TRIUMF

Experimental Techniques: Fundamentals

Martin Alcorta

EBSS2023

2023-07-10

Discovery, accelerated

TRIUMF

Outline

- (Quick) History of radiation detectors
- Fundamentals of detection (what exactly do we measure?)
- Types of detectors
  - Gas → electron/ion pairs -> current
  - Semiconductors, electron/hole pairs → current
  - Scintillators → light -> current
- Signal pulse processing (from signal to counts in a spectrum)

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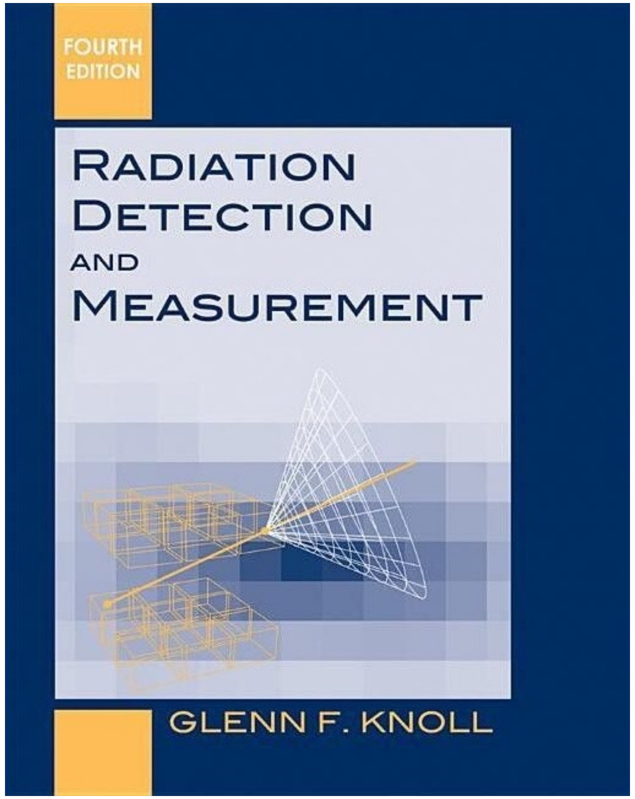
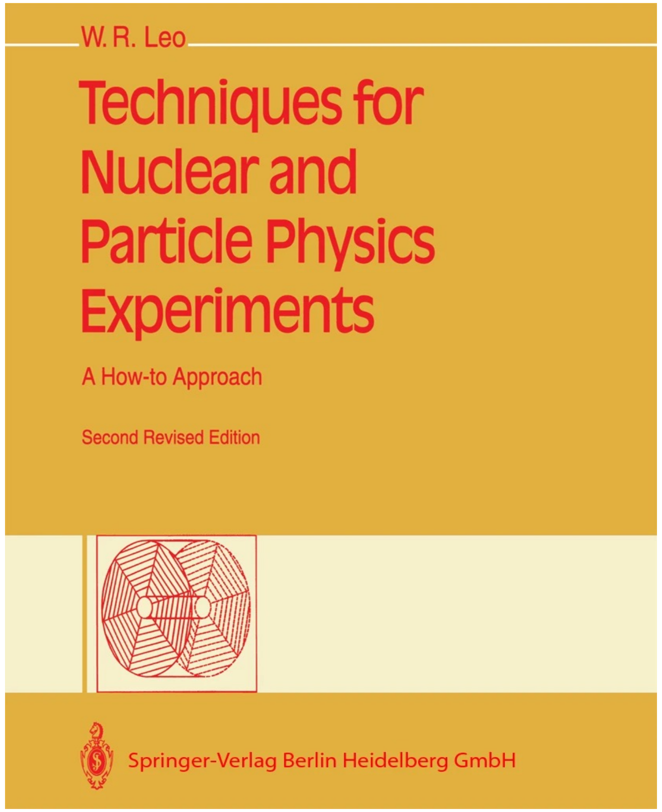
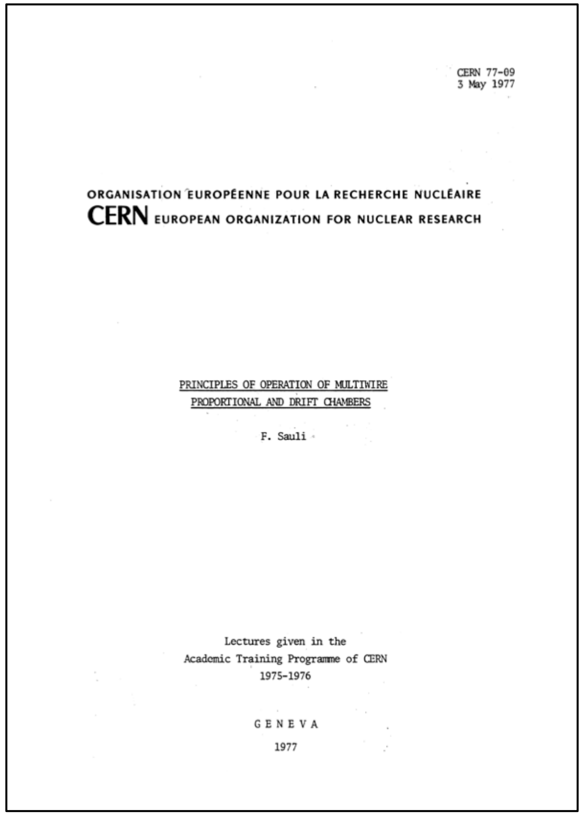
Resources






