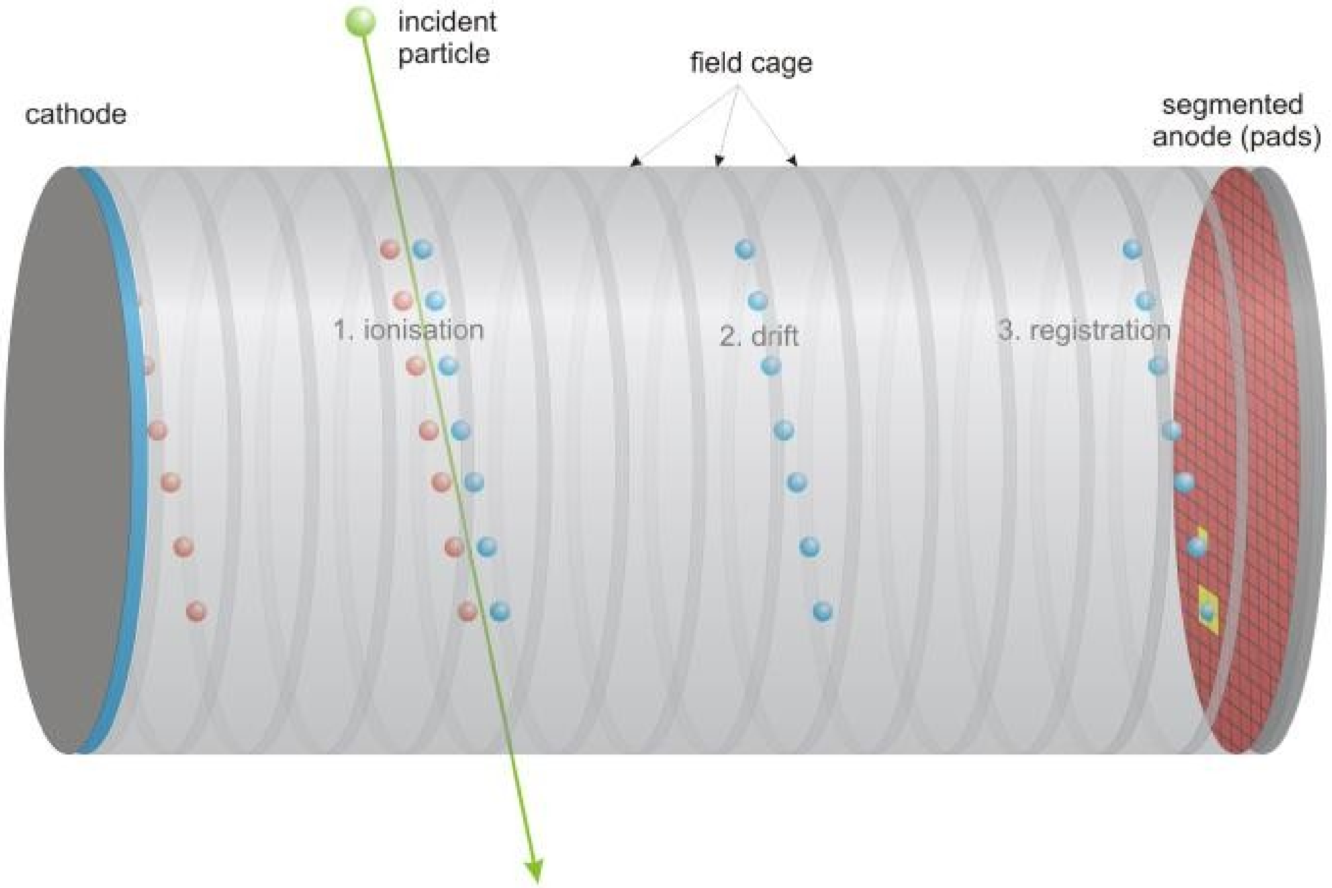
MWPC and TPC

- Multi Wire Proportional Counter
  - Array of wires
  - Spatial information
  - Uniform field away from the wires
- Time Projection Chamber
  - Include a large drift volume
  - Use drift time to reconstruct drift distance
  - 3D reconstruction possible with 2D readout plane





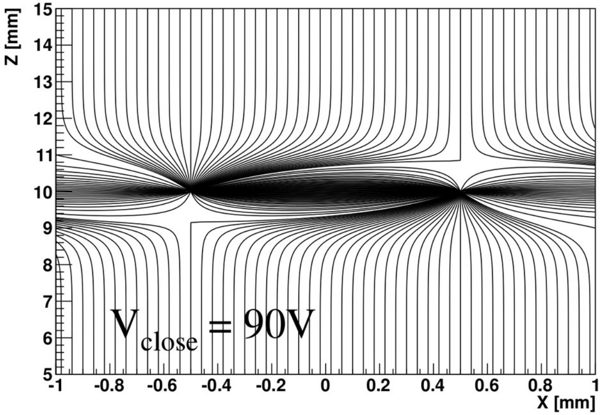
TPC



incident
particle
field cage
cathode
segmented
anode (pads)
1. ionisation
2. drift
3. registration

