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DETECTORS – GAS AND LIQUID

Particle Detection in a Gas Detector

- The detection of ionizing radiation generally follows these steps:
  - Electron-ion pair is created in the medium
  - Electrons drift in an electric field to an anode.
  - The electrons are accelerated in the high field around the anode and create more electron-ion pairs, forming an avalanche.
  - The ions created in the avalanche, drift in the electric field to the cathode inducing a signal on the anode wire.

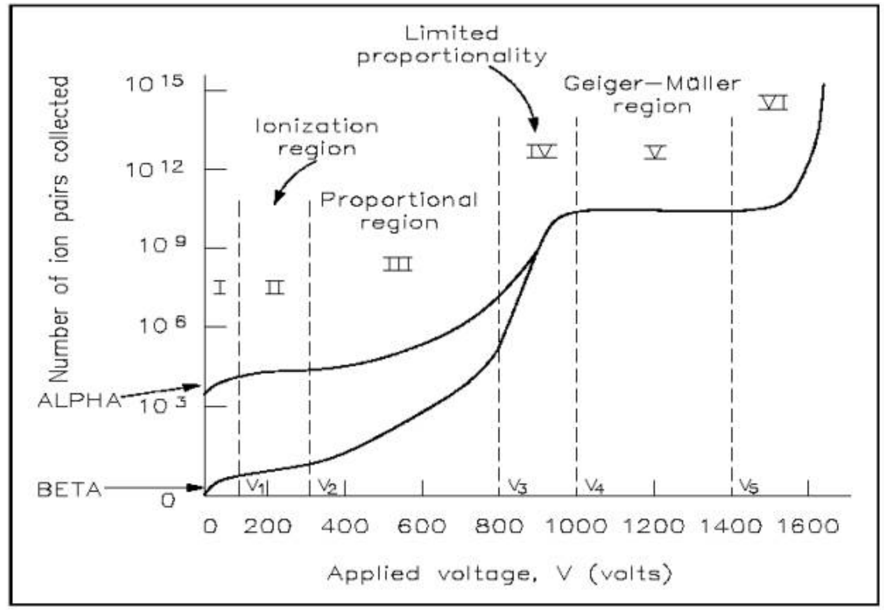
If the electron recombines with the an ion, or is absorbed by an impurity, before it reaches the avalanche region, then it does not contribute to the signal.

The distance that an electron can travel before absorption is the path length.

The path length is determined by the velocity and the lifetime of the electron in the gas.

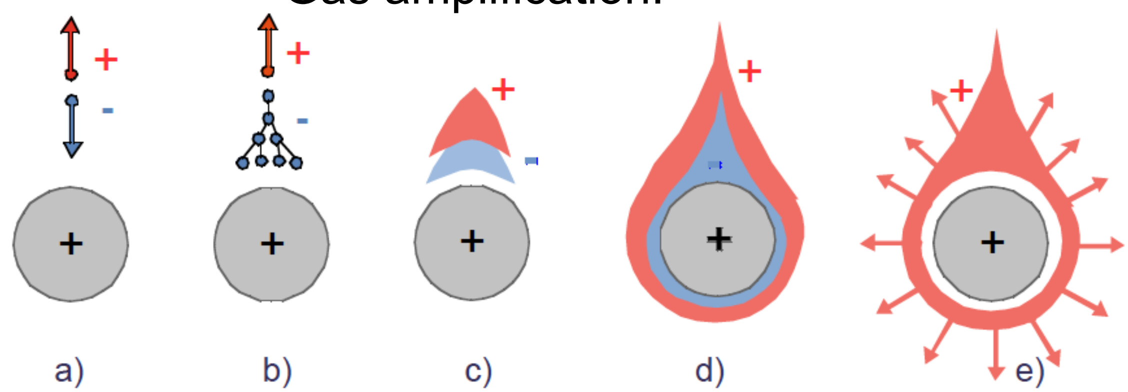
Gas Detectors

- One of the most common detectors operates with gas multiplication.
- Regions of operations.
  - Ionization.
  - Proportional mode
  - Limited proportionality
  - Geiger-Muller region
- Photons are produced in the avalanche process that can spread the avalanche region.



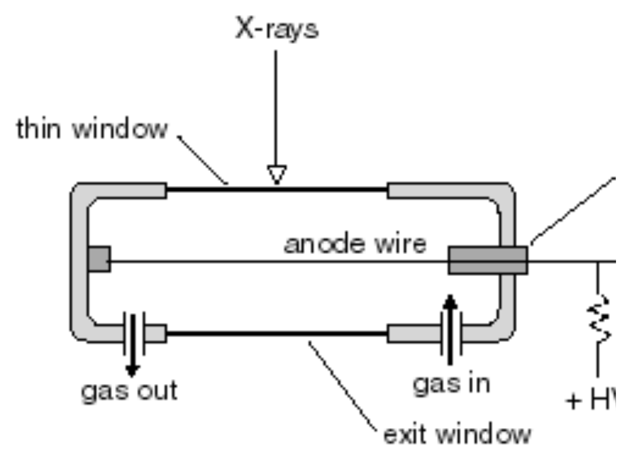
Regions of a gas operation

Gas amplification:



Proportional Tubes

A cylindrical tube with a cathode wire at the center. Electric field high enough to obtain gas gain at the anode wire.



Signal is proportional to the ionization energy in the gas.

Various gasses are used, almost always a mixture of two or more gasses.

Argon with CO_2 is a commonly used gas. It has a high gain and the electron mobility is high.

With any gas detector aging is a concern due to pitting, polymerization etc.

Gas Gain

Approximately 100 electron-ion pairs/cm^2 are created by a mip. To detect this signal efficiently the electric field around the anode wires is used to induce gain

The gain is characterized by the first Townsend coefficient α as:

$$dn = n\alpha dx$$

$$n = n_0 \exp(\alpha x)$$

Giving the gas gain $M = n/n_0$

$$M = \exp\left\{\int_{r_1}^{r_2} \alpha(r)\,dr\right\}$$

E - kV	α	λ
10	~1	1 mm
20	80	125 μm
100	2000	5 μm
200	4000	2.5 μm

D.Futyan

Typical gas gains are $10^4 - 10^6$.

It is the motion of the ions not the electrons that induces the signal at the anode.

Gas Properties

Pure argon is not generally used as argon has an energy level of 11.6 eV can produces continuous discharge in a chamber at gains of ~ 10^3.

Magic Gas was used early on. It consisted of a mixture of Argon (75%) – Isobutane (24%) - Freon (.5%) – Methylal (.5%) and had a gas gain of 10^7.

Improved electronics, safety, environmental concerns, stability of drift velocity etc. lead to choices of gases like Argon-CO_2, Argon-Ethane etc.

As electrons propagate in a gas they can reach velocities of 10^4 m/s. Interactions with the gas atoms cause them to diffuse.

The diffusion is characterized by the diffusion constant *D*, which decreases with pressure and increases with electron energy and temperature. (See Leo)

$$\sigma(x) = \sqrt{2Dt}$$

Electron Loss

After ionization electrons will drift towards to the anode. Ideally you want all of them to reach the anode. Two processes limit this, recombination and attachment.

Recombination:

Electron-ion pairs recombine through electrostatic attraction:

$$X^{+} + e^{-} \rightarrow X + h\nu$$

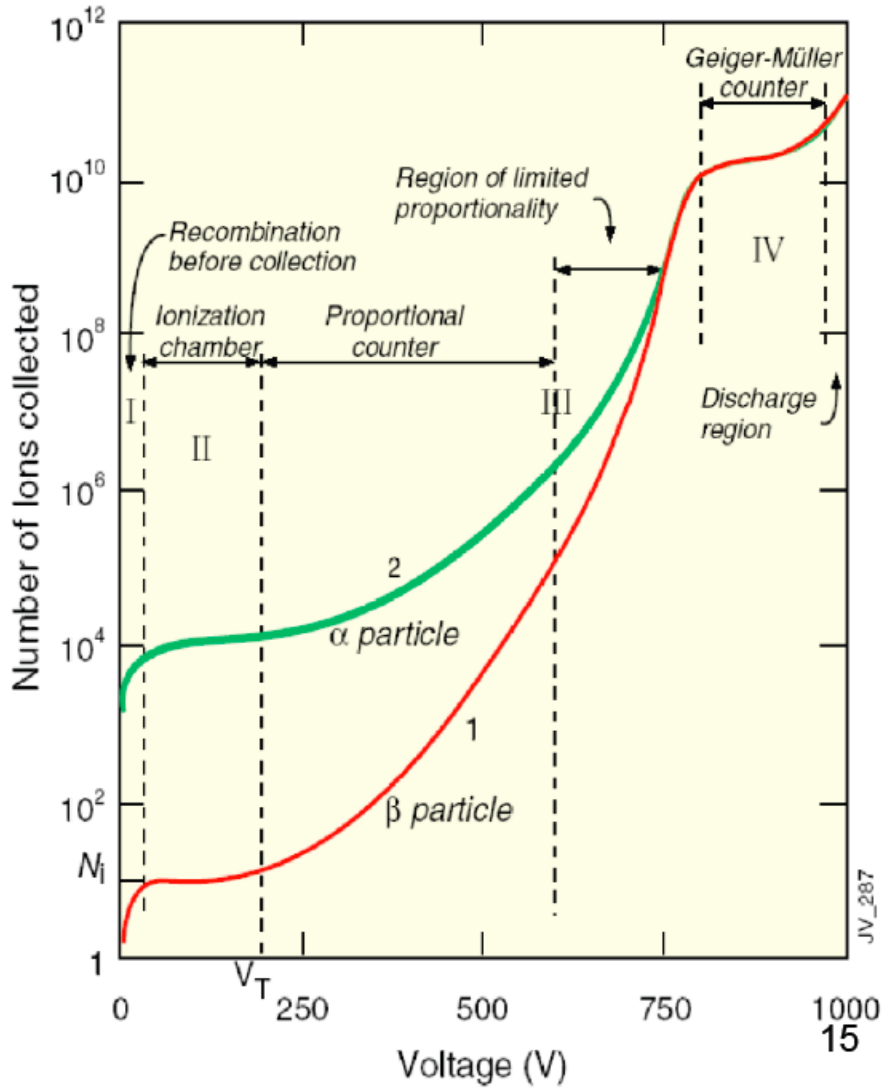
This processes happens in the absence of an electric field and reduces as the *E*-field increases.

