Gaseous Detectors

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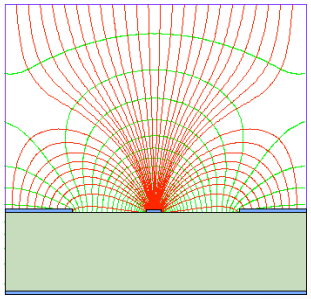
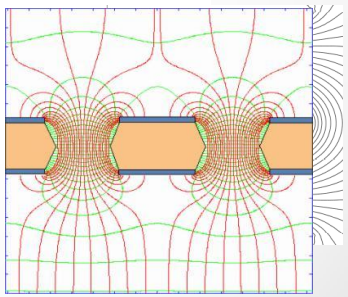
Outline

- From the neutron interaction to the electronic signal
  - Converters
  - Primary Ionization
  - Drift Velocity
  - Multiplication
  - Ramo Theorem
- Which gas?
  - ^{3}He like detectors
  - Solid state neutron converters
- Multiplication Devices
  - Tube
  - MWPC
  - Micro-patterns
    - MSGC, Micromegas, GEM
- Examples of final detectors

Gaseous

Detector





Charged Particle/neutron

μ^+ (E_0) → **Gaseous Detector** → μ^+ $(E_0-\Delta E_0)$

Ionisation (e^-/ions pairs)
Excitation (light)
} $\sim\Delta E_0$

n (E_0) → **Gaseous Detector**

Absorbed in the detector

Released charge particles or photons

Ionisation (e^-/ions pairs)
Excitation (light)
} ~~$\sim E_0$~~

Neutron Converters (1)

Reaction	σ (barn) @ 26 meV	p_1 Energy (MeV)	p_2 Energy (MeV)	Total Energy (MeV)
$n+^{3}He \rightarrow p+^{3}H$	$5.33 \cdot 10^{3}$	.57	.19	.77
$n+^{6}Li \rightarrow \alpha+^{3}H$	$1.21 \cdot 10^{3}$	2.05	2.74	4.79
$n+^{10}B \rightarrow \alpha+^{7}Li$ $n+^{10}B \rightarrow \alpha+^{7}Li+\gamma$	$4.01 \cdot 10^{3}$	1.77 1.47	1.01 0.83	2.79 2.3+.48(γ)
$n+^{235}U \rightarrow Lfi+Hfi$	$5.77 \cdot 10^{2}$	≤80	≤60	~100
$n+^{157}Gd \rightarrow Gd+e^{-}$	$2.51 \cdot 10^{5}$		.07-.182	≤.182

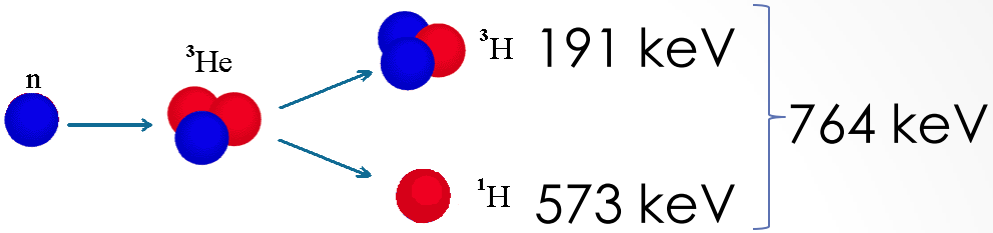
Source: Neutron Data Booklet

http://www.ill.eu/quick-links/publications/

Neutron Converters (2)

Converter	✓	✗
^{3}He	High cross section Gas up to high pressure Low Z → Low γ sensitivity Noble gas Release charged particles with quite high energy	€/litre £/litre $>10^3$ ¥/litre $/litre CHF/litre
^{10}B	High cross section Release charged particles with high energy Gas (BF_3) 20% natural isotopic abundance	Solid→ thin layer Gas → not really high pressure Gas → Toxic

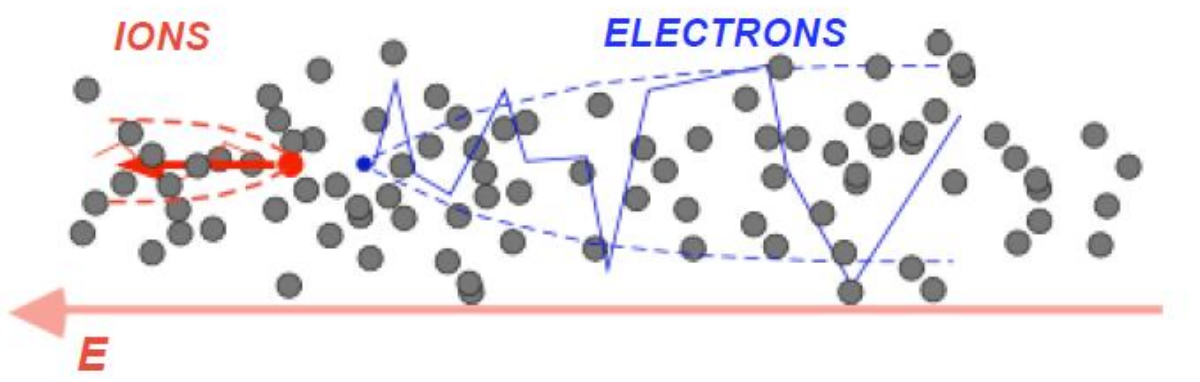
Primary Ionisation



Energy per e^-/ion pair ~30 eV

~$25 \cdot 10^3$ e^-/ion pairs

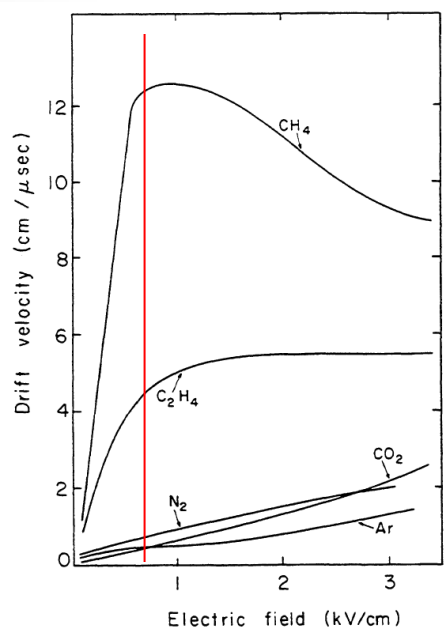
~4 fC

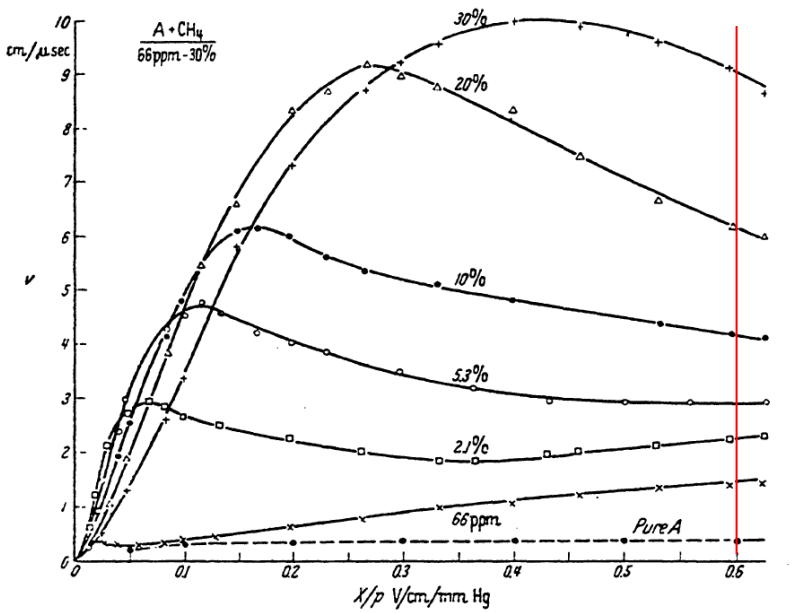


Drift Velocity

- Mean free path
  - Gas Type
  - Temperature ↑
  - Pressure ↓
  - Electric field ⇑
- electrons and Ions ~1000 times

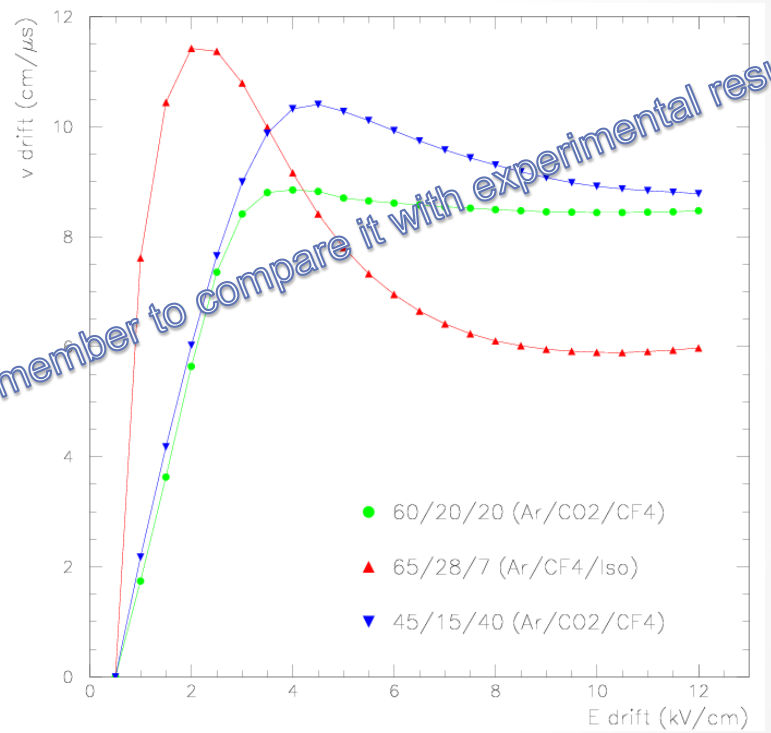
Principles of operation of multiwire proportional and drift chambers, F. Sauli (CERN 77-09, 1977)





Drift Velocity Calculation

- Input
  - Gas mixture
  - Pressure
  - Electrode Geometry
  - Electric Field
  - Magnetic Field
- Output
  - Drift Velocity
  - Attachment
  - Diffusion
  - Multiplication



Simulation will give you a good direction but remember to compare it with experimental results

Garfield http://garfield.web.cern.ch/garfield/
http://cyclotron.mit.edu/drift/www/

Multiplication (1)

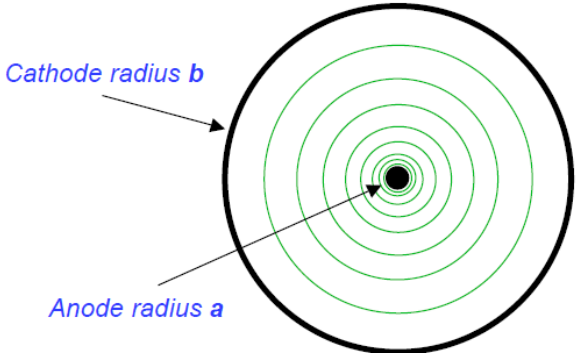
n_0 e^- ~ 4 fC ~ $2.5 \cdot 10^4$ e^-

E ~10 kV/cm

ε → electron's energy

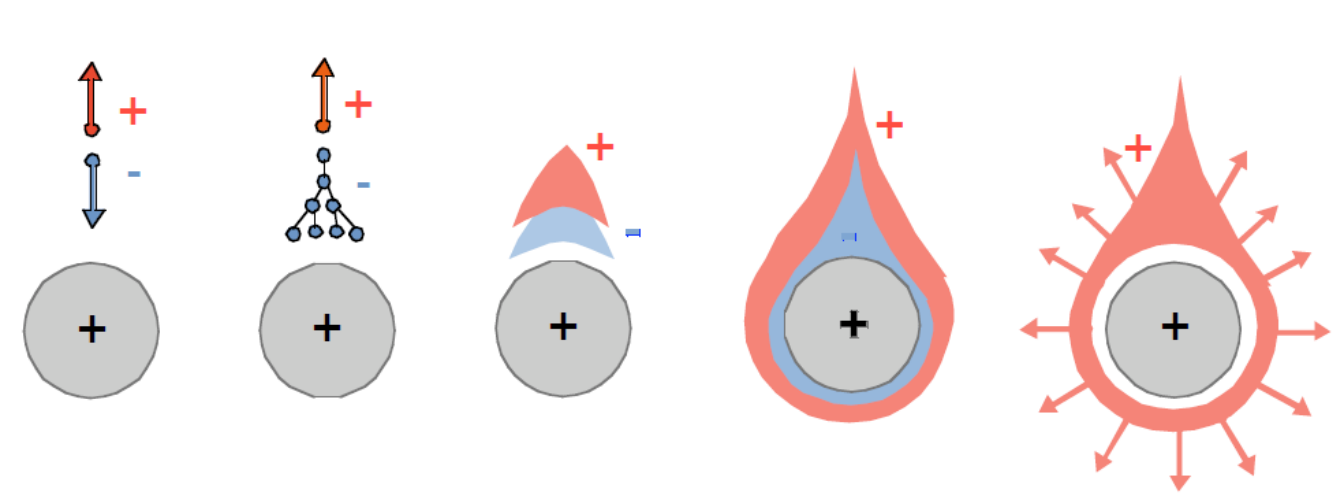
E_i → first ionisation potential of the gas