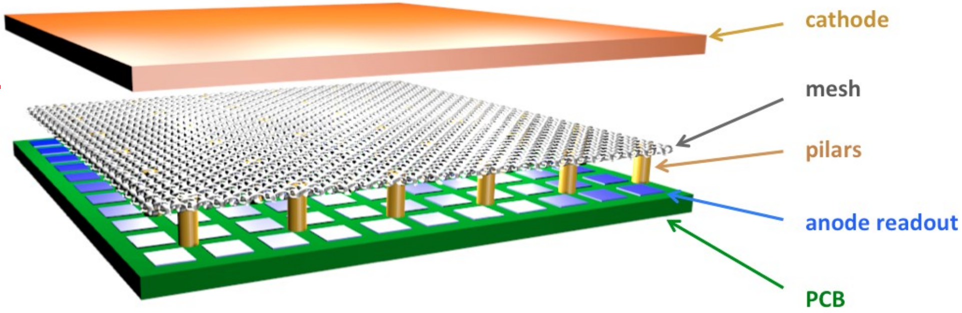
Ion back flow

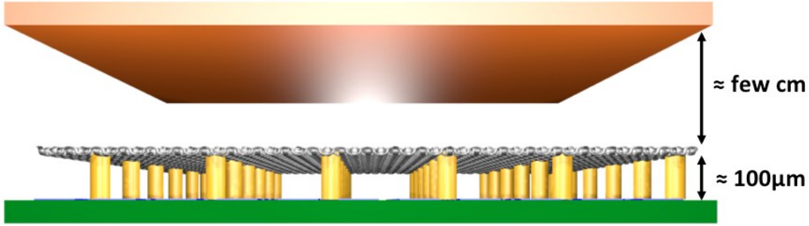
- Many positive ions created in avalanche
  - move ~1000 times slower than electrons
- Drift back into field volume
  - distort field
  - can capture electrons
- Can be stopped with “gate”
  - open during detector readout (wire potential matching drift field)
  - closed until ions neutralised (alternated voltages)
  - creates long dead time
- Can be reduced with different amplification structure

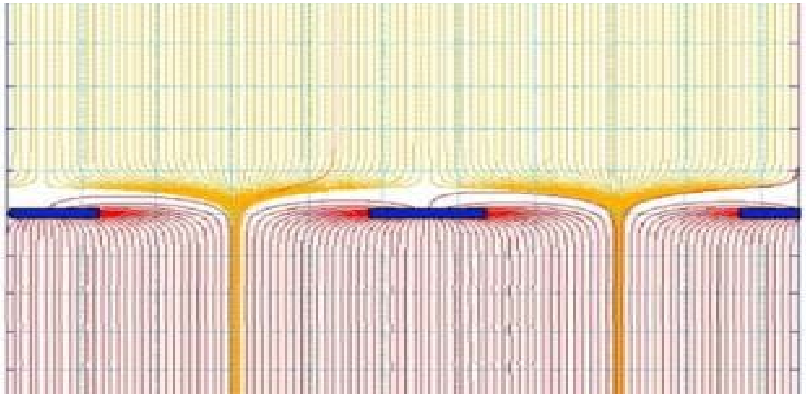


MPGD: Micromegas

- Micromesh Gas amplifier
- Mesh very close to readout plane
  - Almost uniform electric field
  - All electrons collected if drift field much weaker
  - Signal from ion drift
  - Most ions drift back to mesh
- Fairly difficult to manufacture industrially