Electron Attachment:

Electrons are captured as the propagate within the gas by electro-negative atoms that are impurities in the gas

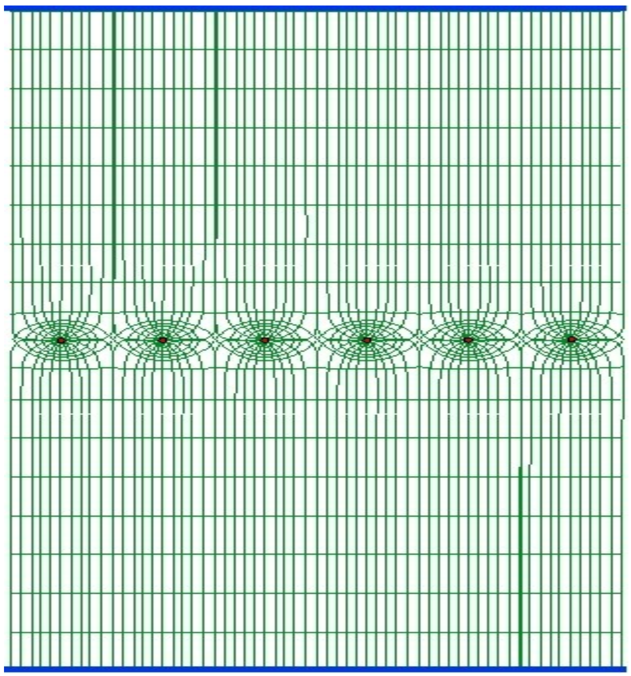
$$X + e^{-} \rightarrow X^{-} + h\nu$$

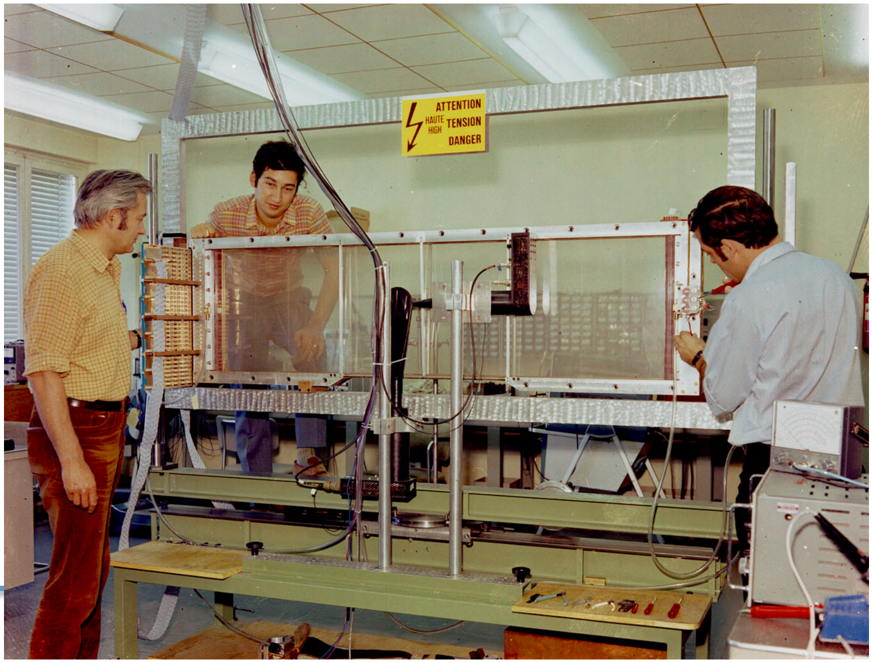
The presence of O_2, H_2O, CO_2 can rapidly reduce the efficnecy of a gas detector.


Geiger-Müller counter
Region of limited proportionality
Recombination before collection
Ionization chamber
Proportional counter
I
II
III
IV
Discharge region
2
α particle
1
β particle
Number of Ions collected
Voltage (V)
V_T
N_i
JV_287
15

Modern Detectors

The invention of the multiwire proportional chamber by Georges Charpak in 1964. Nobel prize in 1992.





The basic idea was to remove the walls of proportional tubes and wind several layers of wires around frames (cathode and anode)

MWPCs

MWPCs were used in many experiments as tracking devices. They were used extensively in fixed target experiments for spectrometers. They were easy to make and the electronics was relatively simple.

The wire used was typically gold plated tungsten wire 15 - 20μm in diameter.

The limitations of MWPCs was the mechanical stability of the anode wires: electrostatic instabilities and sagging due to gravity.

Limiting the wire spacing to about 2 mm giving a resolution of $2/\sqrt{12} = 0.58$ mm.

Information was only in one dimension.