Multiplication if ε>Ei



$$E = 2CV_a/r$$

$$C = 1/\ln(r_c/r_a)^2$$



Multiplication (2)

- Townsend coefficient
  - mean free path for ionisation λ=average distance an electron has to travel before getting a chance to be involved in an ionizing collision
  - $\alpha = 1/\lambda$

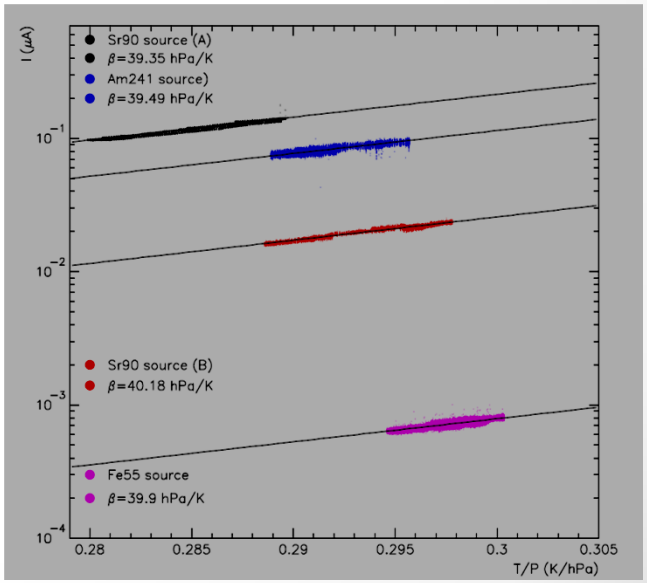
$$n = n_0 e^{\alpha \cdot x}$$

$$n = n_0 \exp\left(\int_{x_1}^{x_2} \alpha(x) dx \right)$$

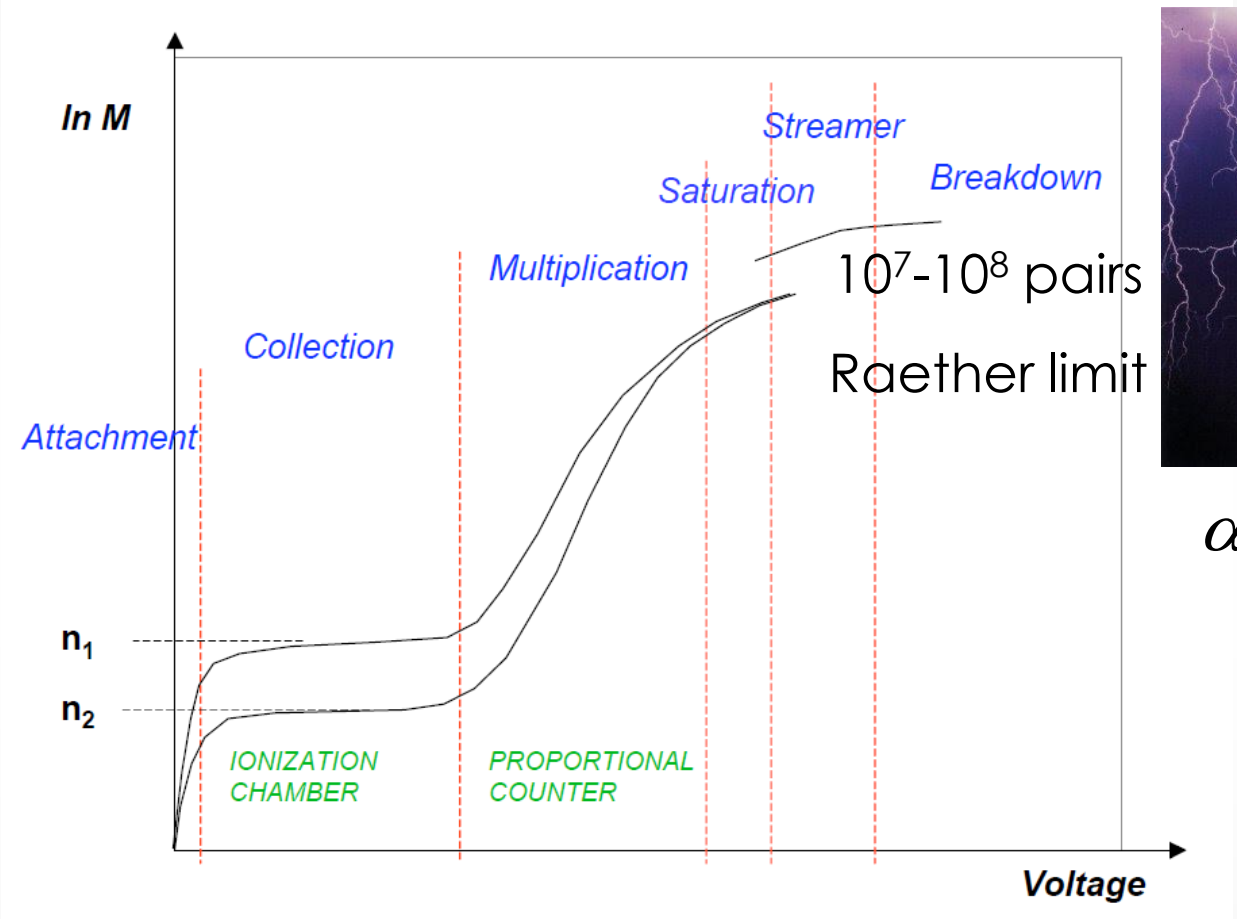
$$M = n / n_0$$

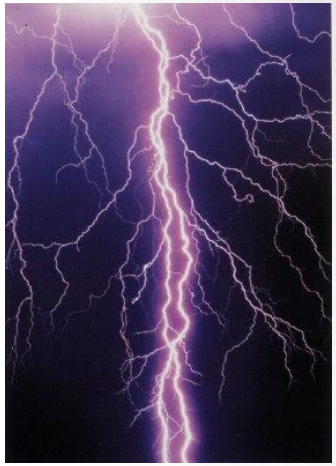
- Temperature and Pressure

$$M \propto e^{T/P}$$



Multiplication (3)





$$\alpha \cdot x \approx 20$$

Electron avalanches and breakdown in gases, H. Raether (Butterworth, London 1964)

Signal shape

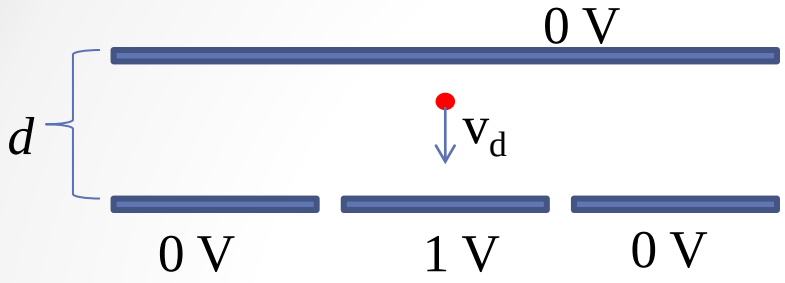
- The signal induced on the electrodes is an *induced* current
- The signal start to grow when the electron start to move toward the electrode
- Also the ion, that moves in the opposite direction, induce a signal on the electrode were the electron is collected

$$i(t) = q\mathbf{E_W} \cdot \mathbf{v_d}$$

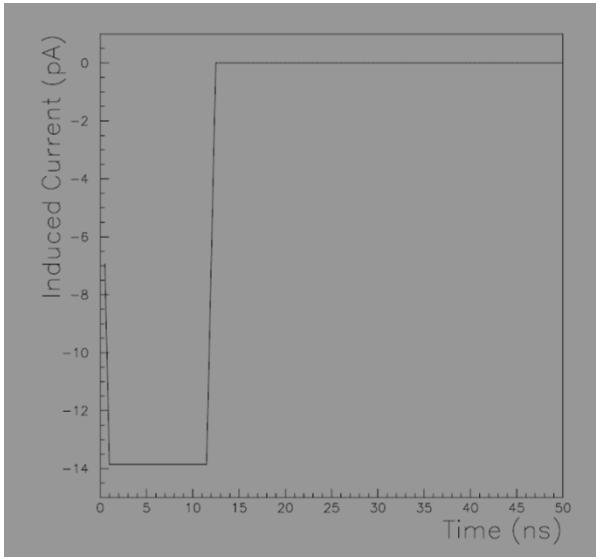
- Weighting field $\mathbf{E_w}$: electric field in the drift volume of the charge obtained with all the electrodes at 0 V except the one where we want to calculate the induced signal that is at 1 V
- $\mathbf{V_d}$ is the drift velocity of the charged particle

S. Ramo, Current induced in electron motion, Proc. IRE 27, 584 (1939)
Radeka, Low Noise Techniques in Detectors, Ann. Rev. Nucl. Part. Sci. 1988, 38, 217

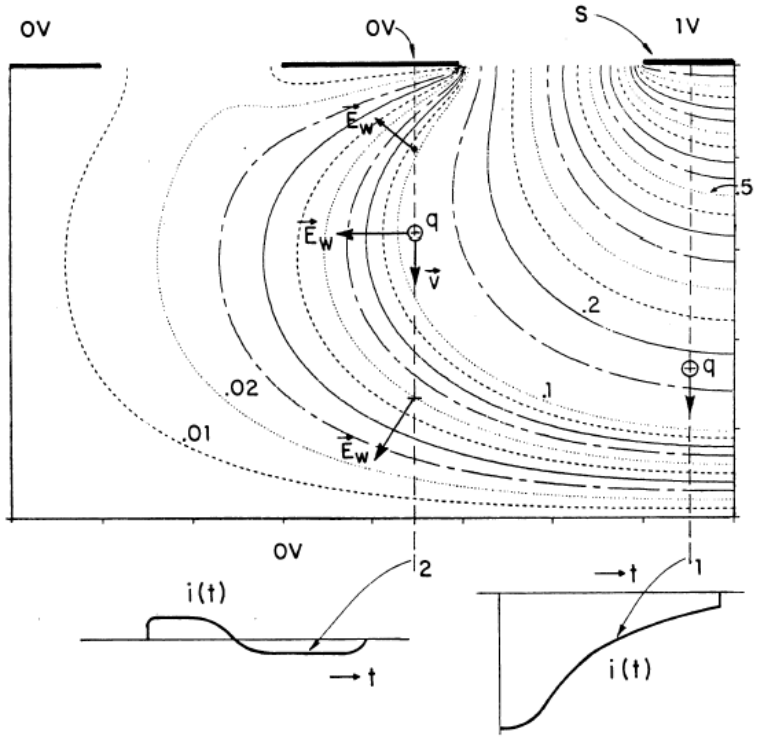
Signal shape examples (1)



$$i(t) = q\mathbf{E_W} \cdot \mathbf{v_d} = q\frac{1}{d}v_d$$



Signal shape examples (2)



Radeka, Low Noise Techniques in Detectors, Ann. Rev. Nucl. Part. Sci. 1988, 38, 217

Signal Shape (3)

- Cylindrical detector
- Signal induced by the movement of positive ions on the anodes

$$E = V_a \frac{1}{r \ln \frac{r_c}{r_a}} = E_a \left(\frac{r_a}{r}\right) \Rightarrow \mathbf{v}_+ = \frac{d\mathbf{r}}{dt} = \mu_+ E_a \frac{r_a}{r}$$

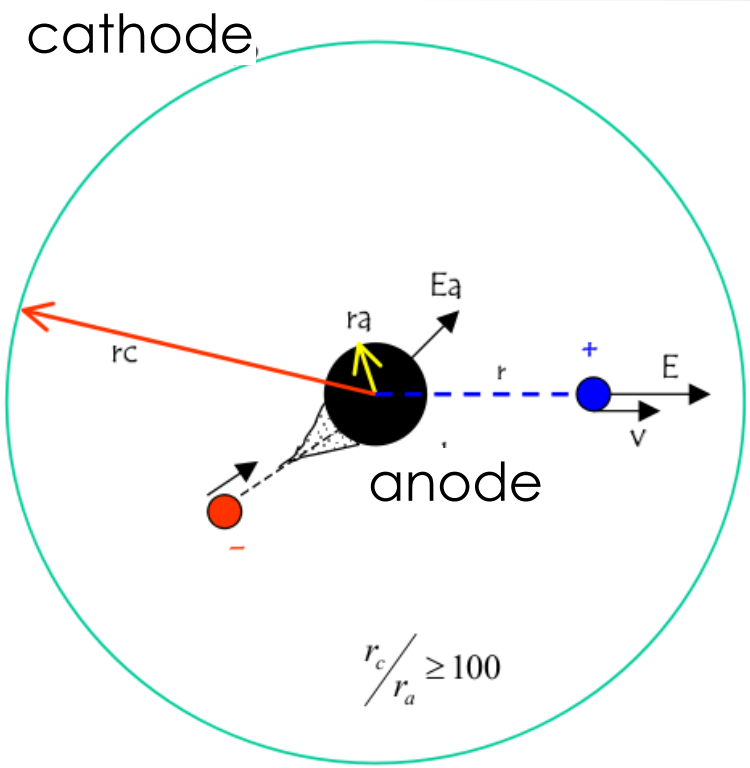
$(v = \mu E)$

Weighting Field

$$\xrightarrow{V_a = 1} E_w = \frac{1}{r \ln \frac{r_c}{r_a}}$$

$$\mathbf{E_w} \parallel \mathbf{v} \Rightarrow i(r) = -q\mathbf{E}_w \cdot \mathbf{v} = -q\mu_+ E_a \frac{r_a}{r^2 \ln \frac{r_c}{r_a}}$$

$$r^2 = r_a^2 + 2\mu_+ E_a r_a t = r_a^2 \left(1 + \frac{t}{t_0}\right) \qquad t_0 = \frac{r_a}{2\mu_+ E_a}$$