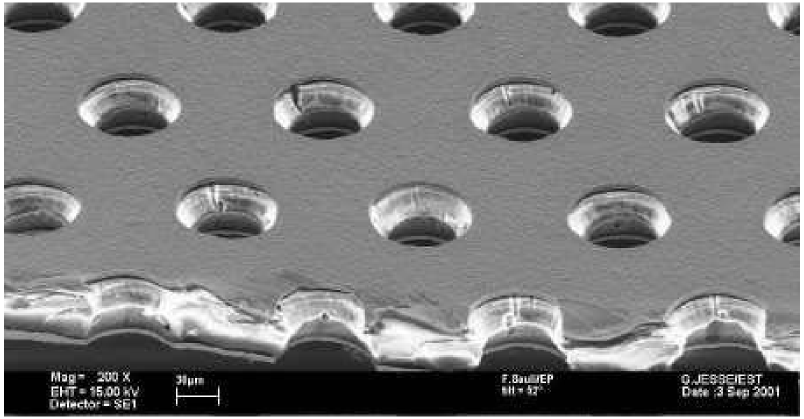


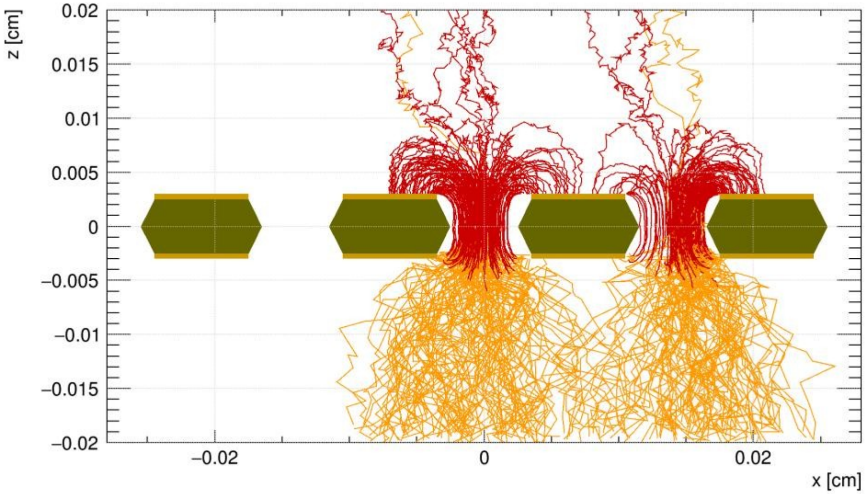




MPGD: GEM

- Gas electron multiplier
- Holes in insulating layer coated with metal on both sides
  - Amplification in hole, field depends on exact geometry
  - Signal from electrons
  - stackable
  - Electron shower spreadout by diffusion in transfer region
- Many manufacturing processes from commercially available materials