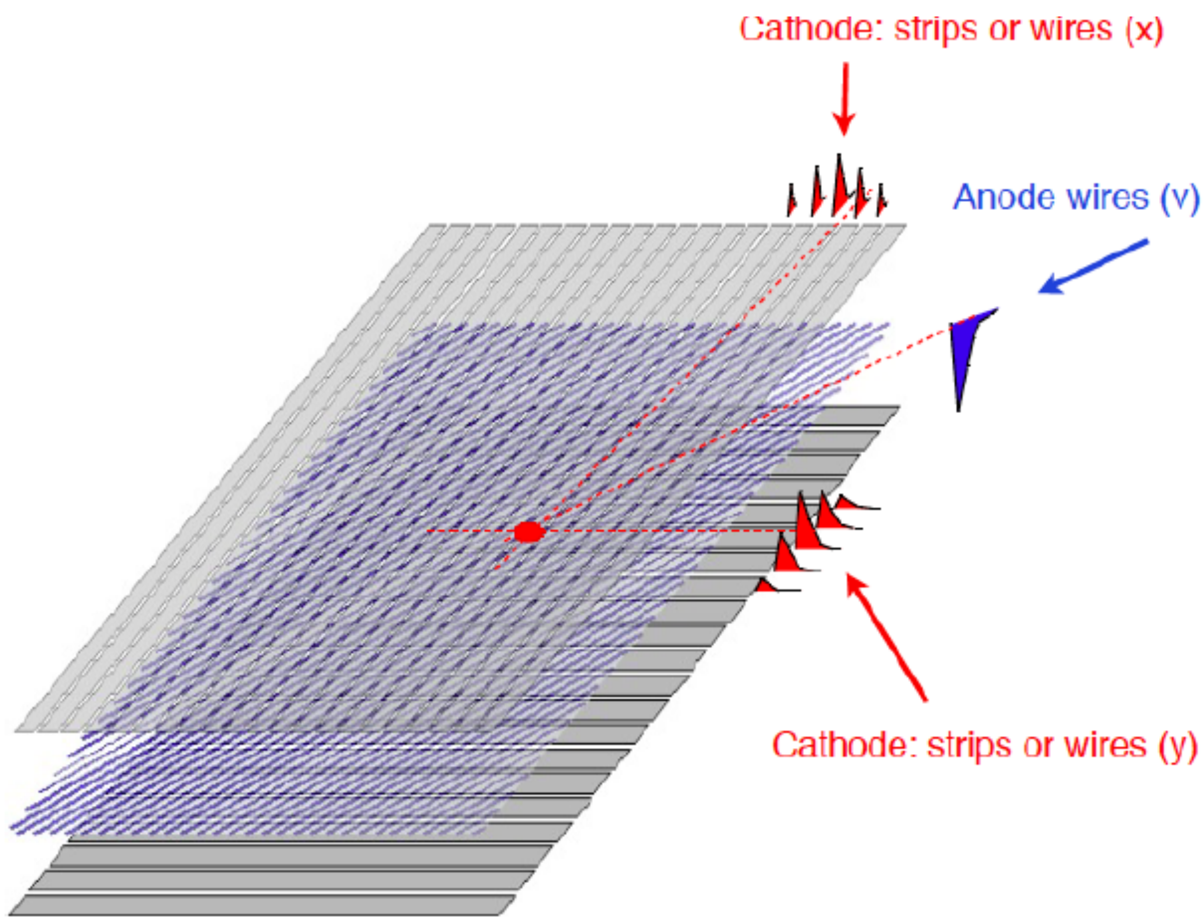
2-D Detectors

- Methods to extract the second dimension from a single plane of a wire chamber were, among others:
  - Charge division.
    - Both ends of the wire are connected to a low impedance amplifier. The anode current measured is $\propto$ 1/R or 1/L.
    - Compare the amplitude of the two signals to get the location of the avalanche.
    - Accurate to .5% of the wire's length were achieved
  - Delay lines.
    - Early technique: magnetostrictive delay lines were used and the arrival time used to obtain the location.
  - Two planes.
  - Readout of the signal induced on the cathode.
    - Cathode Strip Detectors – Used in the endcap muon system of CMS.

Cathode Strip Chambers

A major development was the introduction of cathode strip chamber.

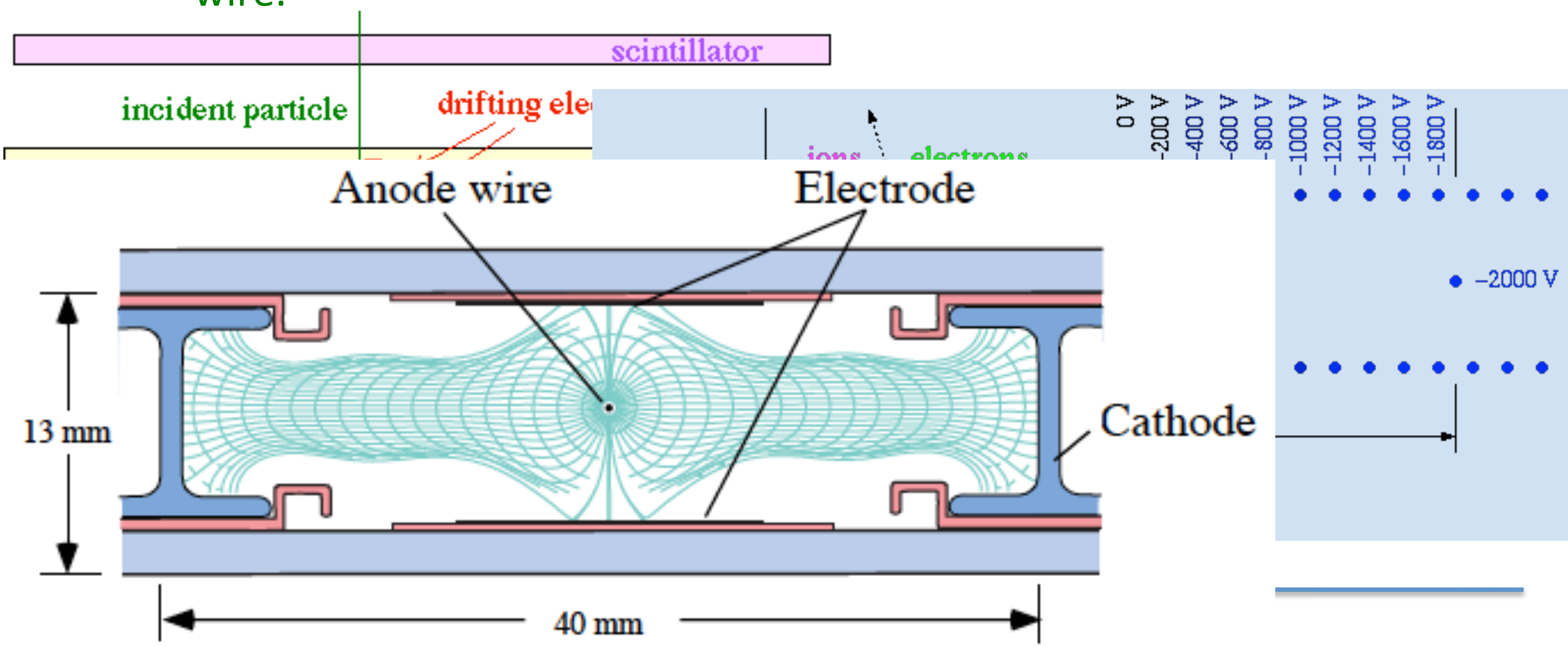
2-D readout was achieved in a single chamber by dividing the cathode into strips orthogonal to the sensor wires.



By measuring the centroid of the induced charge over several strips a resolution of ~50μ could be achieved.

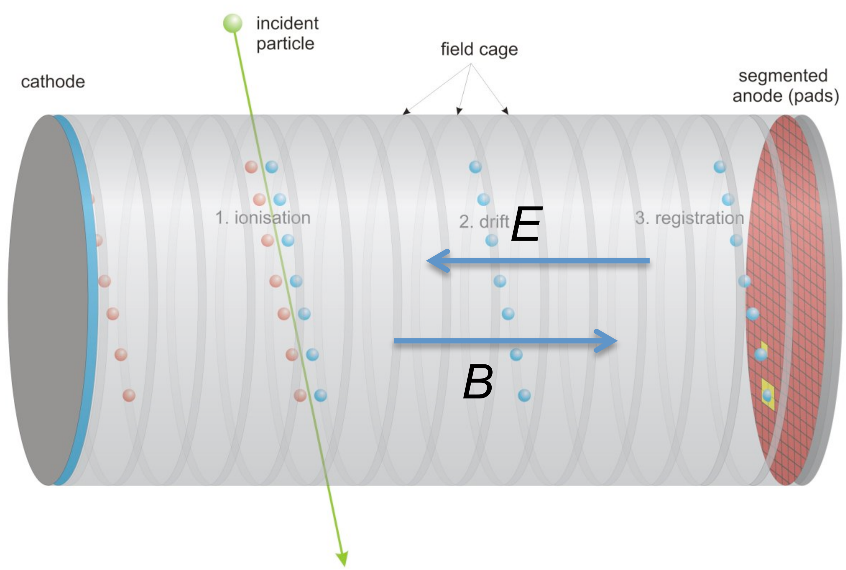
Drift Chambers

- Limitation of CSCs and MWPCs was the number of wires and electronic channels.
- Solution was the drift chamber.
  - Increase spacing between the wires.
  - Create uniform drift field between anode and cathode wires.
  - Measure difference between particle's passage and signal at anode wire.



TPC

- The next major step in the technology of gas detectors was the Time Projection Chamber or TPC.
  - Invented by Dave Nygren in the mid-seventies.
  - 3-D track measurement.
  - Chamber divided into two halves with cathode plane at the center.
  - Parallel electric and magnetic fields limit lateral diffusion of the electrons



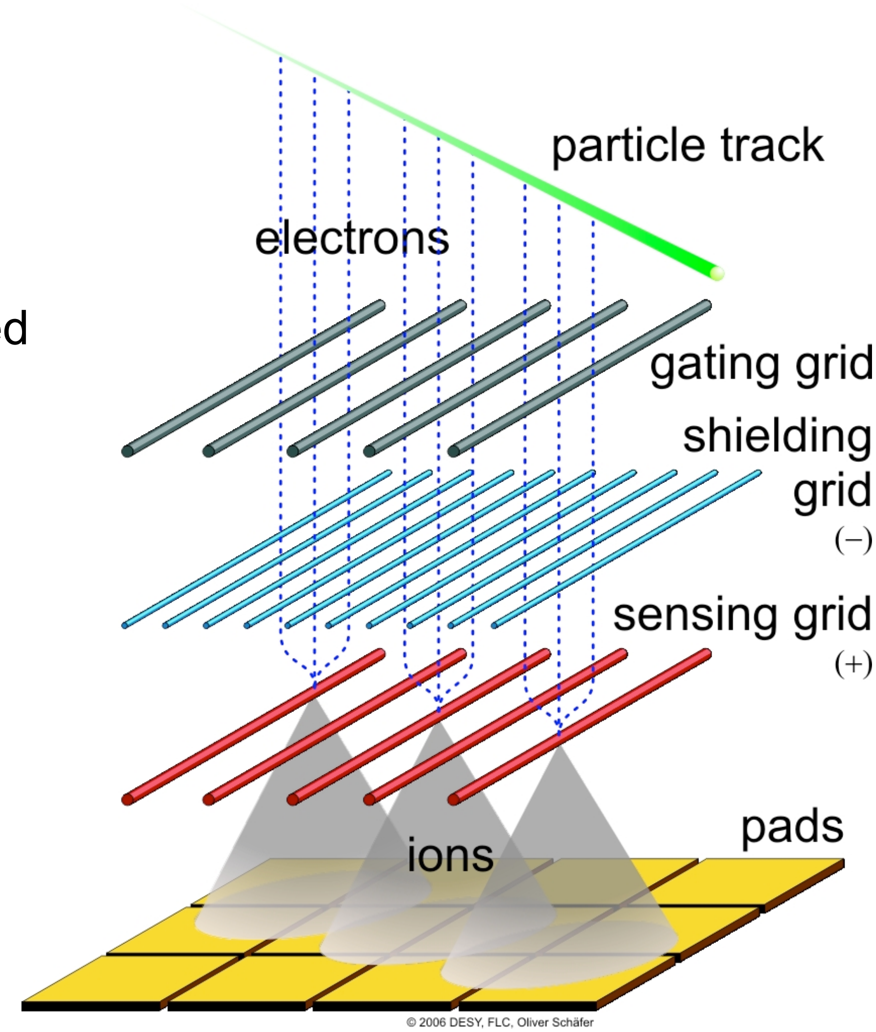
The electrons spiral around the the direction of the B-field. E- and B-fields keep the Lamor radius to ~1 μm.