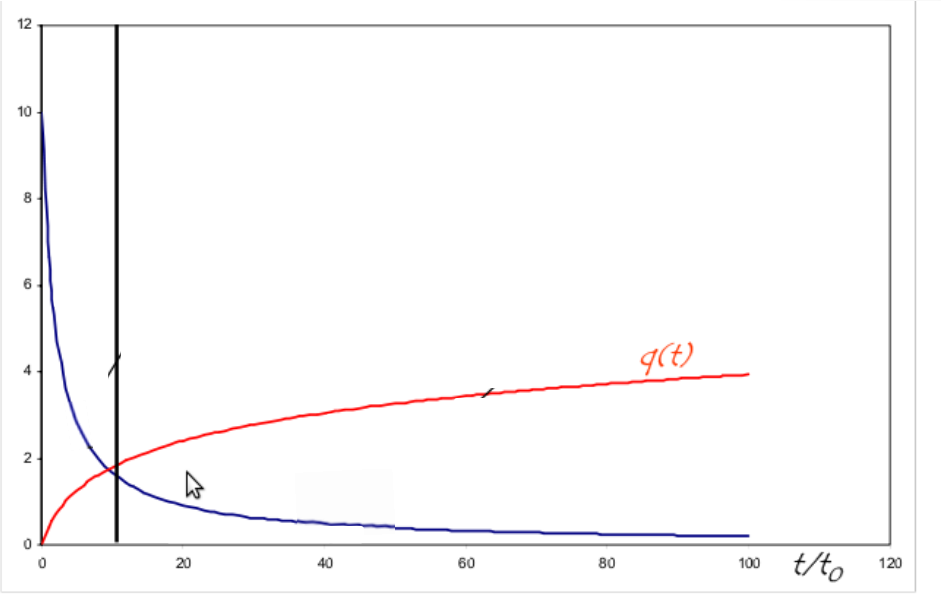
Radeka-Lai

Signal Shape (4)

$$i(t) = \frac{i_0}{1 + \frac{t}{t_0}}$$

$$i_0 = q \frac{1}{2t_0 \ln \frac{r_c}{r_a}}$$

$$q(t) = q \frac{\ln(1 + \frac{t}{t_0})}{2 \ln \frac{r_c}{r_a}}$$



From a neutron to an electronic signal

- Neutron absorbed in the detector
  - Primary Ionisation
  - Ion and electron drift
  - Multiplication
  - Signal shape

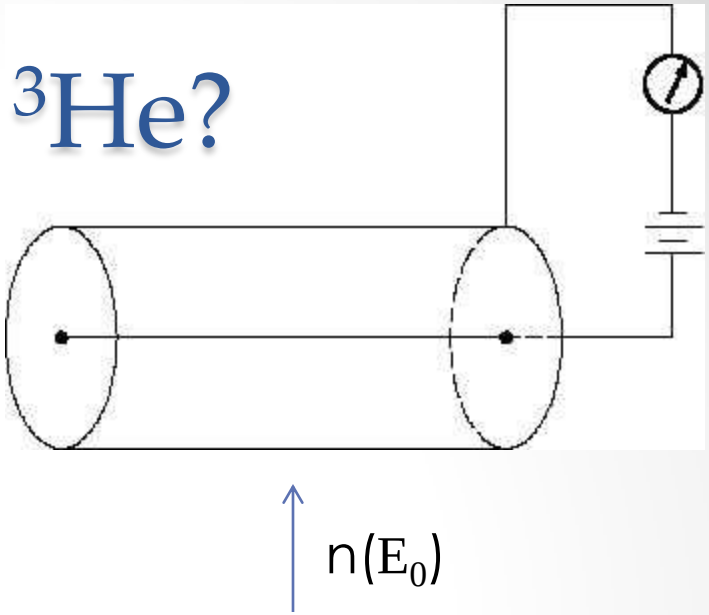
Which Gas?

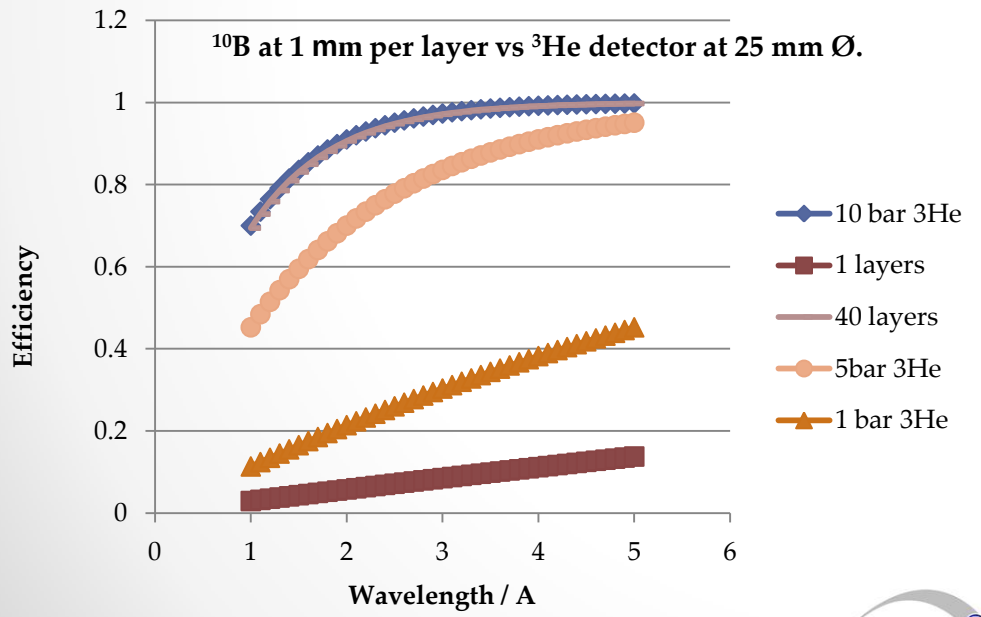
- ^{3}He based detector
  - How much ^{3}He?
  - Do we need other gas in the mixture?
- ^{10}B based detector
  - BF_3 detector
  - ^{10}B Solid converters detectors

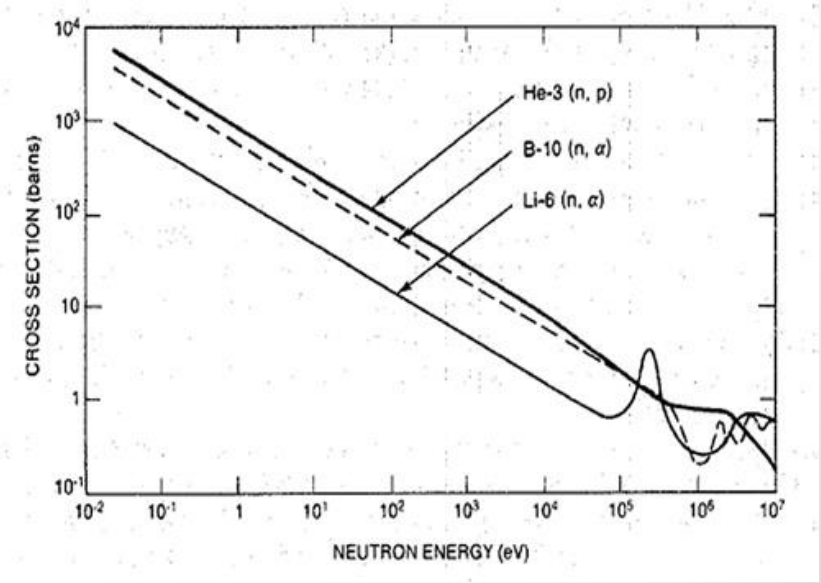
http://consult.cern.ch/writeup/garfield/examples/gas/trans2000.html

How much ^{3}He?

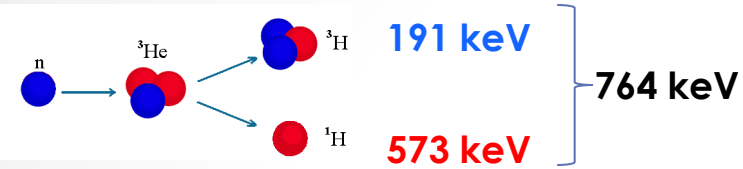
- Absorption law: $J = J_0 \exp(-\sigma A_d x)$
- Efficiency: $\varepsilon = 1 - \exp(-\sigma A_d x)$
- $A_d = \rho N_A / M_W$
- $\sigma = \sigma(E_0)$

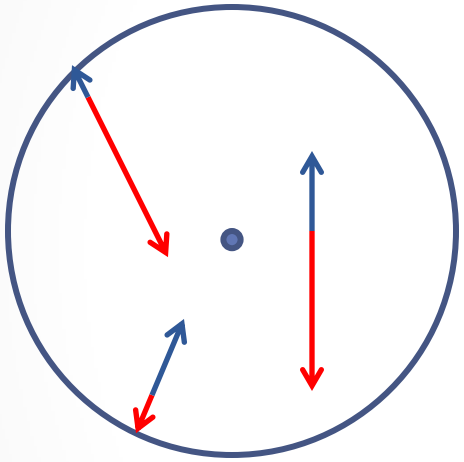


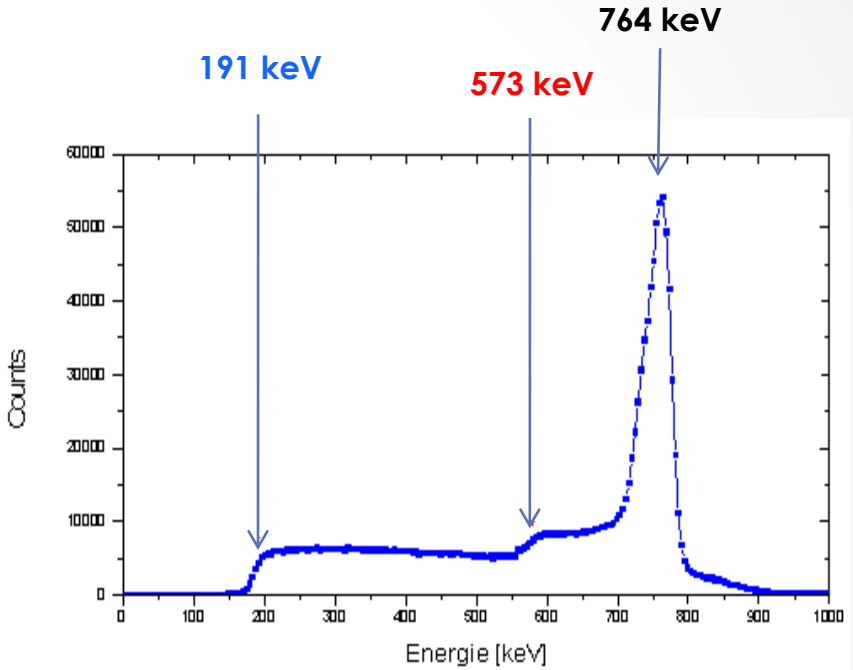




Pulse Height Spectrum (PH)