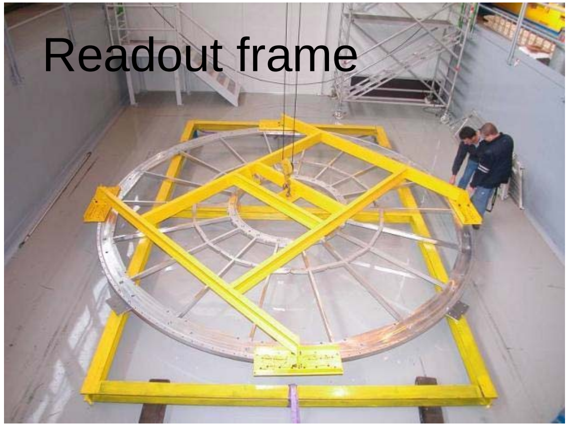


(very biased) Examples of TPCs

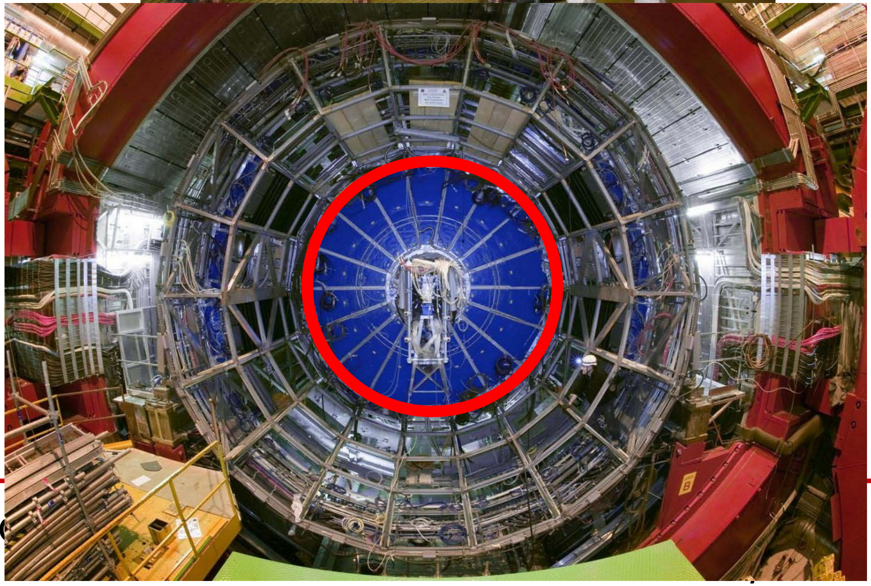
ALICE TPC

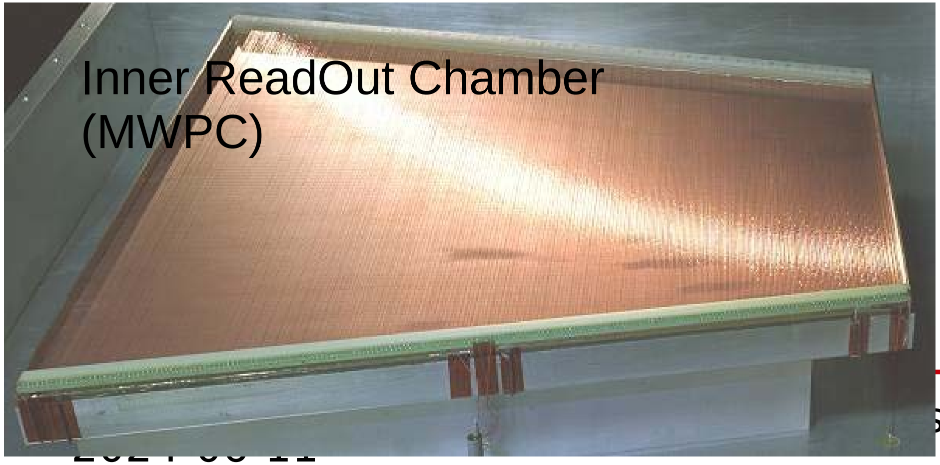
- MWPC readout
- Gating grid to suppress ion backflow
  - Long dead time, compatible with original physics program and beam configuration
- Designed for up to 20,000 track
  - High multiplicity in heavy ion collisions
  - Pile up in pp collisions
- High luminosity upgrade
  - Gating not possible (too much dead time)
  - Sophisticated GEM stack to minimise ion backflow
  - Large field distortions corrected offline