Time Projection Chamber

Limitations:

- Ion build up in gas volume – fixed by gating grid near to anodes.
- Slow - Electron drift velocities of of 50 – 100 μm/ns → ~40μsec drift time.

Major workhorse in the LEP era



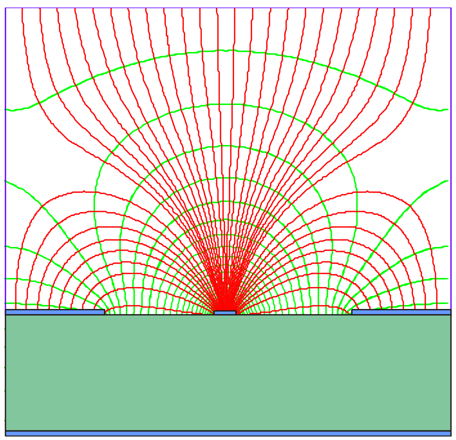
Micro-Pattern Gas Detectors

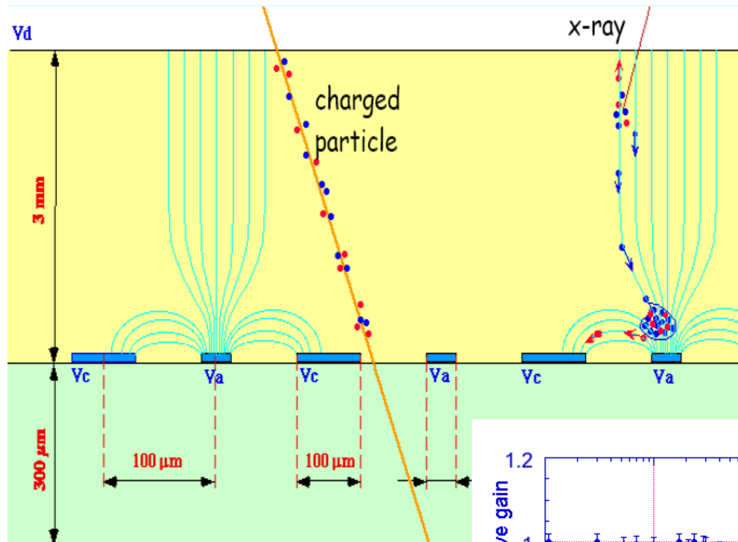
Using large area lithography techniques used in manufacturing of PCBs with feature size of ~ 10 μm it became possible to reach much greater precision than possible in MWPCs.

There has been many different investigations using this technology. I will concentrate on three major areas – MSGCs, Micromegas and GEMs.

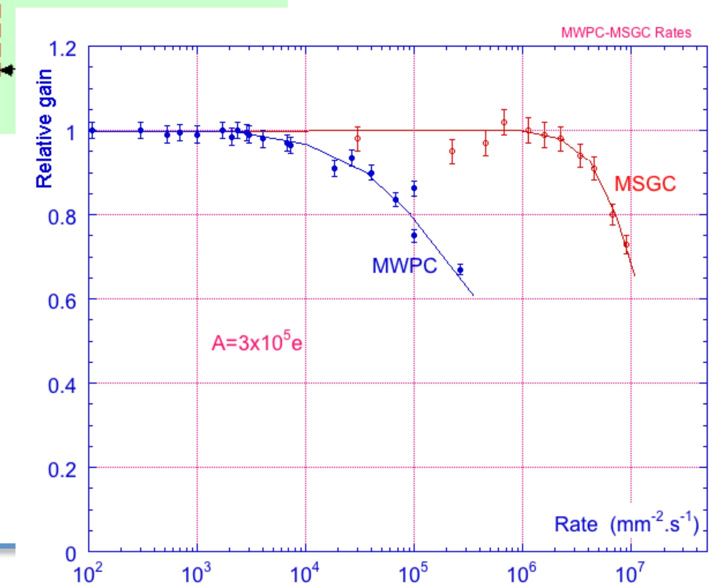
MSGCs

MicroStrip Gas Chambers were one of the first exploitations of the new lithography techniques.





While TPCs were optimal for low-rate environments MSGCs worked well up to rates of 1 MHz/mm^2.



MSGCs

MSGCs do not small diameter wires to achieve the gas gain, instead they use high electric fields inside fields inside small gaps.

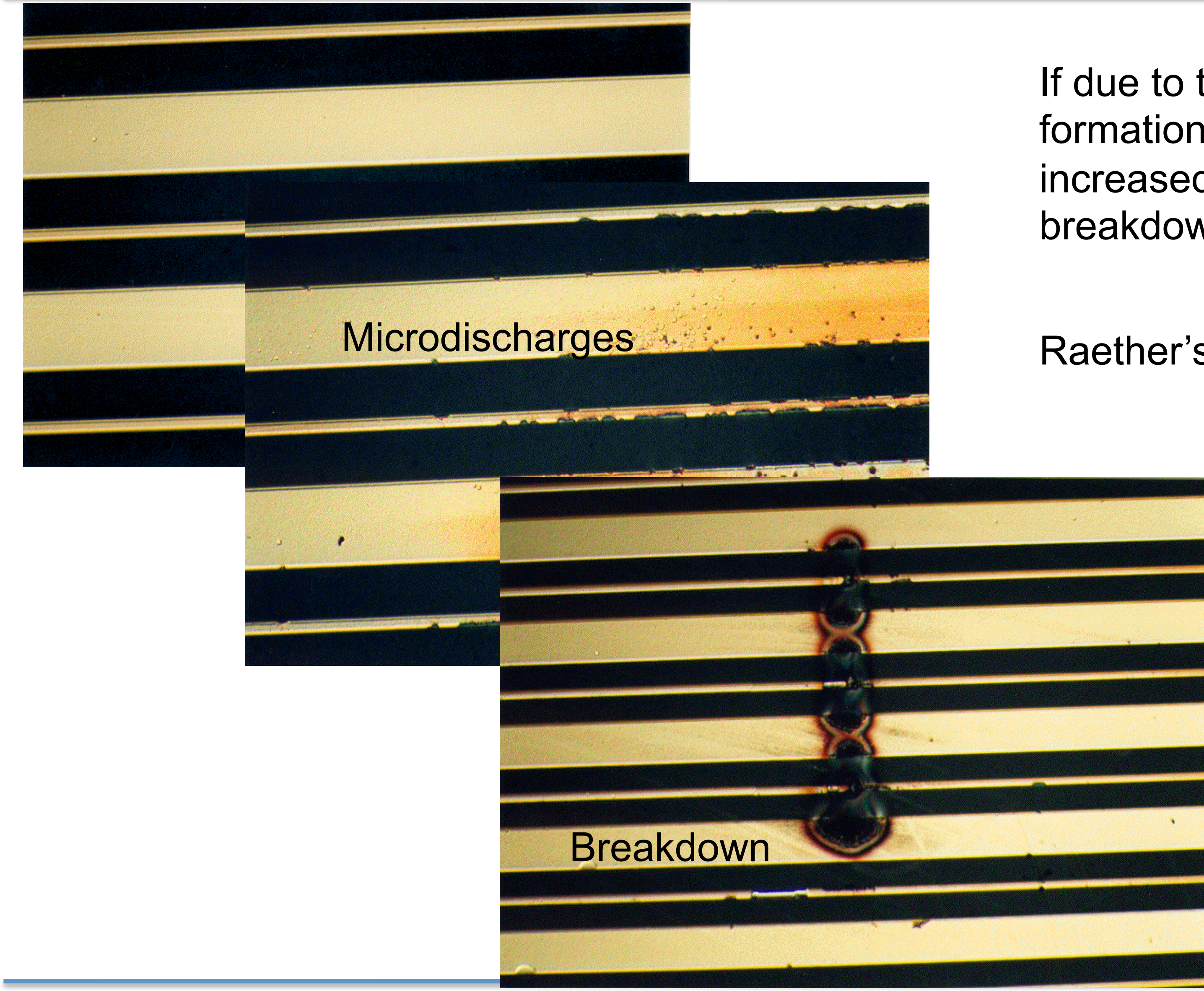
It was observed early on that the gain of MSGCs was limited to 10^4, about a factor of 100 less than typically obtained with MWPCs

At this relatively low gain there was an onset of ‘streamer’ formation.