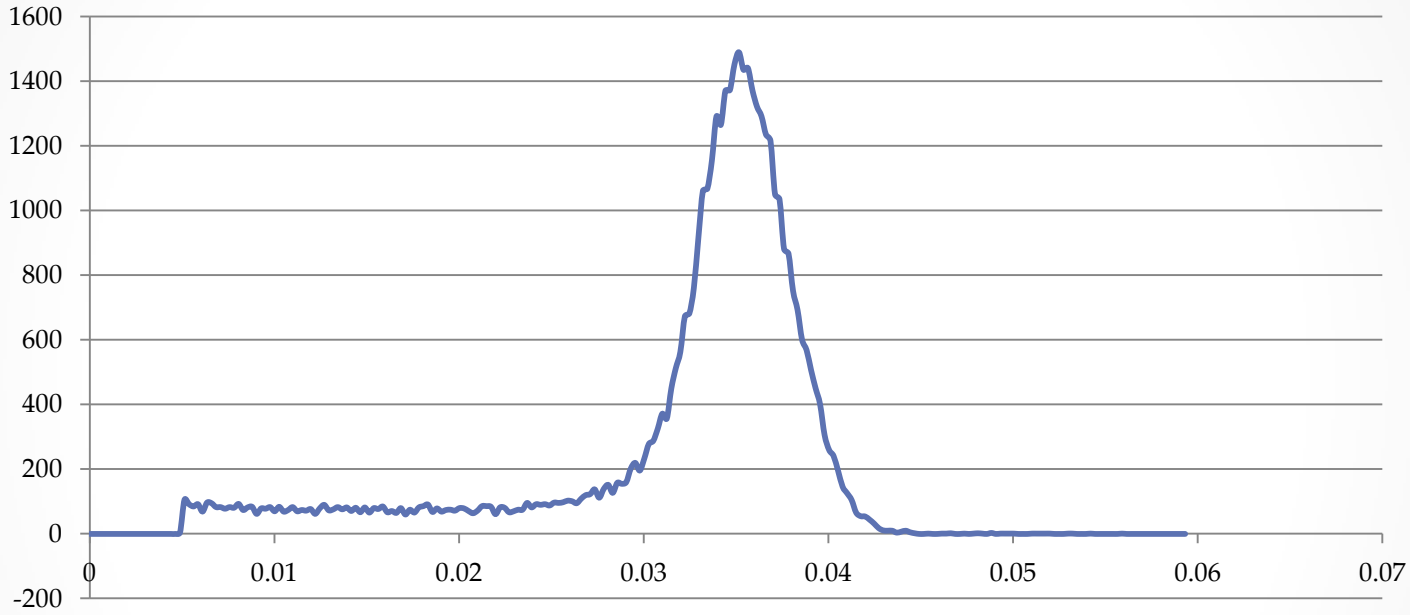




Reduce the range of the charged particles

Stopping gas: Ar, CF_4 (few bars)

Pulse Height Spectrum (PH)



6 bar CF_4

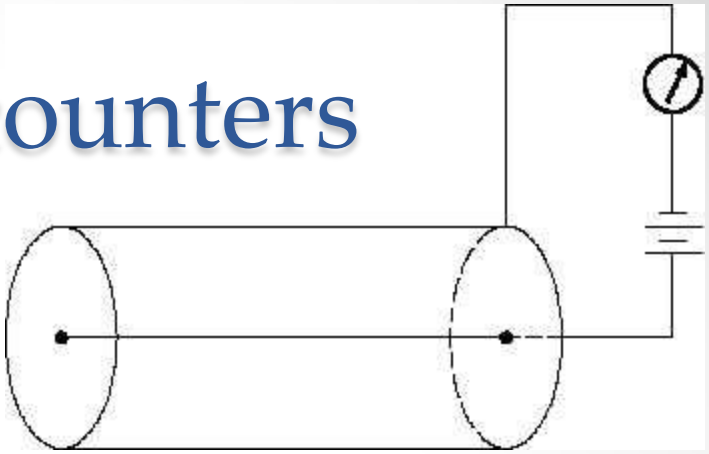
^{10}B solid converters detectors

- Neutron conversion is not in the gas
- Charged particle ionize the gas in front of the ^{10}B layer
- In principle any gas can be used
- Ar based gas mixture preferred: Ar/CO_2 (70/30)
- Constant gas flux inside the detector
- Sub-atmospheric pressure to have high gain at low voltage
- Up to 2 bar pressure to reduce the range of charged particles and increase the position resolution of the detector (position resolution<2 mm)

Multiplication Devices

- Proportional counters
- Resistive wire tubes
- Multi Wire Proportional Counter MWPC
- Micropattern gas detectors
  - Micro Strip Gas Chambers (MSGC)
  - Micromegas
  - Gas Electron Multipliers (GEM)
  - Many others

Proportional counters

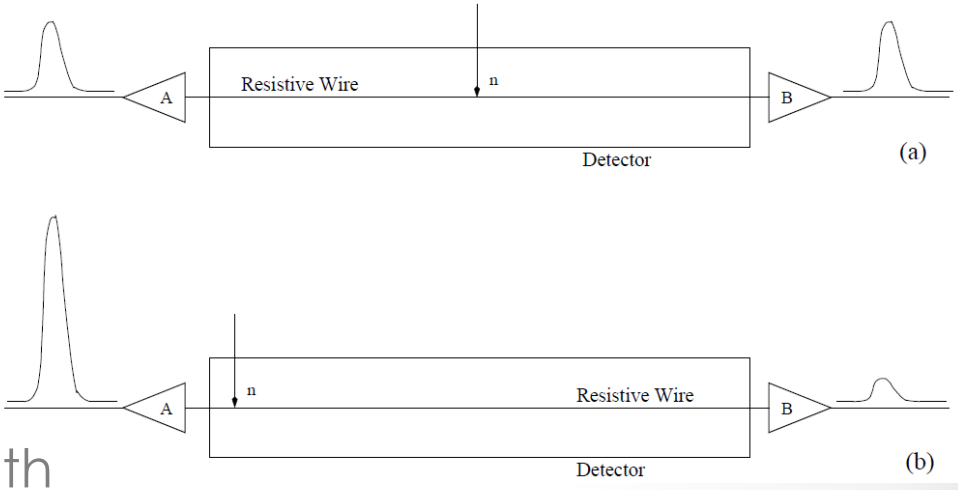


- Able only to count neutrons
- No position information
- Time information
- Still used in some instruments
- Used as beam monitor

- 5 to 25 mm diameter
- ~25 μm wire diameter
- 5 to 15 bar ^{3}He
- Gain ~30

Resistive Wire Detectors

- Widely used to detect neutrons
- Position sensitive 1D
- Readout at both sides of the wire
- Resistance of ~10 kΩ
- Length from .5 to 4 m
- Diameter: 8 mm, ½",1"
- Up to 15 bar ^{3}He
- Position resolution <1% of the length
- Rate capability up to 300 kHz
- Array of detectors to cover large area instruments



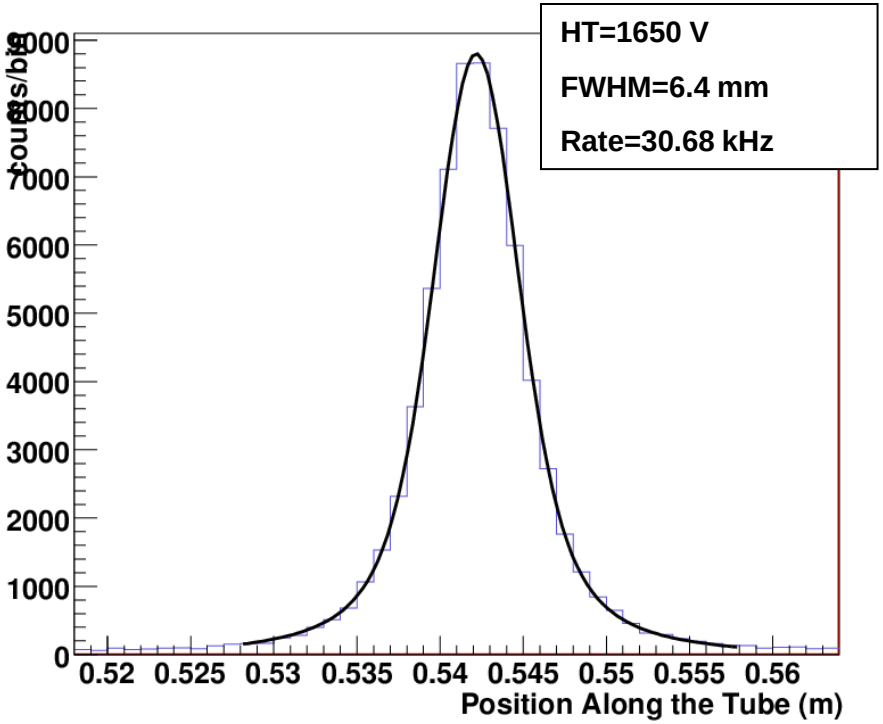
$$x = \frac{A}{A+B}$$

Resistive Wire Detectors

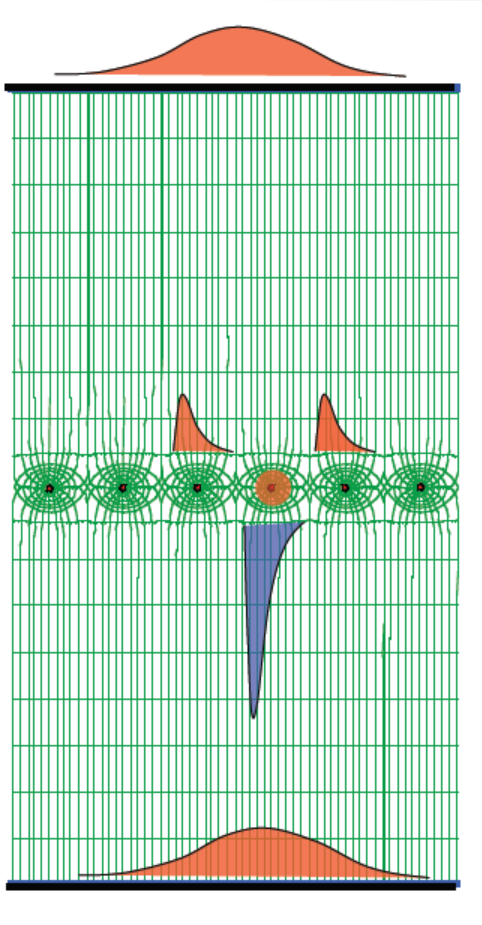
1 mm long

8 mm diameter

15 bar ^{3}He



Multi Wire Proportional Chamber (MWPC)

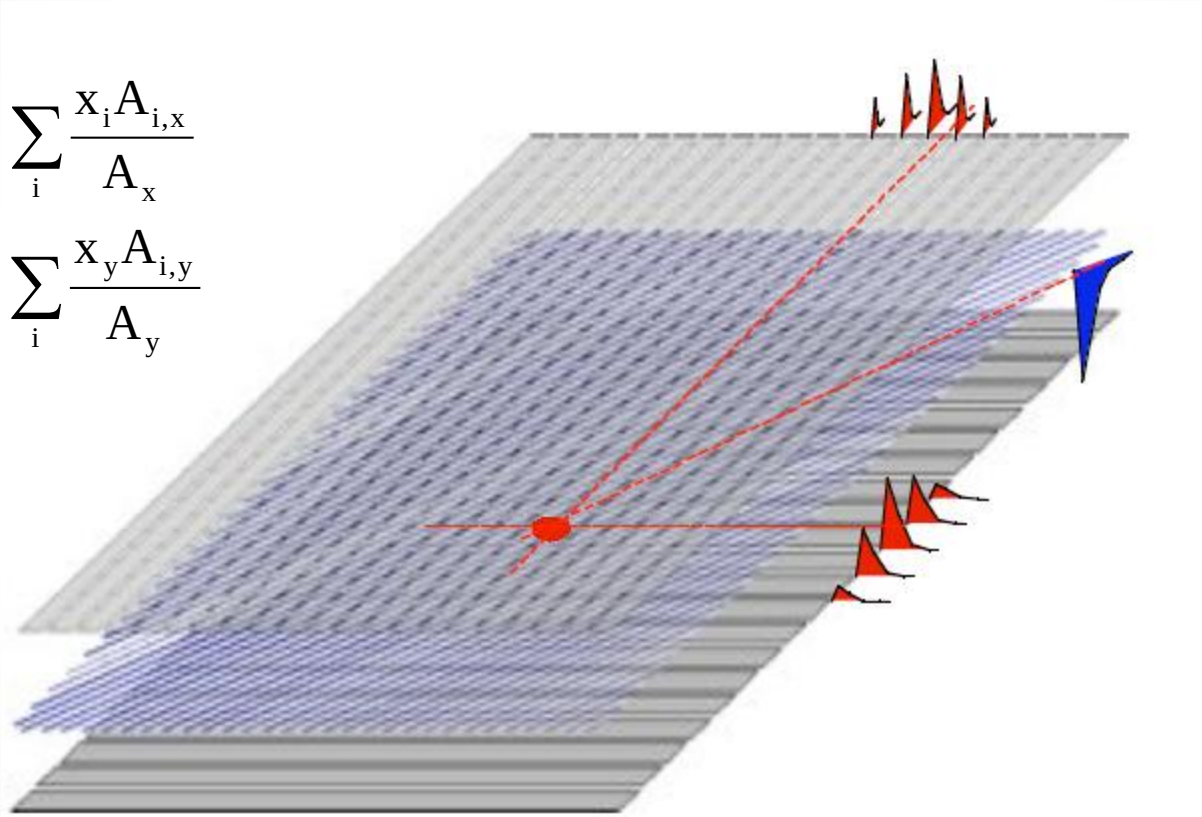


G. Charpak et al, Nucl. Instr. and Meth. 62(1968)235

Multi Wire Proportional Chamber (MWPC)