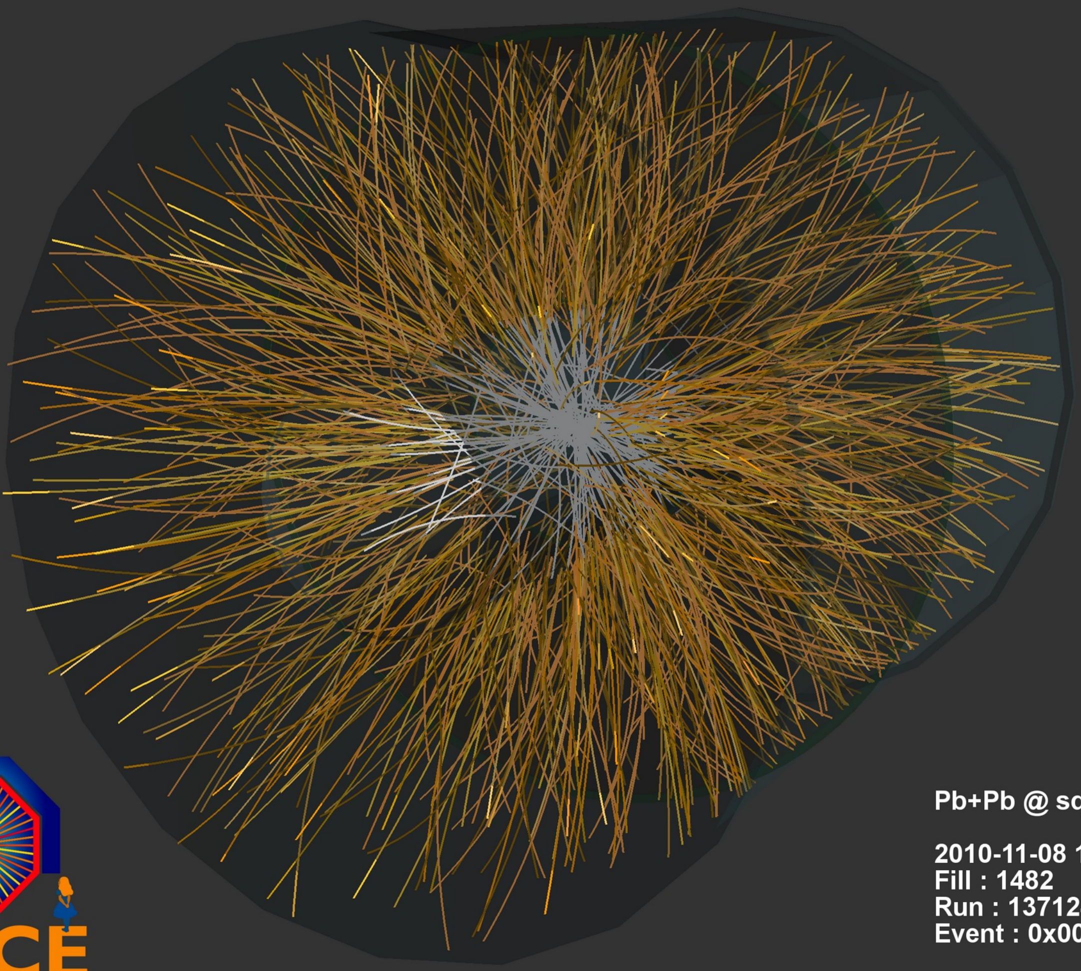
ALICE TPC



- 88m3
- up the 20,000 tracks per event
- 0.5T magnet







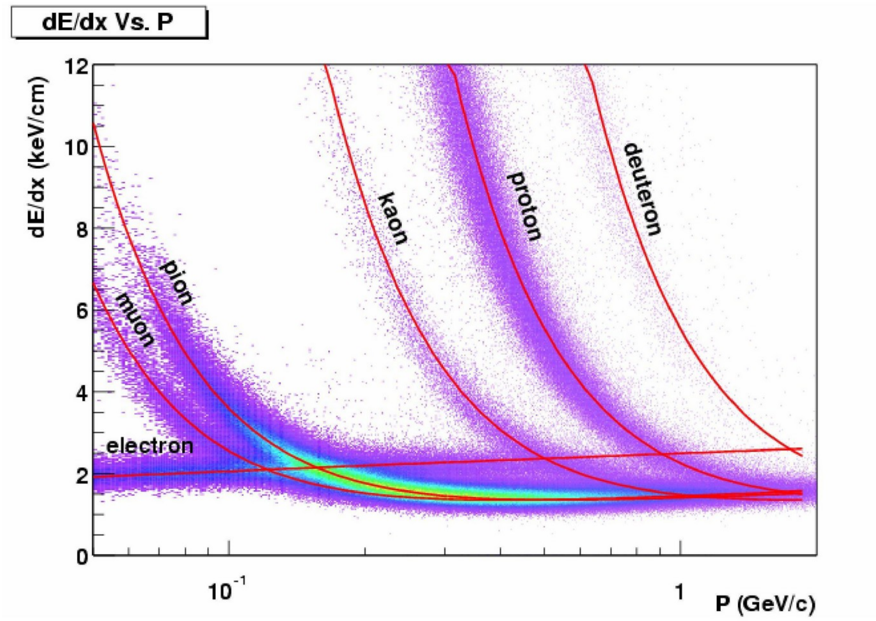
ALICE

Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:36:37
Fill : 1482
Run : 137124
Event : 0x000000009D4C1693