Streamers occur when photons are generated within the avalanche and they propagate away from the avalanche region, ionize and cause a secondary avalanche to start.

A plasma is setup in the gas that in turn modifies the E-field in the gap increasing the local avalanche gain – eventually a spark is created between the anode and cathode.

Discharge in MSGCs



If due to the plasma formation the gain is increased beyond 10^8 breakdown occurs.

Raether's limit is $M = 10^8$.

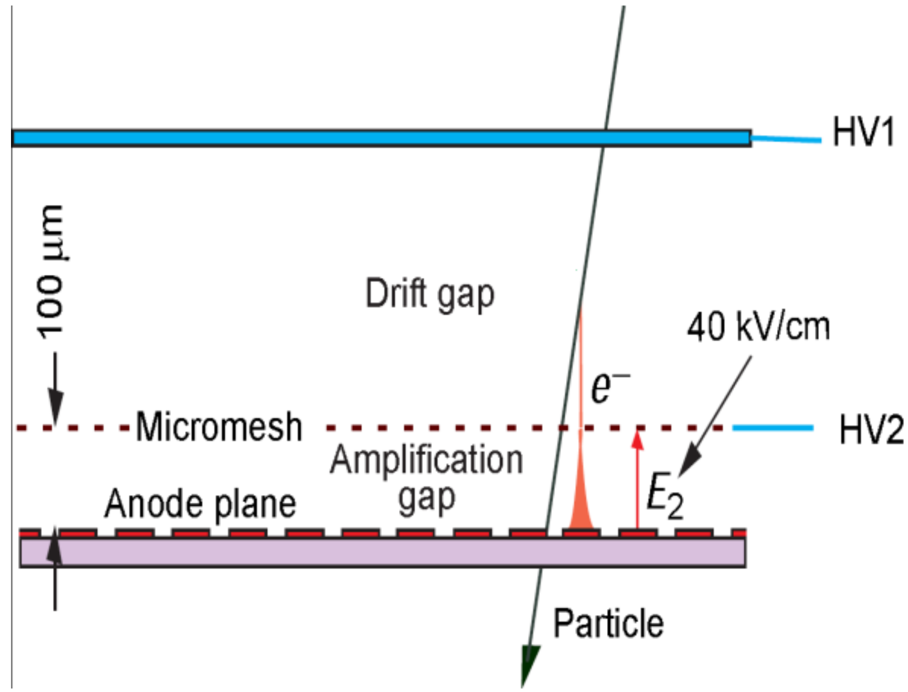
The Next Generation

Two main directions to achieve protected high gain.

Micromegas.

Multi-volume chambers with two regions:

- low field region where the initial ionization occurs
- high field region where gas amplification occurs.



Y. Giomataris et al, NIM A376(1996)29

The Next Generation

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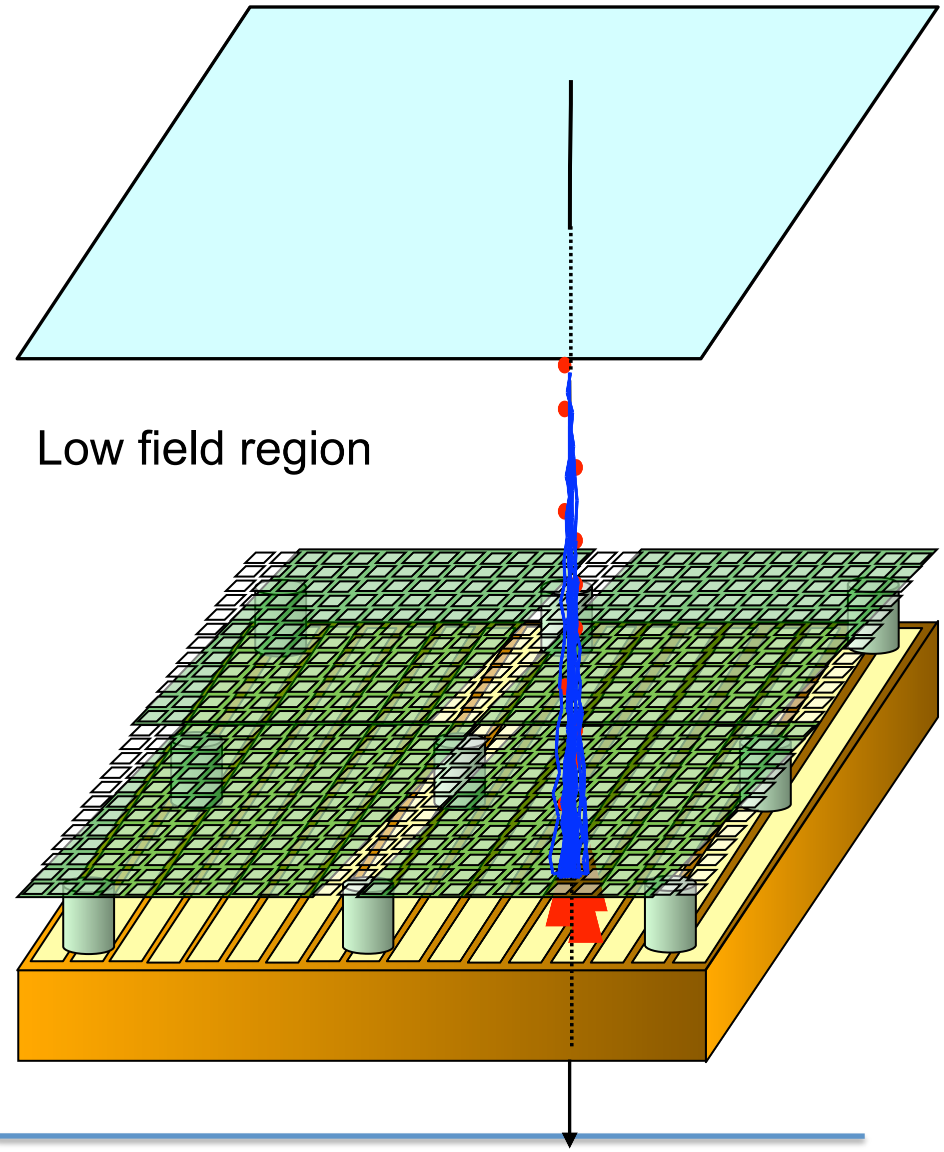
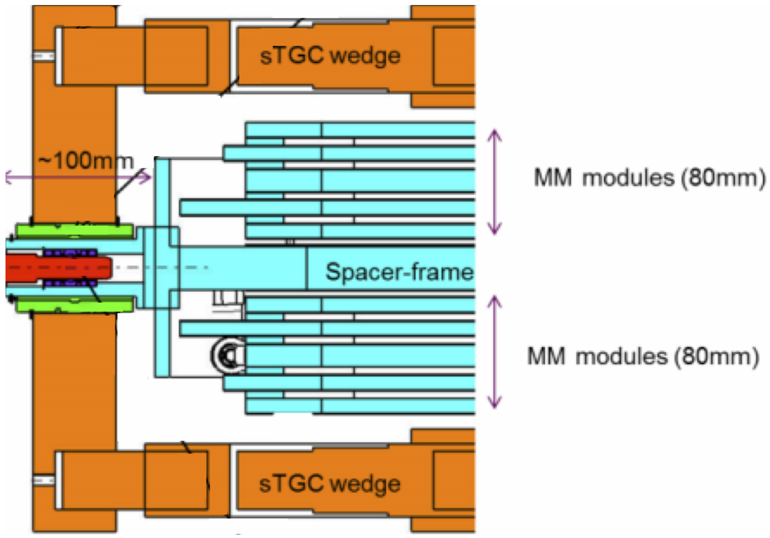
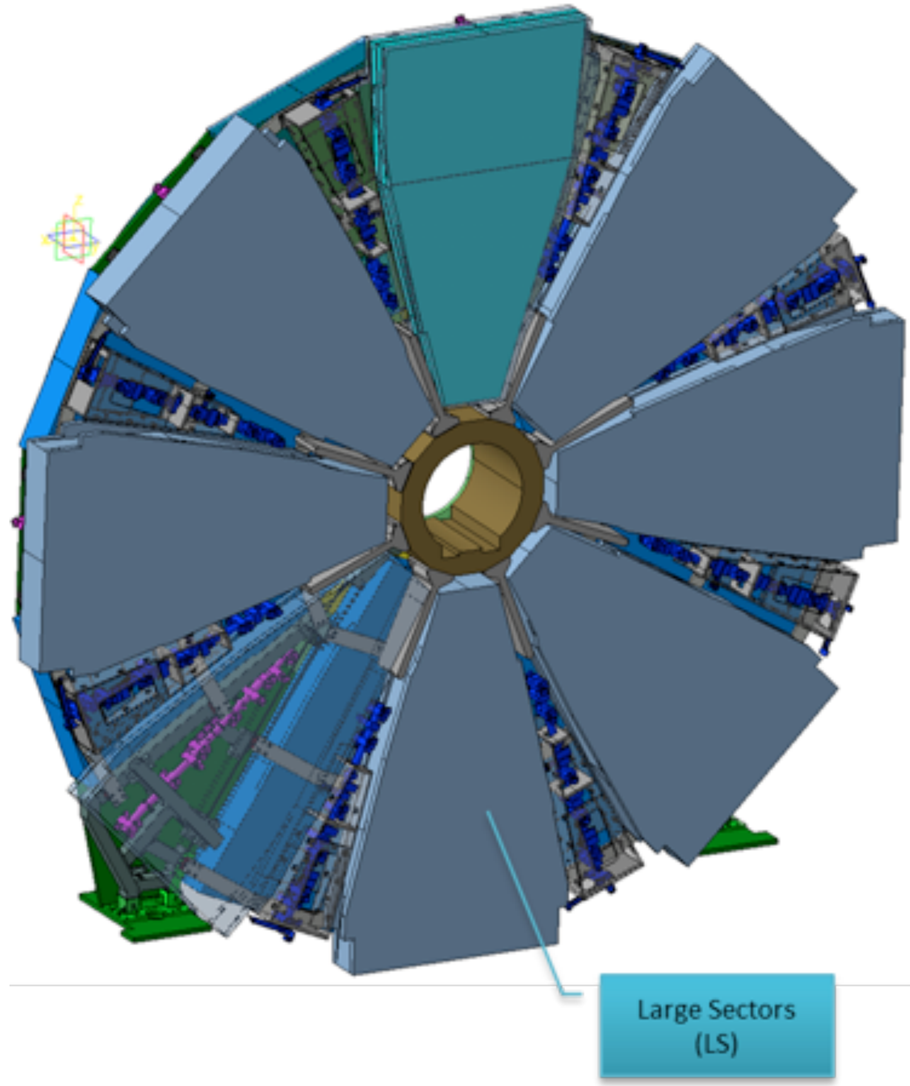