$$x_0 = \sum_i \frac{x_i A_{i,x}}{A_x}$$

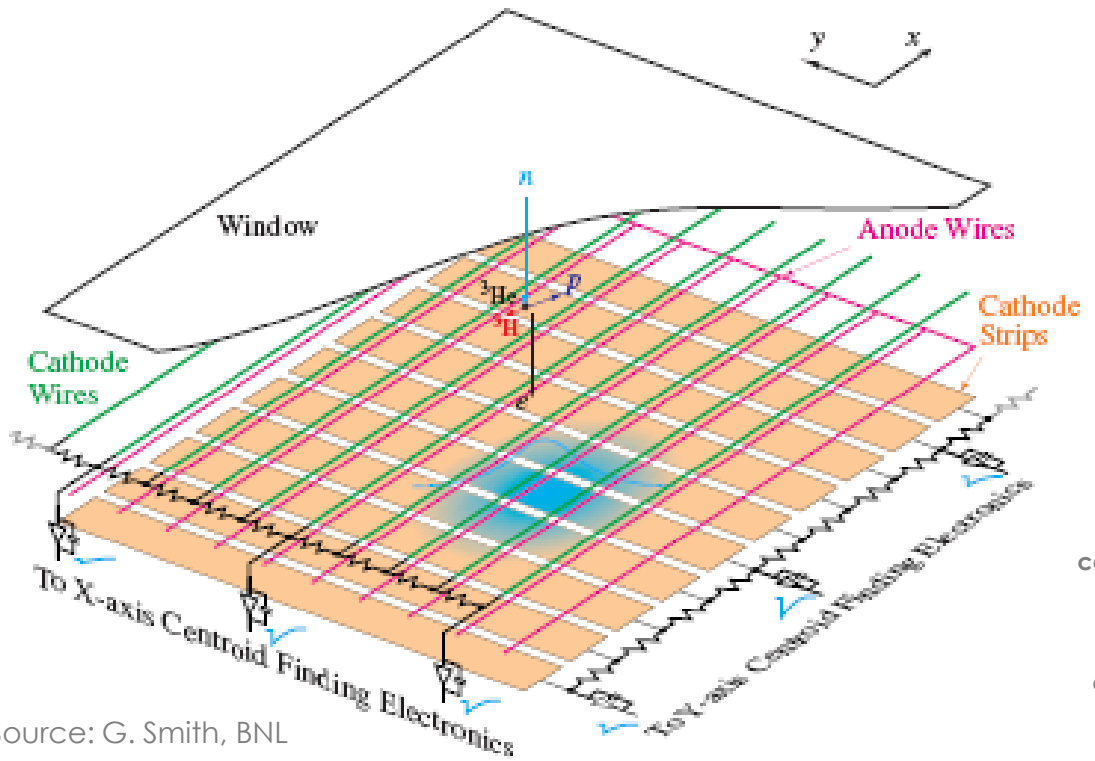
$$y_0 = \sum_i \frac{x_y A_{i,y}}{A_y}$$



G. Charpak and F. Sauli, Nucl. Instr. and Methods 113(1973)381

E. Gatti et al, Nucl. Instr. and Meth. 163(1979)83

Multi Wire Proportional Chamber (MWPC)



Source: G. Smith, BNL

anode wires: 8 -15μm

spacing s: ≥ 1 mm

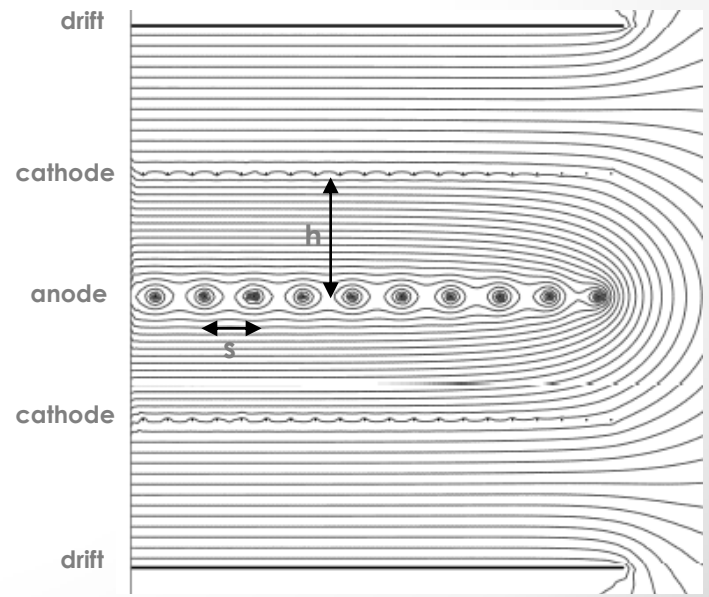
gap h: ≥ 2 mm

gas: $^3He+CF_4$, C_3H_8

gain: 100 -1000

Al-window: 8 mm

readout: x,y - cathode



Electric field:

$z << s$: $E(x,z) \sim Q / (2\pi\varepsilon_o) \cdot 1/r$

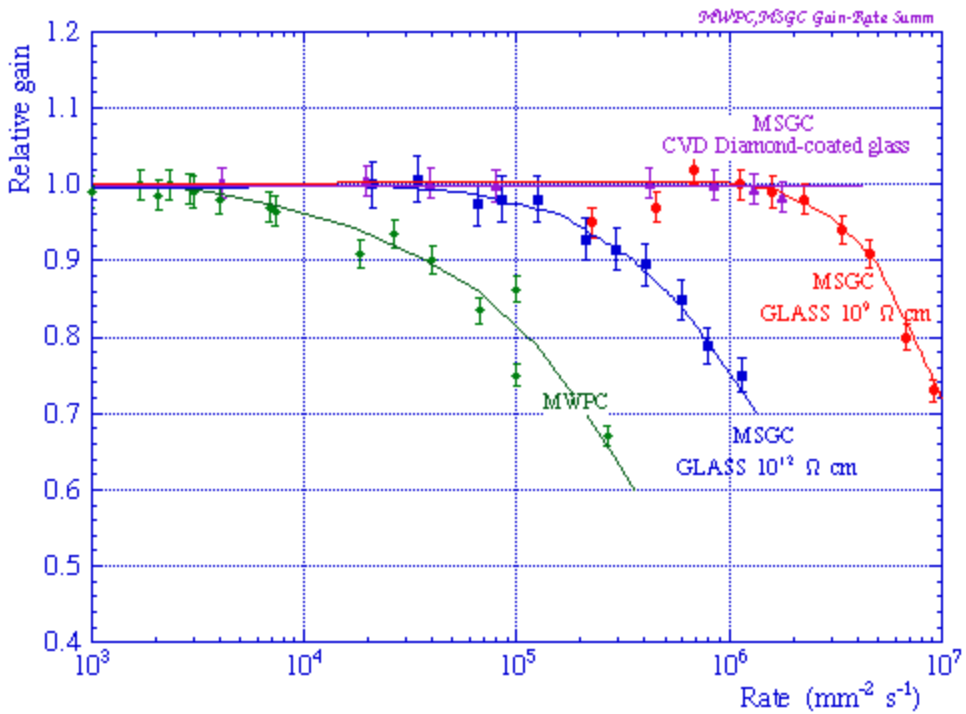
$z > s$: $E(z) \sim Q / (2s\varepsilon_o)$

Micro-pattern gas detectors

- End of '80
- Overcome manufacture difficulties of MWPC
- Improve rate capability
  - Fast ion collection
  - Short distance (μm) between anodes and cathodes
- Photolithography technique
- Separation between multiplication and signal formation volumes
- MSGC, Micromegas, GEM

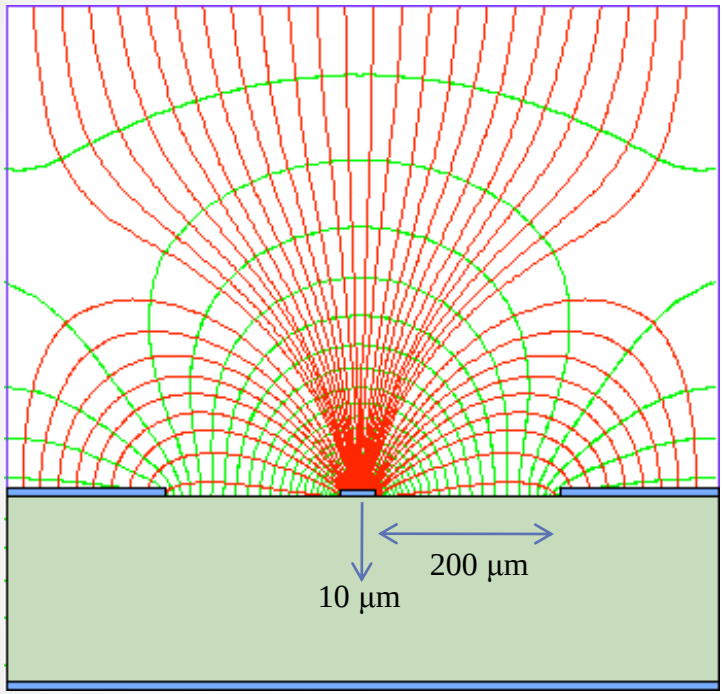
F. Sauli and A. Sharma, Micro-pattern gaseous detectors, Ann. Rev. Nucl. Part. Sci. 49(1999)341

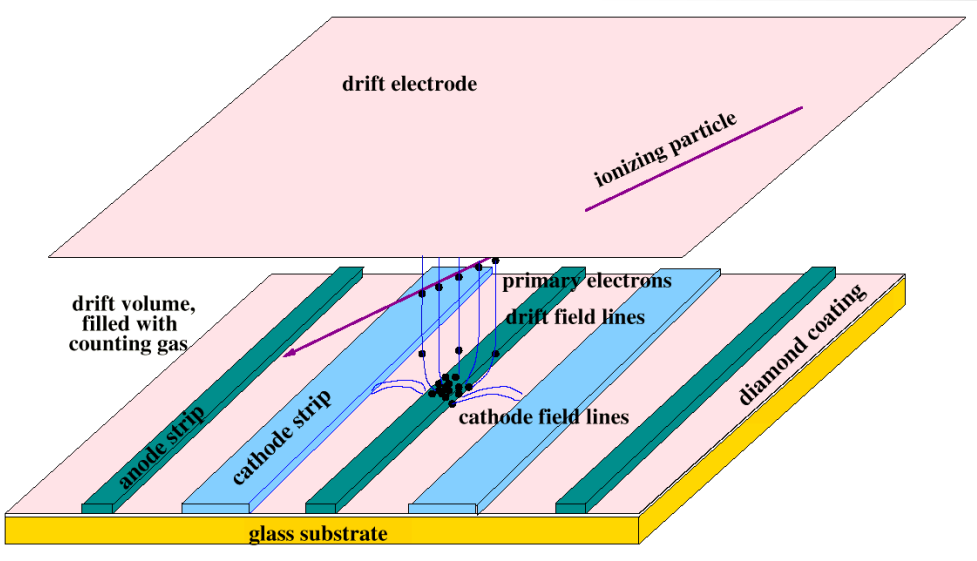
Rate Capability



http://gdd.web.cern.ch/GDD/

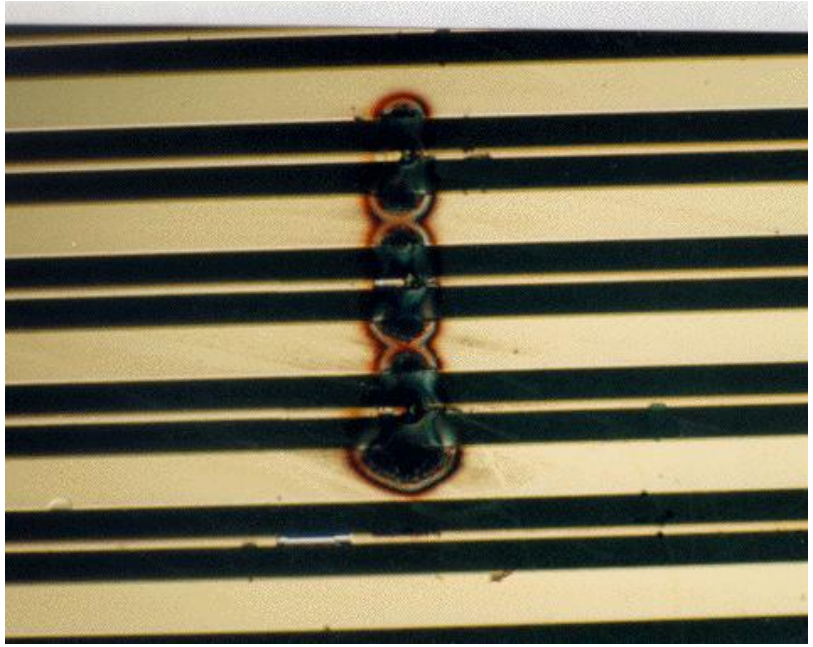
Micro Strip Gas Chamber (MSGC)