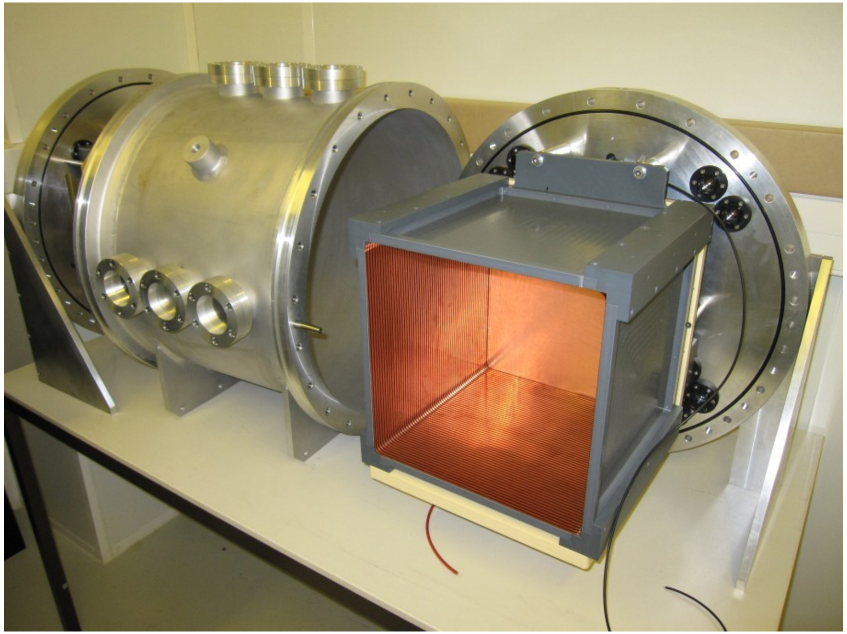
Particle identification in TPC

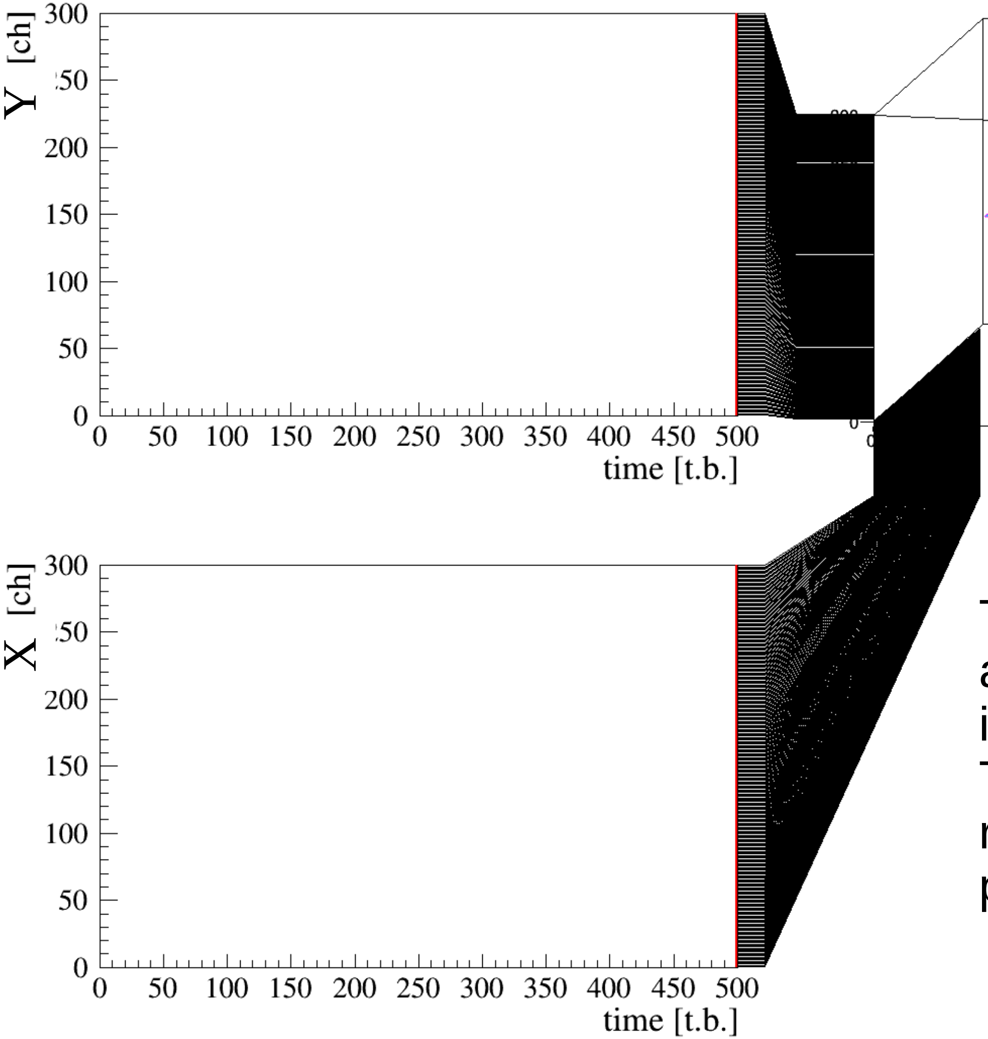
- Magnetic field to measure momentum
- dE/dx depends on velocity
- Separation possible in low momentum region
- Statistical PID in relativistic rise
- No PID in ultrarelativistic plateau

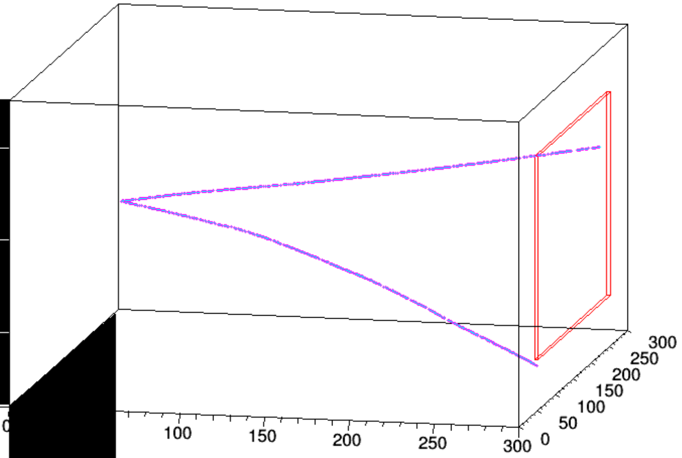


HARPO TPC

- HARPO
- Gamma ray telescope
  - e+e- pair production
  - 1-100MeV
  - sensitive to polarisation
- Tested in gamma ray beam
- Prototype for satellite concept