ATLAS New Small Wheel

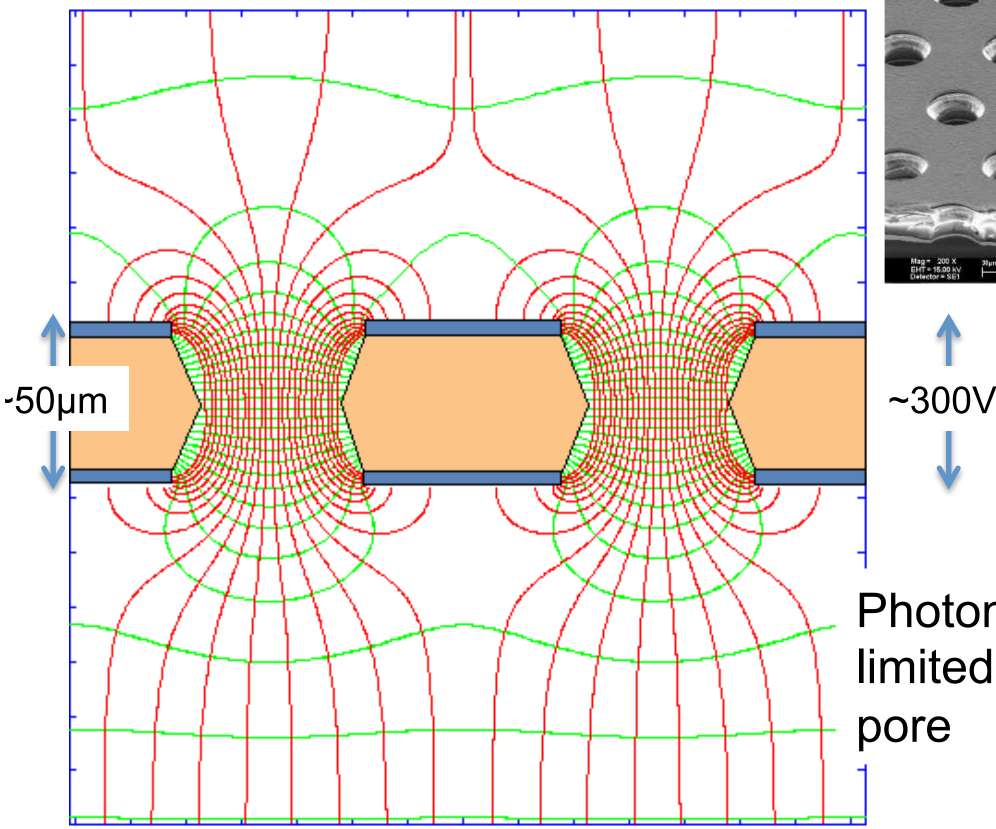


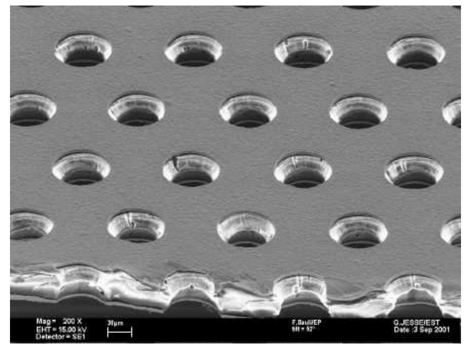
The first major application of micromegas will be the ATLAS New Small Wheel 2,500 m^2 of chambers.



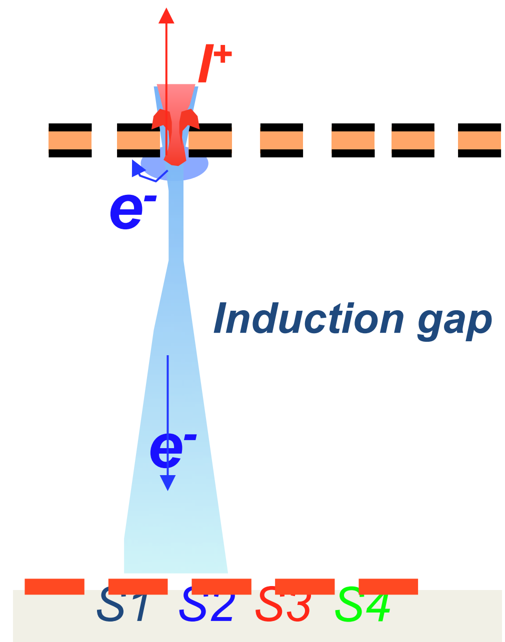
GEMs

Gas Electron Multipliers are similar in concept to Micromegas. Two volumes a drift region and collection region. Gas gain occurs inside micropores of a thin sheet of mylar or FR4.





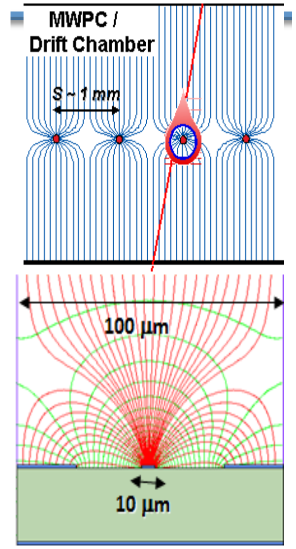
Photon propagation limited to within the pore



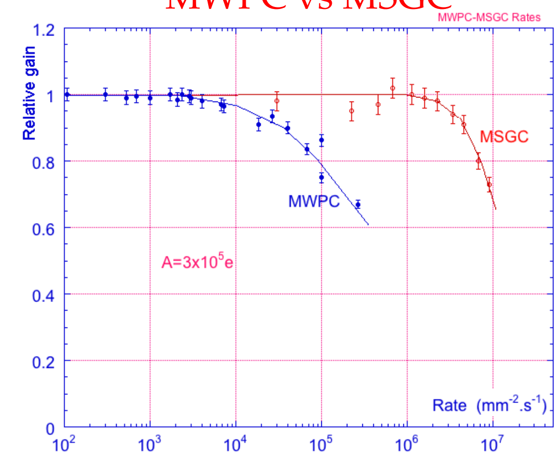
F. Sauli, Nucl. Instr. Meth. A386(1997)531