A. Oed, Nucl. Instr. and Meth. A263 (1988) 351

MSGC vs Sparks



- No application in high energy physics

- Some application in neutron scattering
- High gain: up tp 10^3
- Good position resolution: ~.5 mm

Gas Electron Multiplier (GEM)

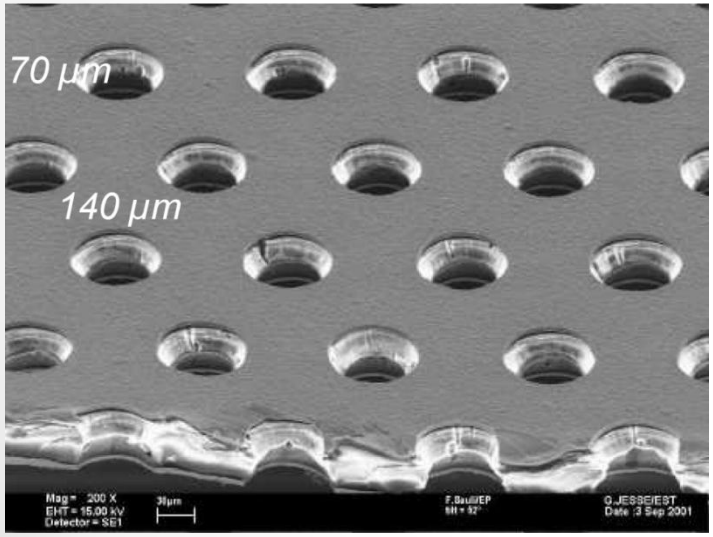
Thin metal-coated polymer foil chemically etched with 50÷100 holes/mm^2

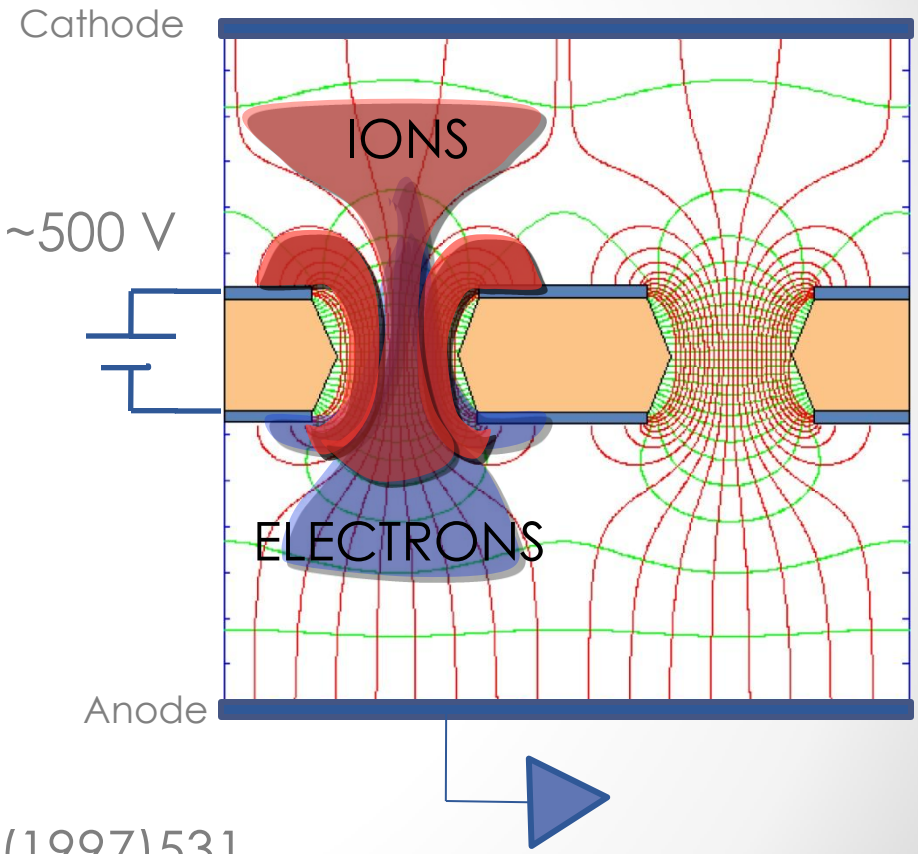
STANDARD GEM:

50 μm kapton

5 μm copper

70 μm holes at 140 μm pitch

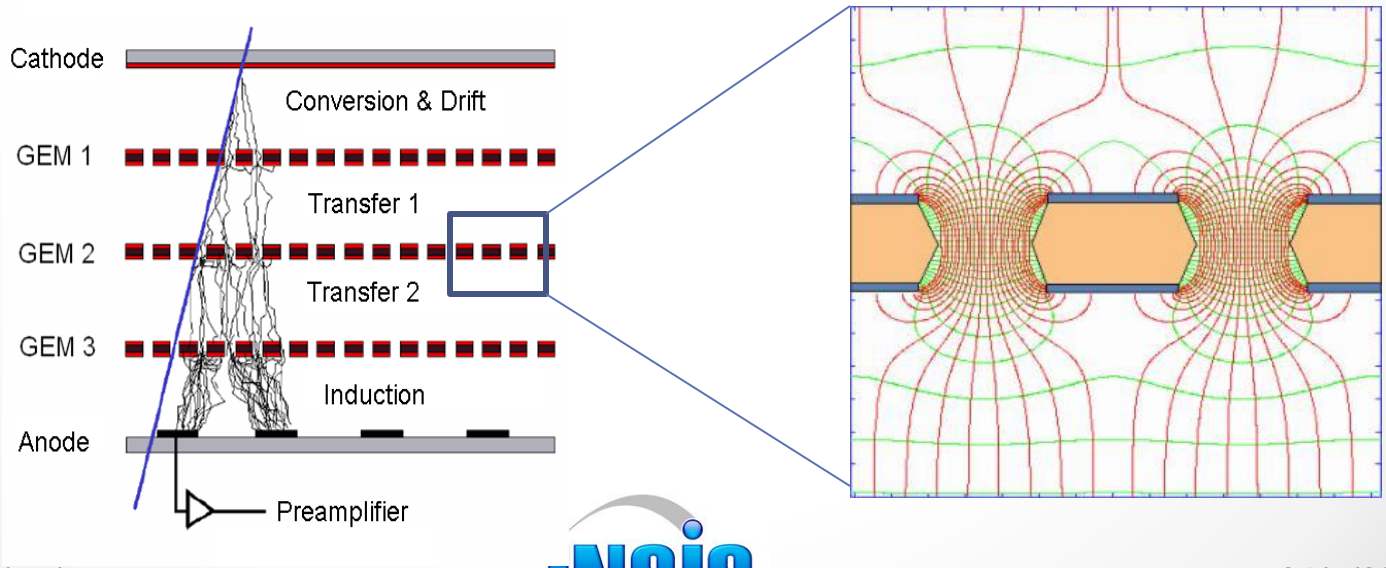




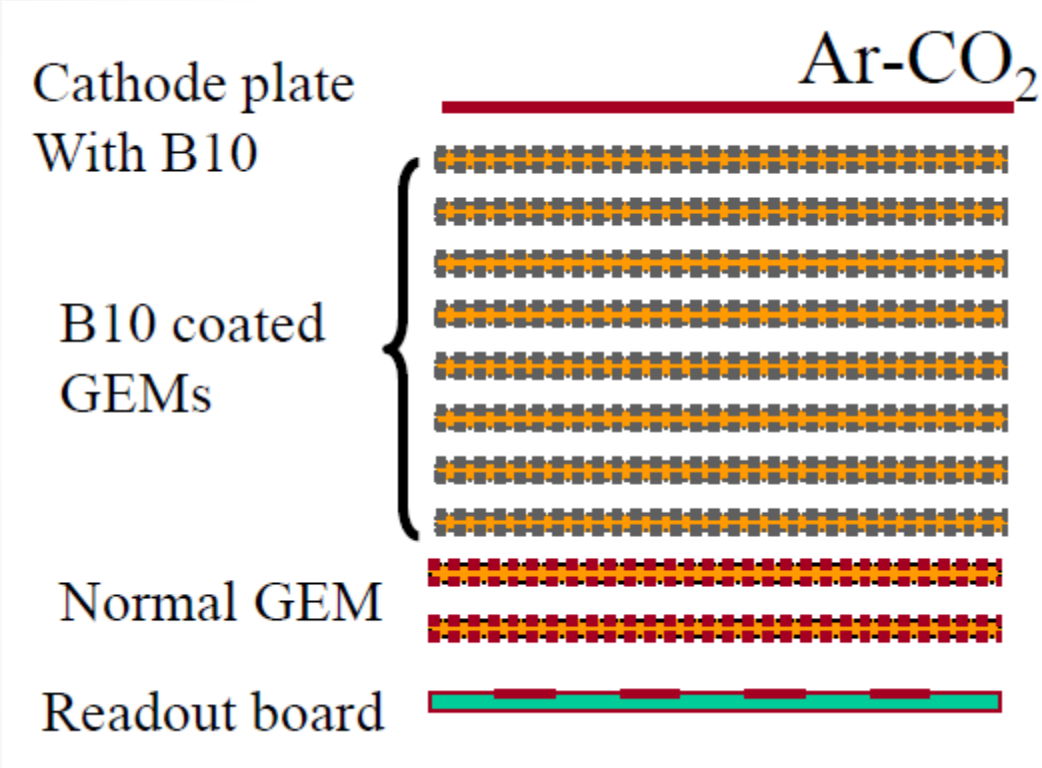
F. Sauli, Nucl. Instr. and Meth. A386(1997)531

Gas Electron Multiplier (GEM)

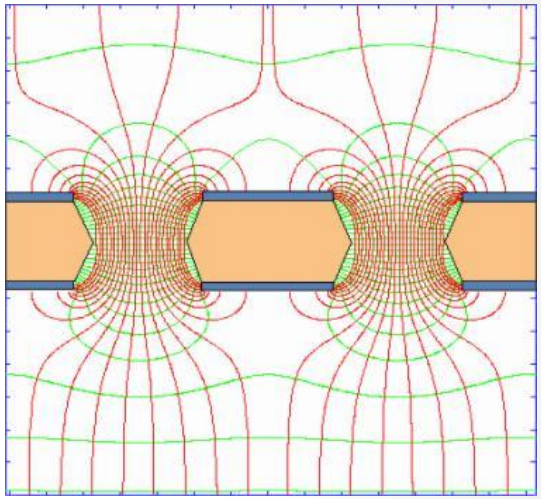
- At atmospheric pressure
  - Separation between multiplication volume and signal inducing volume
  - High rate capability > 100 kHz/mm^2
  - Robust against sparks
  - Good position resolution
- At high gas pressure
  - GEM voltage > 500 V→ more energy release in a spark event
  - High extraction field → impossible to collect electrons in a second GEM



Gas Electron Multiplier (GEM)