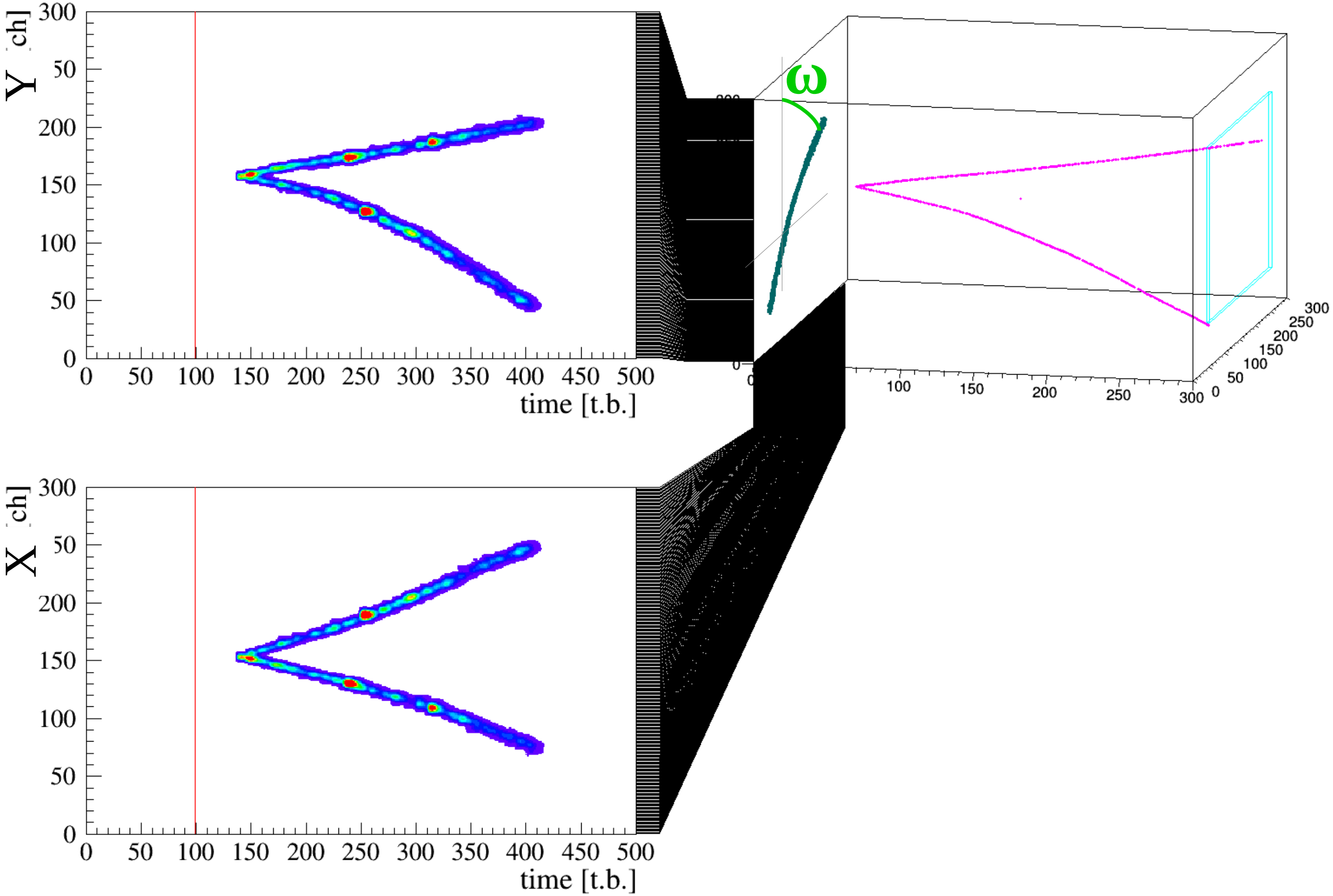






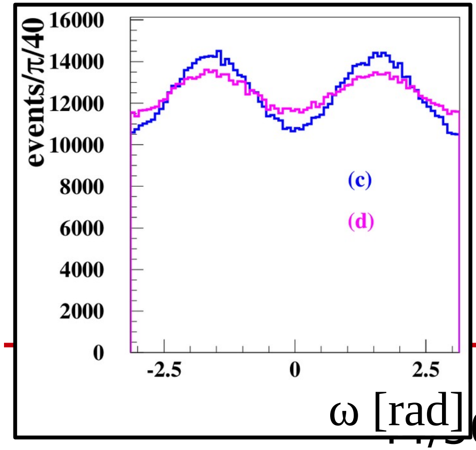
The electrons drift along the electric field in a few microseconds. The are amplified and read out on the readout plane