Variations on the Theme (M. Titov)

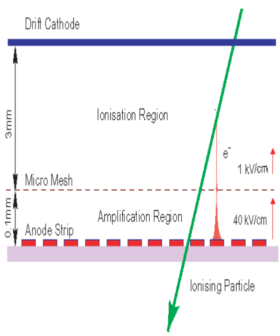
- Micromegas
- GEM
- Thick-GEM, Hole-Type and RETGEM
- MPDG with CMOS pixel ASICs ("InGrid")
- Micro-Pixel Chamber (mPIC)



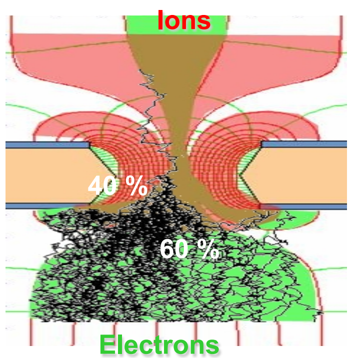
Rate Capability:
MWPC vs MSGC



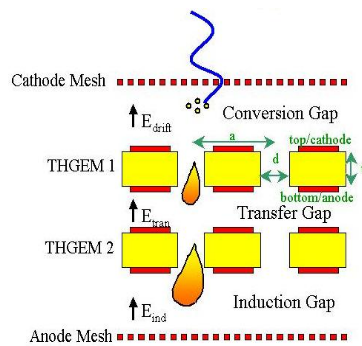
Micromegas



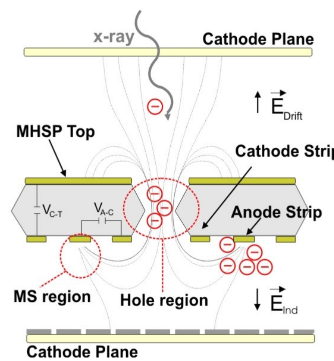
GEM



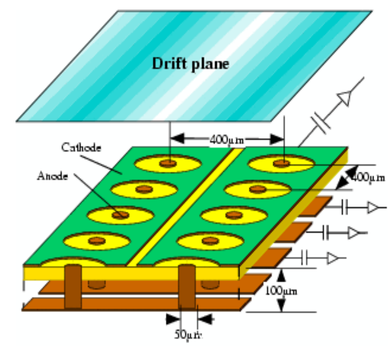
THGEM

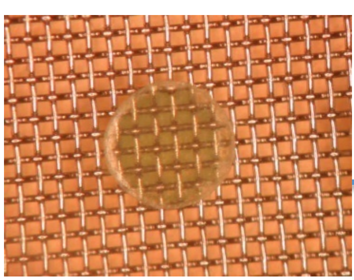


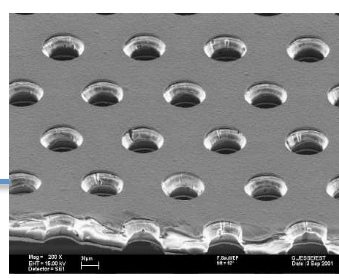
MHSP

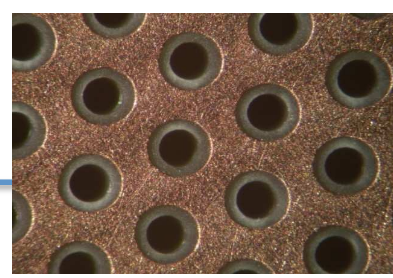


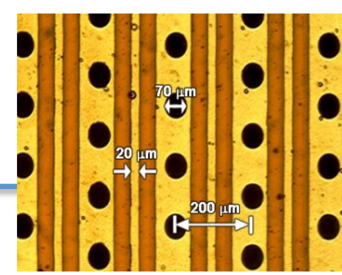
mPIC

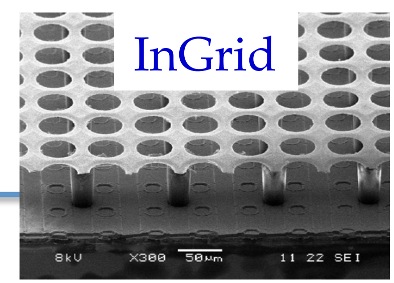




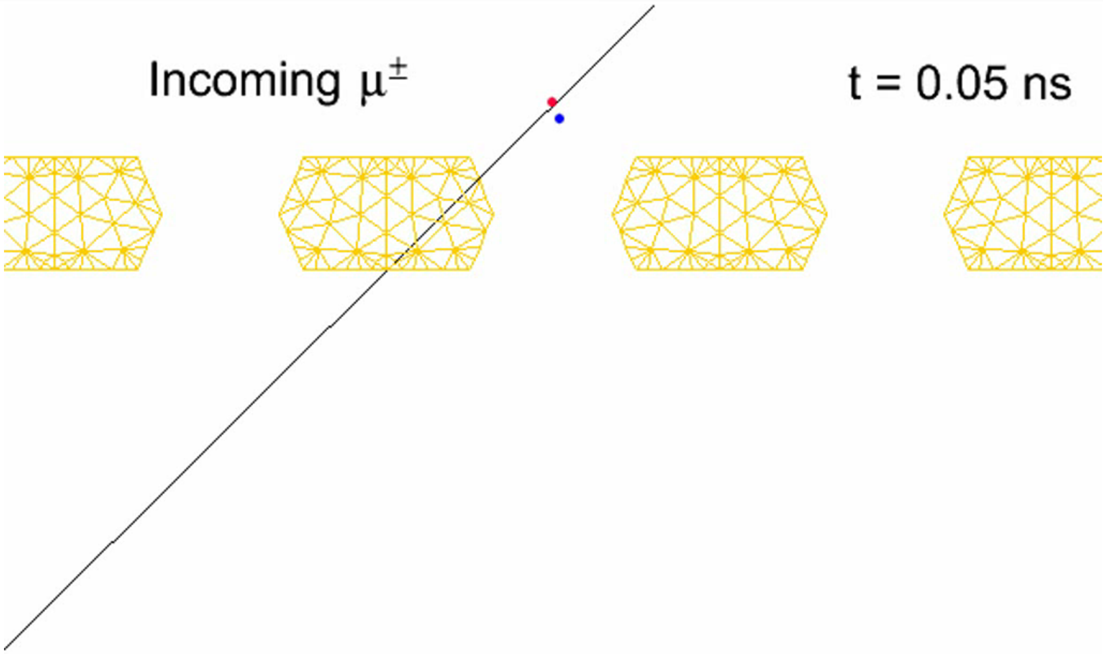








GEM simulation

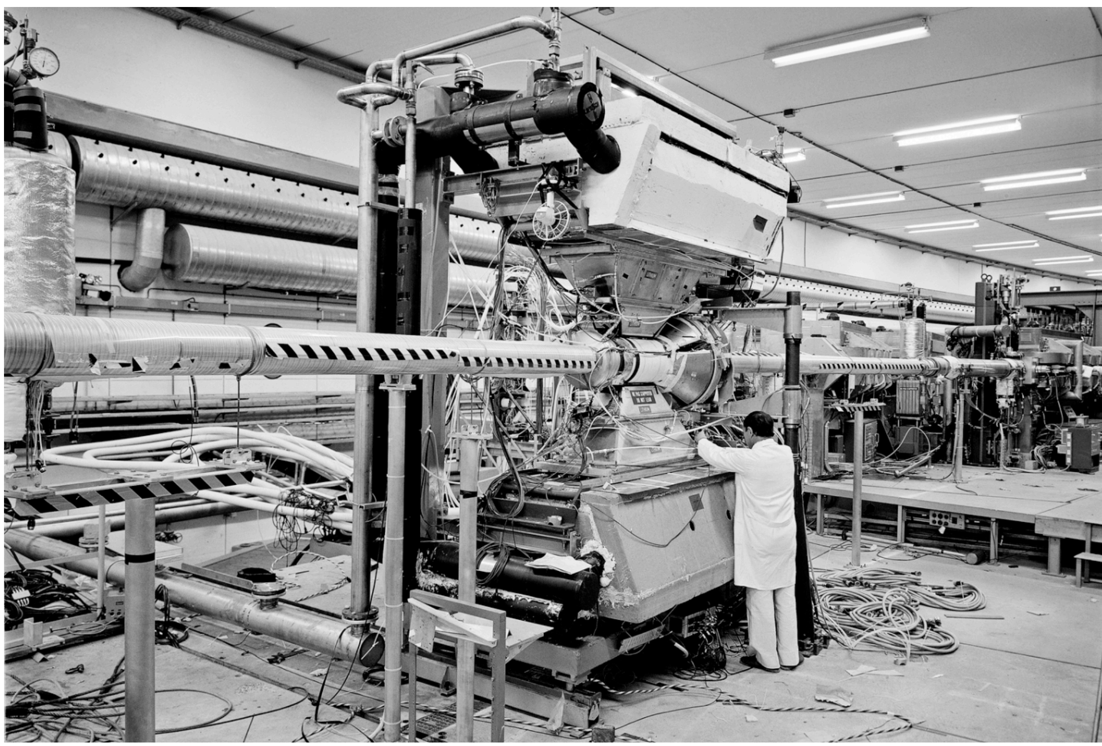


M. Titov

Liquid Argon Detectors

Suggested by L. Alavarez in 1968, pursued by C. Rubbia from the 1970’s, first used by B. Willis in calorimeters and the basis of the ATLAS EM calorimeters and now planned for the four 10 kT detectors for DUNE.