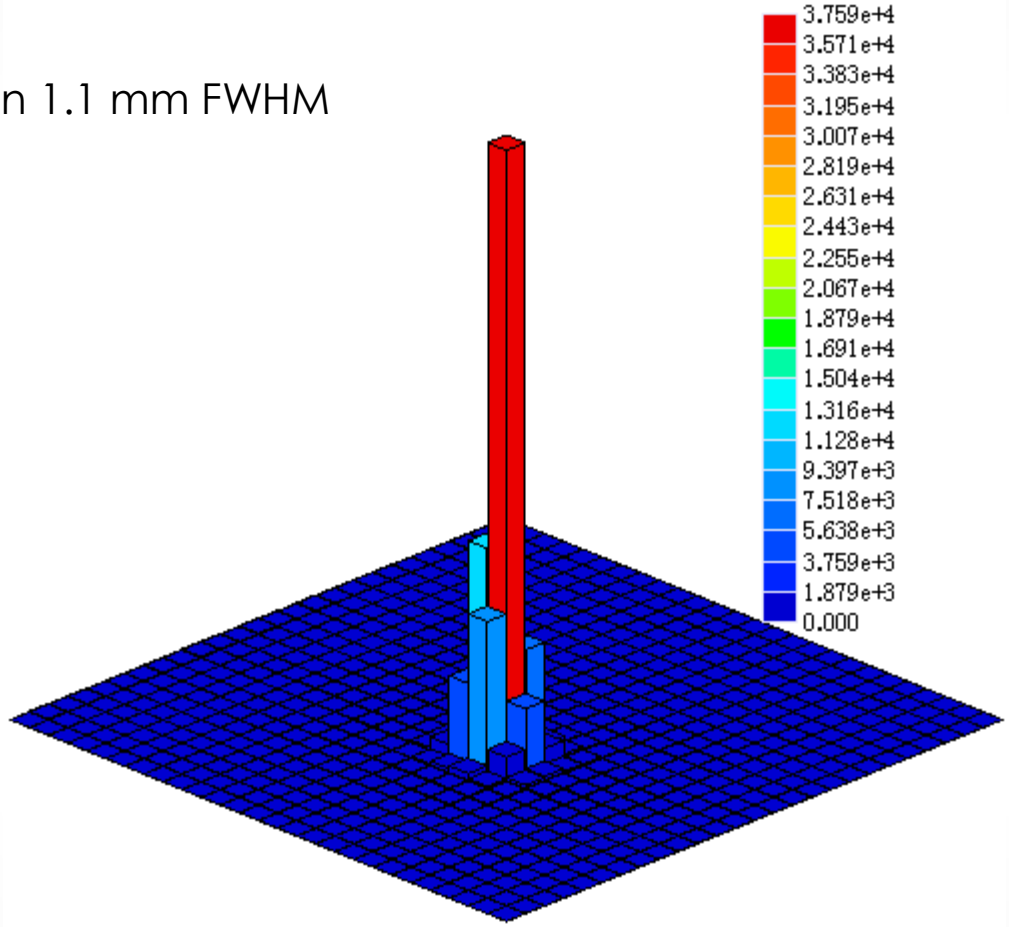
Efficiency ~50% at
1.8 Å with 20 layers



http://www.physi.uni-heidelberg.de/Forschung/ANP/Cascade/Konzept/

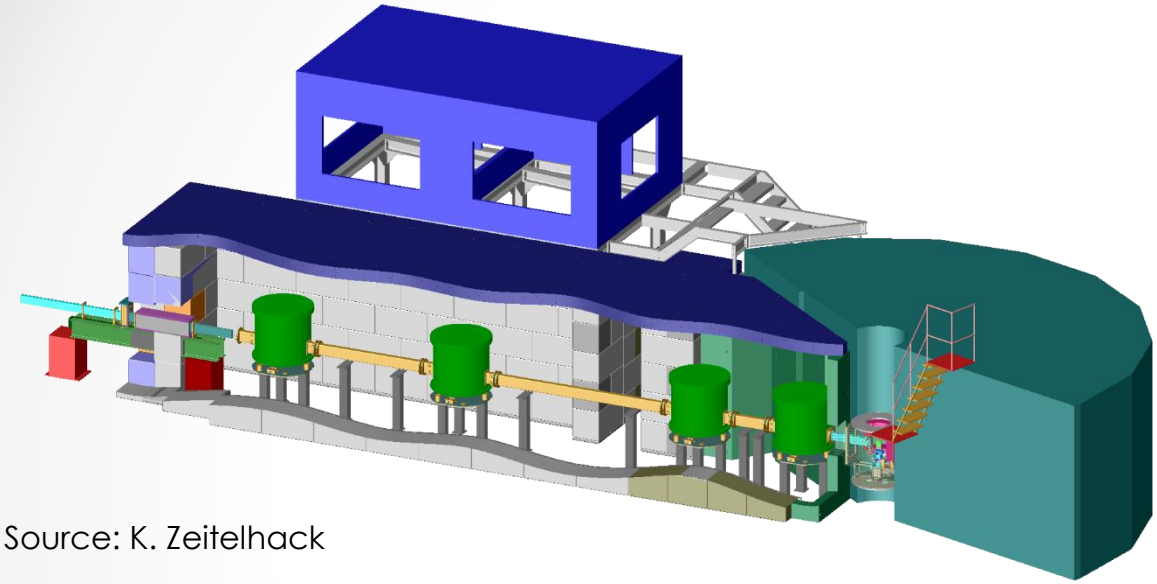
Gas Electron Multiplier

Position resolution 1.1 mm FWHM



S. Uno, IEEE Transaction Nuclear Science, Vol. 55, N. 5, October 2008, 2698-2703

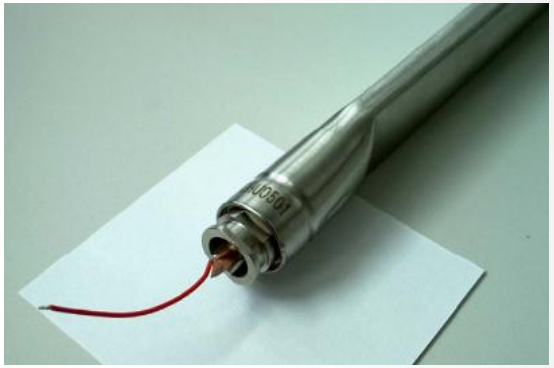
TOF-TOF at FRM-II



Source: K. Zeitelhack

Detectors

- 1000 detectors
- 10 bar ^{3}He
- 40 cm x 3 cm x <1.3>



WISH at ISIS Target Station 2

760 (1520) RWD

1m long

8 mm Ø

15 bar ^{3}He

<8 mm FWHM

389120x2 pixels

~5000 time channels

Merlin at ISIS Target Station 1

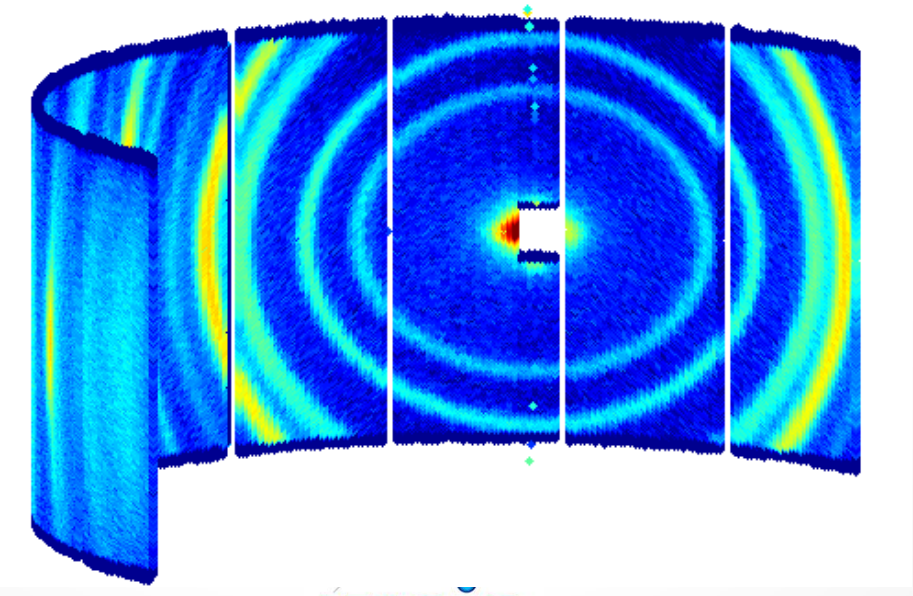
280 RWD

3 m long

25.4 mm Ø

10 bar ^{3}He

3 bar Ar



IN5 at ILL

3m long

25.4 mm Ø

4.5 bar ^{3}He

~3000 l of ^{3}He

LET at ISIS Target Station2

384 RWD

4 m long

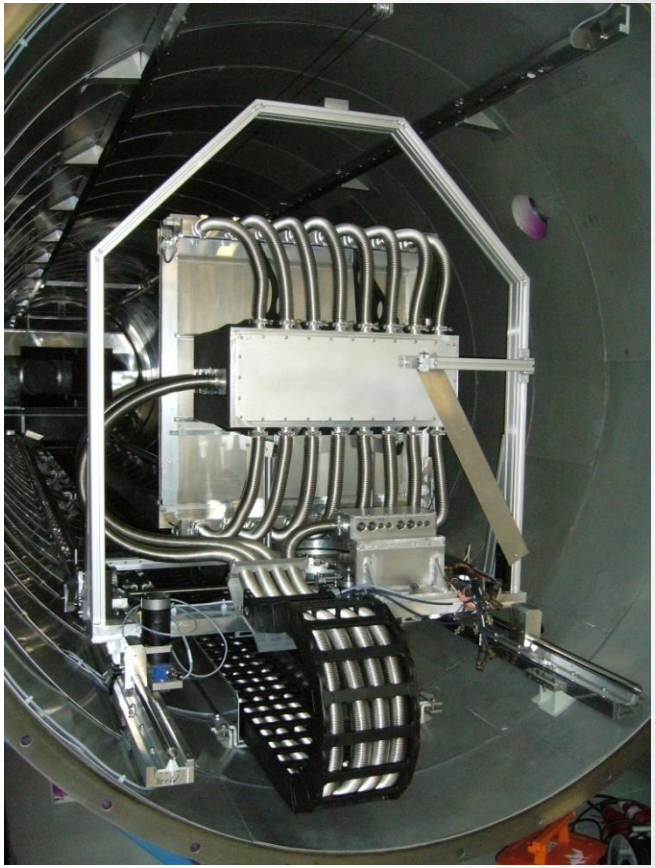
25.4 mm Ø

10 bar ^{3}He

3 bar Ar

n (E_0)