(very biased) examples of TPC



The azimuthal angle **ω** is related to the polarisation direction

expected distribution



Other Ideas: Optical TPC

- Use scintillation light instead of electrons
  - Potential for primary scintillation detection → prompt signal for drift time measurement
  - Readout with commercial camera → no custom electronics

Other Ideas: Optical TPC

- Use scintillation light instead of electrons
  - Potential for primary scintillation detection → prompt signal for drift time measurement
  - Readout with commercial camera → no custom electronics
- Constraints on gas mixture
  - Quencher normally opaque to scintillation...
  - Wavelength shifting gas (e.g. CF_4)
- Usually slower (long exposure)
  - Good for low BG experiments (e.g. CYGNO)

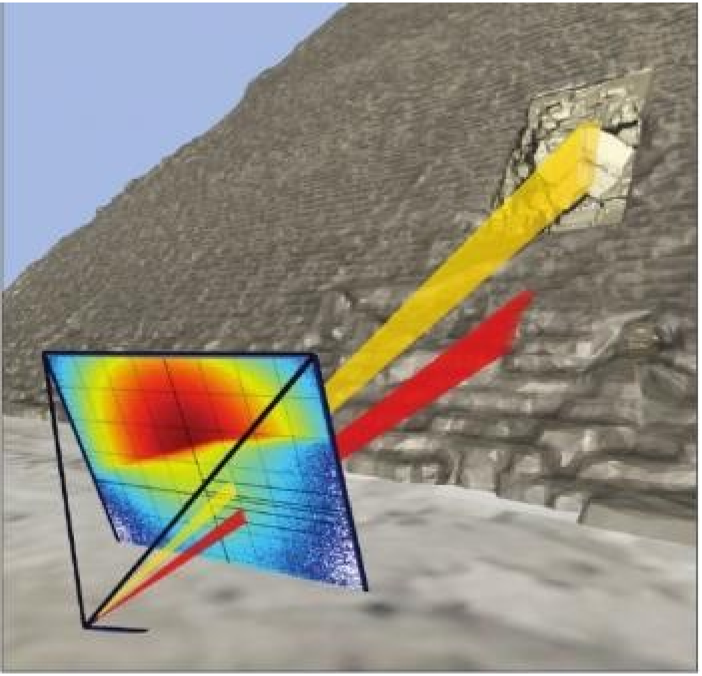
Other ideas: Negative ion TPC

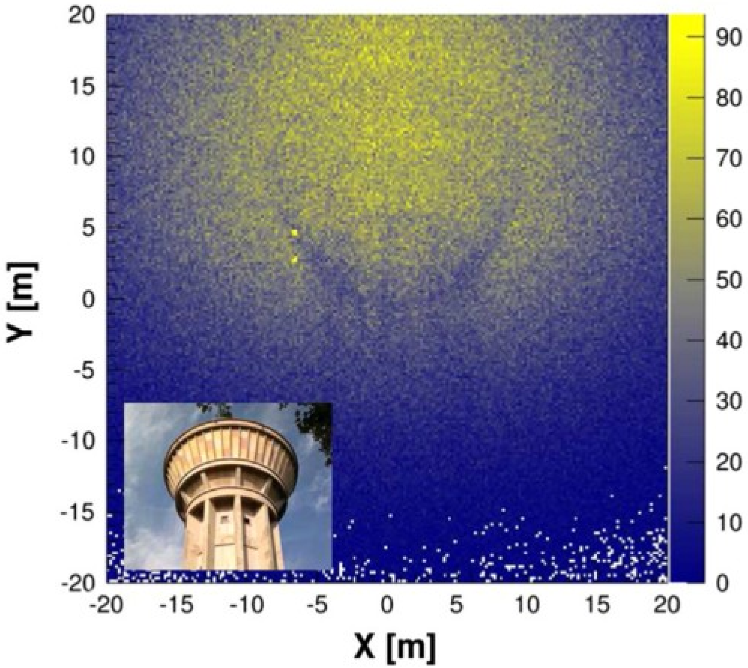
- Idea: use ion drift instead of electron
  - Slower, less diffusion
  - Capture is a feature, not a bug
  - Ion drift velocity is tricky due to electron exchange between molecules
- Interesting for large volume, low rate
  - e.g. directional dark matter

Cool application: ScanPyramid

- Micromegas as muon tracker
- Resistive layer to spread charge over multiple readout strips
- Multiplexing to reduce number of readout channels (and therefore power consumption)
- Point at pyramid to do an “X-ray” using cosmic muons

Cool application: ScanPyramid





Conclusion

- Gaseous detectors are a old reliable technology
- Particularly interesting for large size detectors (low cost)
- Gas selection can be tricky, but also offer flexibility
- New technological developments make the detectors cheaper and more reliable