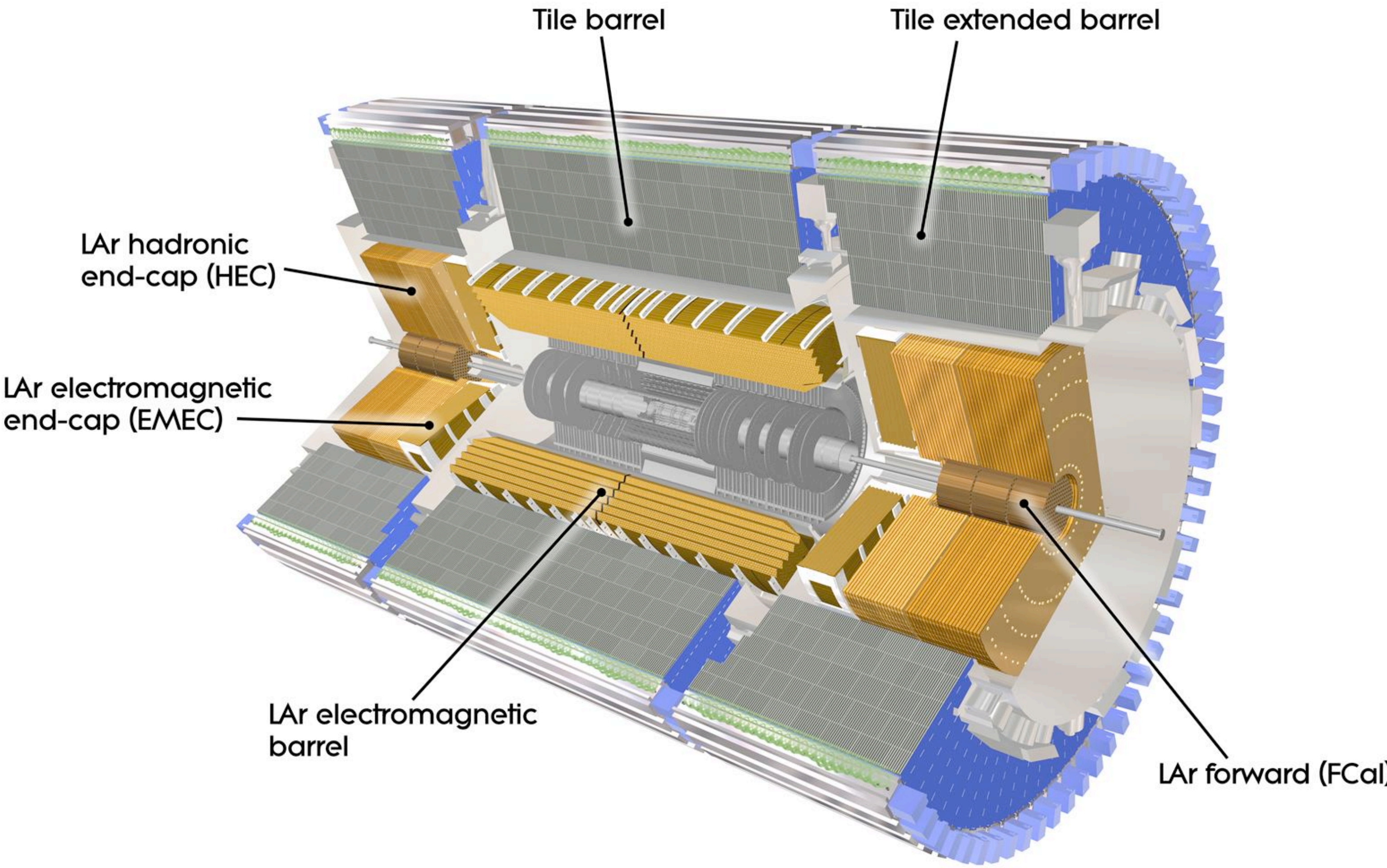
Source: A. Marchionni, Ann. Rev. Nucl. Part Sci, 2013.63 269-90



Two of the liquid argon calorimeters at the ISR (R806)

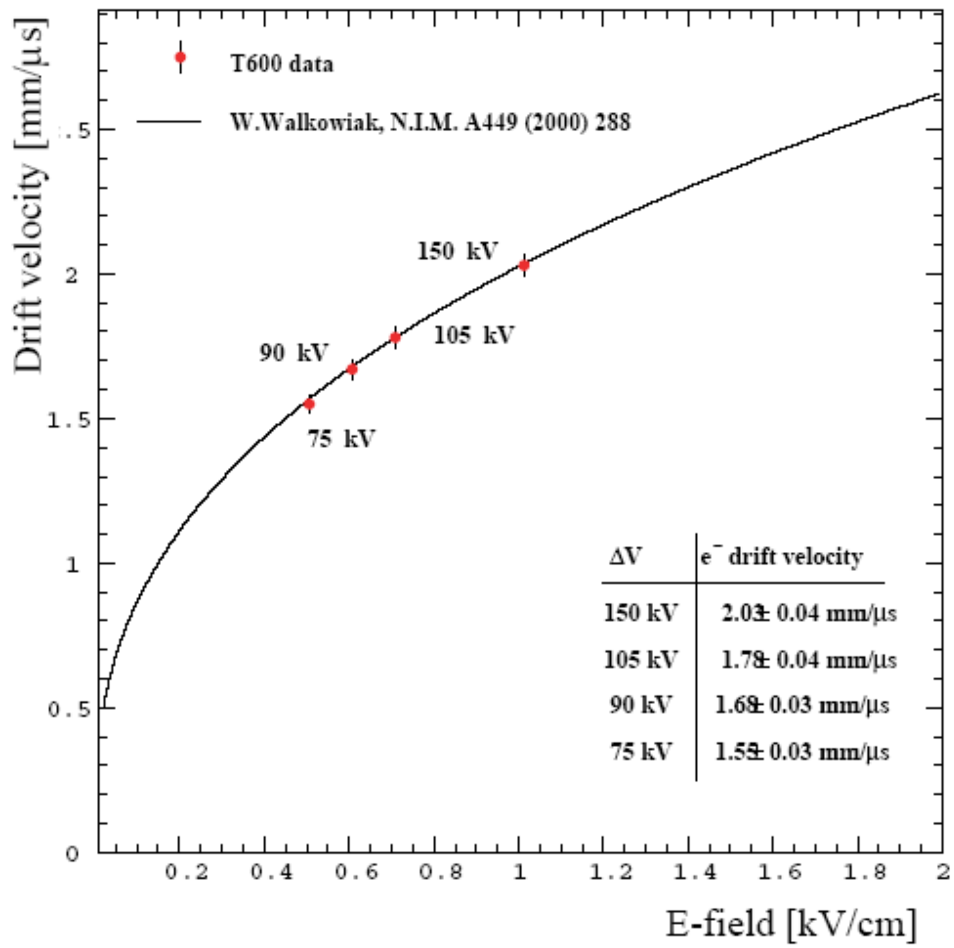
Used in H1 and D0 experiments.

ATLAS Liquid Argon Detectors



Liquid Argon

Boiling Point	87K
Density	1.41 gm/cm^3
$dE/dx\|_{min}$	1.5 MeV/cm^2
Λ_{int}	120 g/cm^2
X_o	19.5 g/cm^2
Critical energy	32 MeV
Ionization energy	~13.7 eV
V_{drift} at 1 KV/cm	2mm/µsec
Electron Mobility	500 m^2/V.s



Liquid Argon is a cheap commodity produced in the liquefaction of air

Purity

The great technical challenge to make an efficient large volume Liquid Argon detector is achieving a long electron lifetime.

Path length = Mobility x Electric Field x Lifetime $L = \mu\ [m^2/V.s] \times E[V/m] \times \tau[s]$

Electron velocity $v = \mu \times E$

The electron lifetime is (mostly) determined by the electron attachment to impurities.
Most important one is Oxygen.

$$\tau_e[\mu s] \sim 300/\rho[ppb]$$

With V = 2mm/μsec, to achieve drift lengths of 2 m requires purity levels at ~ 0.1 ppb

Liquid Argon is also a great scintillator, emitting light with a wavelength of 120 nm.

The detection of light will be a subject of the next lecture.