SANS-1 at FRM II



- 128 RWD
- 1 m long
- 8 mm Ø
- 15 bar ^{3}He

Sans 2D at ISIS Target Station 2

2 MWPC

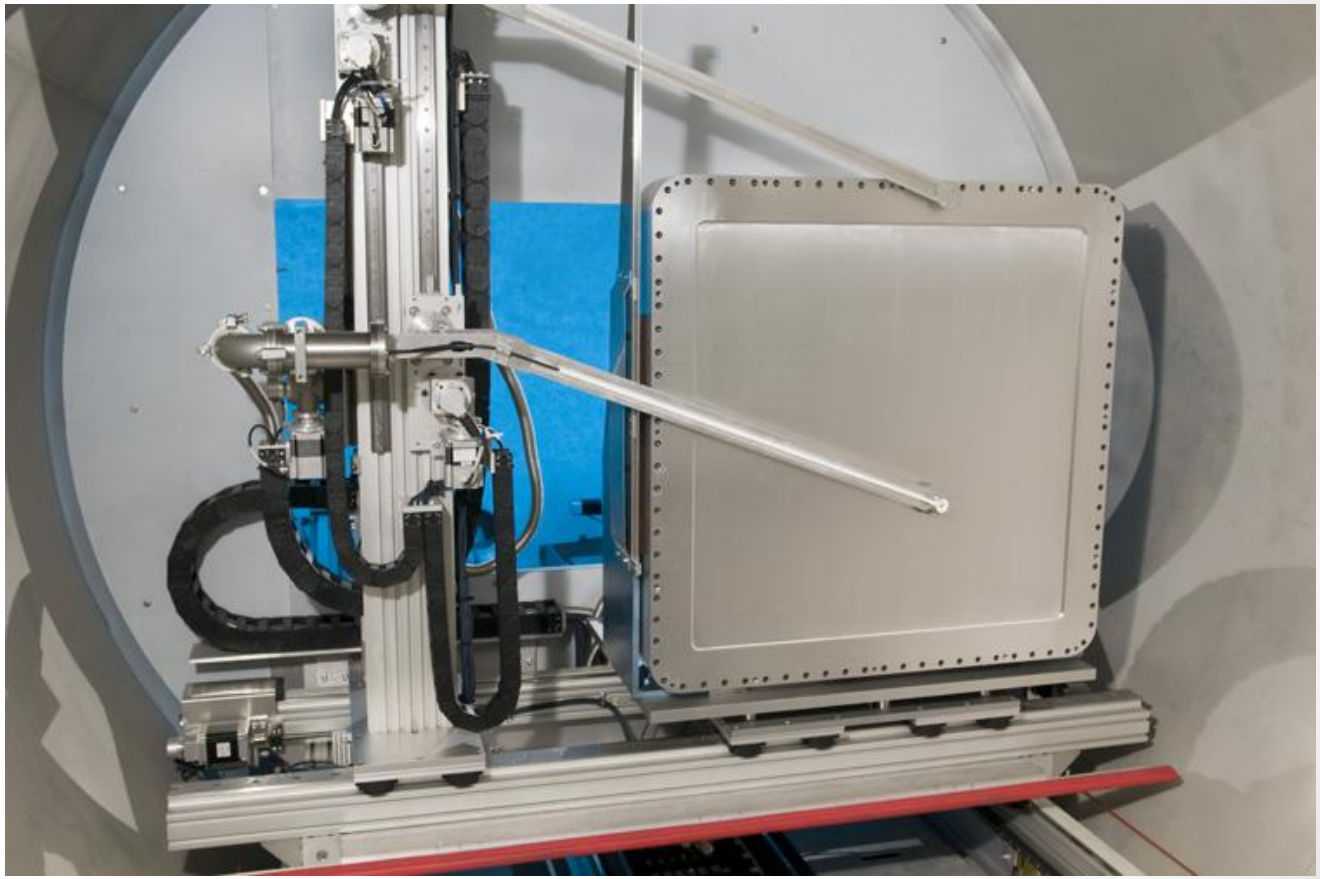
1 m^2

5 mm wire pitch

5 cm deep

<1 bar ^3He

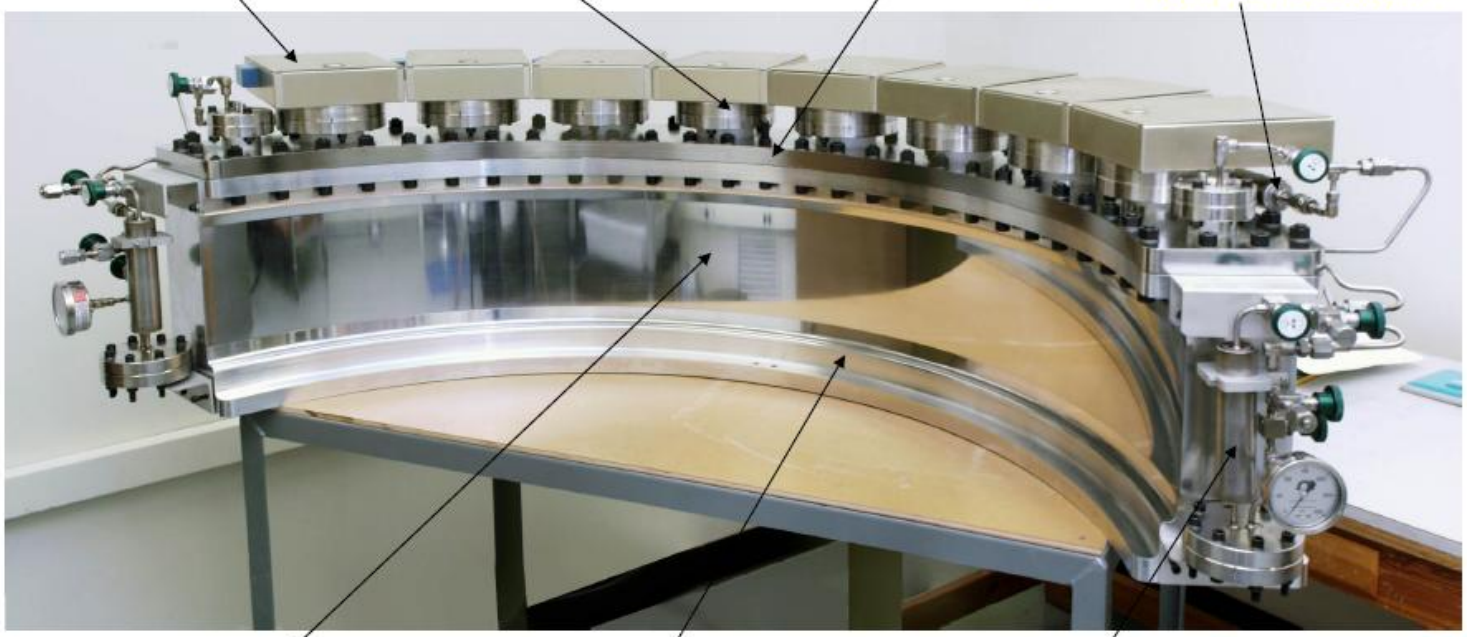
<1 bar CF_4



MWPC at Brookhaven

120° Two-Dimensional Thermal Neutron Detector for Protein Crystallography

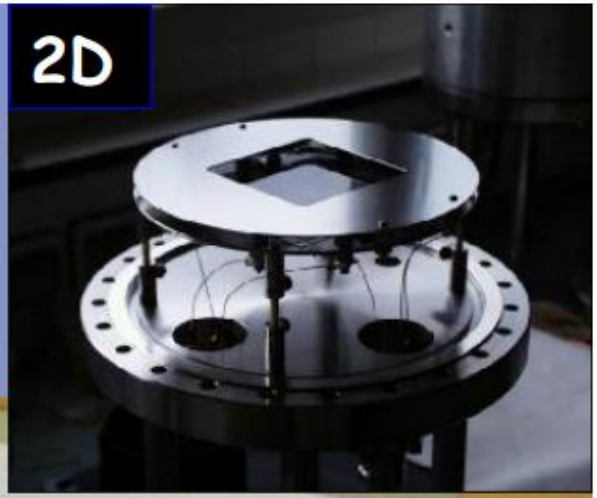
- 0.3 m^2 area, $>10^5$ resolution elements, 1.5 mm FWHM
- Single gas volume, continuously sensitive readout
- Timing resolution → 0.15Å wavelength bandwidth
- 8 independent. wire segments → modularity, high count rate, $> 10^6\ s^{-1}$
- Encoding electronics optimized for high throughput, low noise
- Decoding with high performance digital signal processing

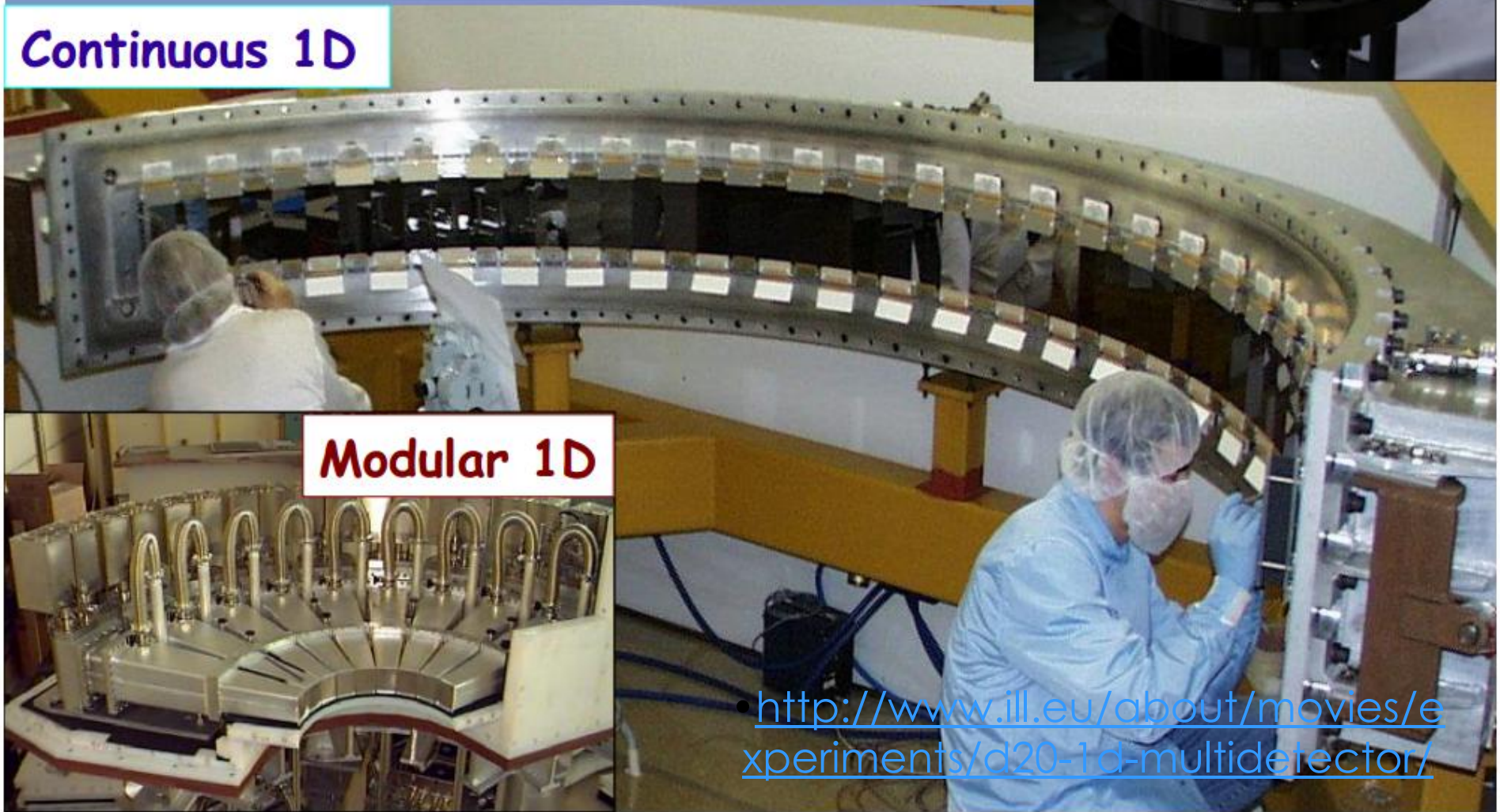


INSTRUMENTATION DIVISION

BROOKHAVEN NATIONAL LABORATORY

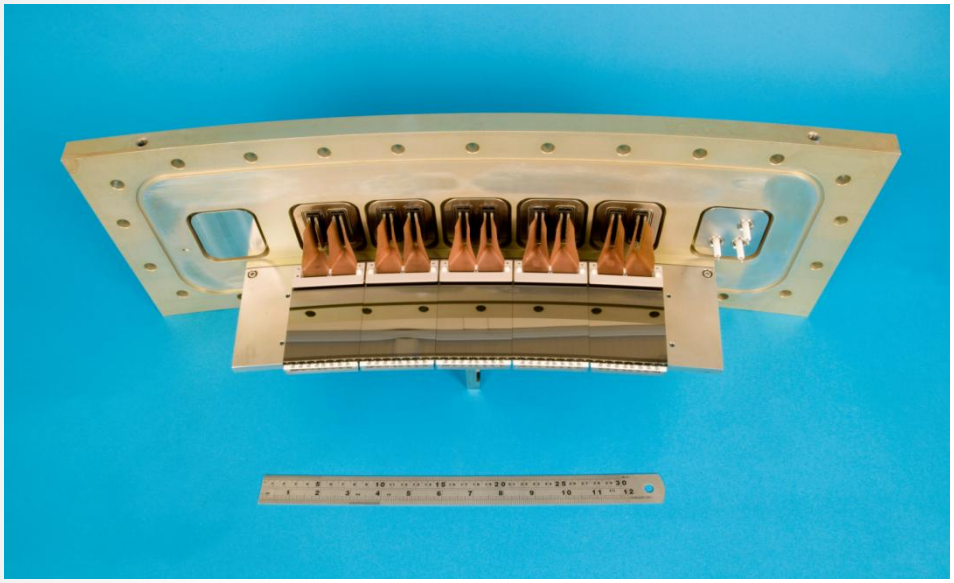
MSGC neutrons detectors at the ILL

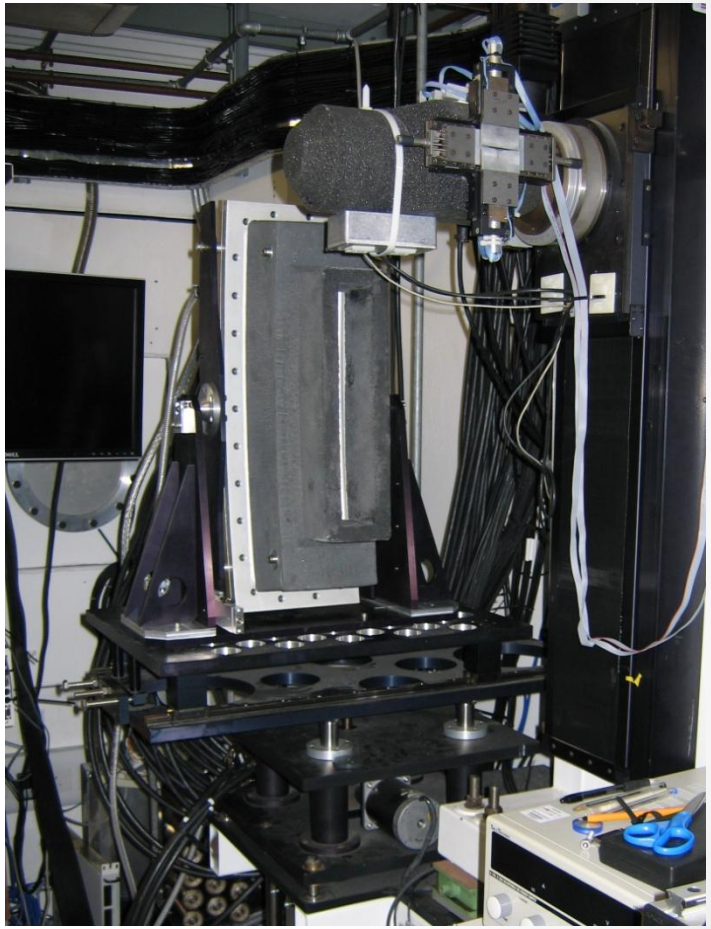




- http://www.ill.eu/about/movies/experiments/d20-1d-multidetector/

OSMOND for ISIS Reflectometers





Conclusions

- From the neutron to the signal, passing through some gas...
- How to multiply the electrons and how to collect as quick as possible the slow ions
- Existing detectors on instruments
- ^{3}He detector is the most used, but...

Where did I copy?

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- Radiation detection and measurements, G.F. Knoll (Wiley, New York 1999)
- Instrumentation in high energy physics, ed. by F. Sauli (World Scientific, Singapore 1992)
- Electron avalanches and breakdown in gases, H. Raether (Butterworth, London 1964)

- G. Charpak and F. Sauli: High-resolution electronic particle detectors, Ann. Rev. Nucl. Part. Sci. 34(1984)28

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- F. Sauli and A. Sharma: Micropattern Gaseous Detectors, Ann. Rev. Nucl. Part. Sci. 49(1999)341

- ***http://www.cern.ch/GDD***