CERN 77-09
3 May 1977

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CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PRINCIPLES OF OPERATION OF MULTIWIRE PROPORTIONAL AND DRIFT CHAMBERS

F. Sauli

Lectures given in the
Academic Training Programme of CERN
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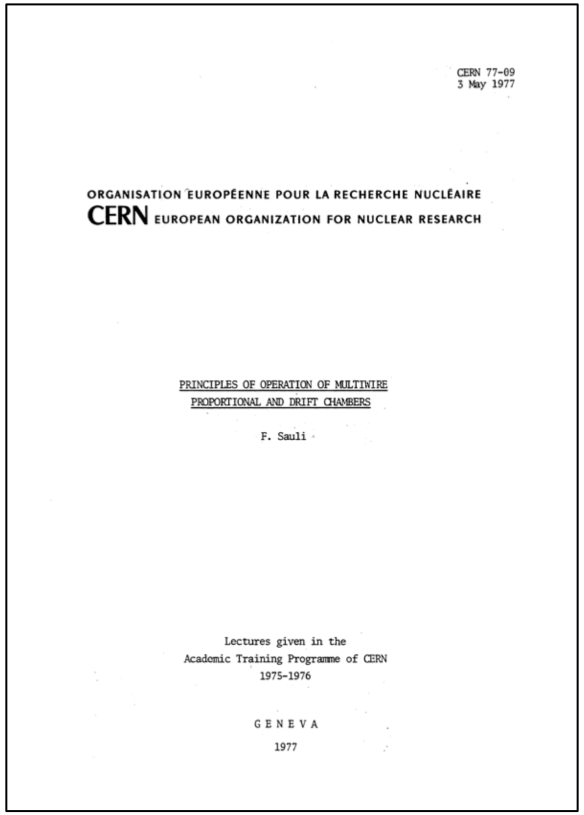
GENEVA
1977

https://cds.cern.ch/record/117989/files/CERN-77-09.pdf

Resources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Radiation Detectors: Brief History

An Electrical Method of Counting the Number of α-Particles from Radio-active Substances.

By E. Rutherford, F.R.S., Professor of Physics, and H. Geiger, Ph.D., John Harling Fellow, University of Manchester.

(Read June 18; MS. received July 17, 1908.)

1908, Ernest Rutherford and Hans Geiger: “An electrical method of counting the number of α-particles from radio-active substances”

E. Rutherford and H. Geiger, Proceedings of the Royal Society A, **81**. 546

Radiation Detectors: Brief History

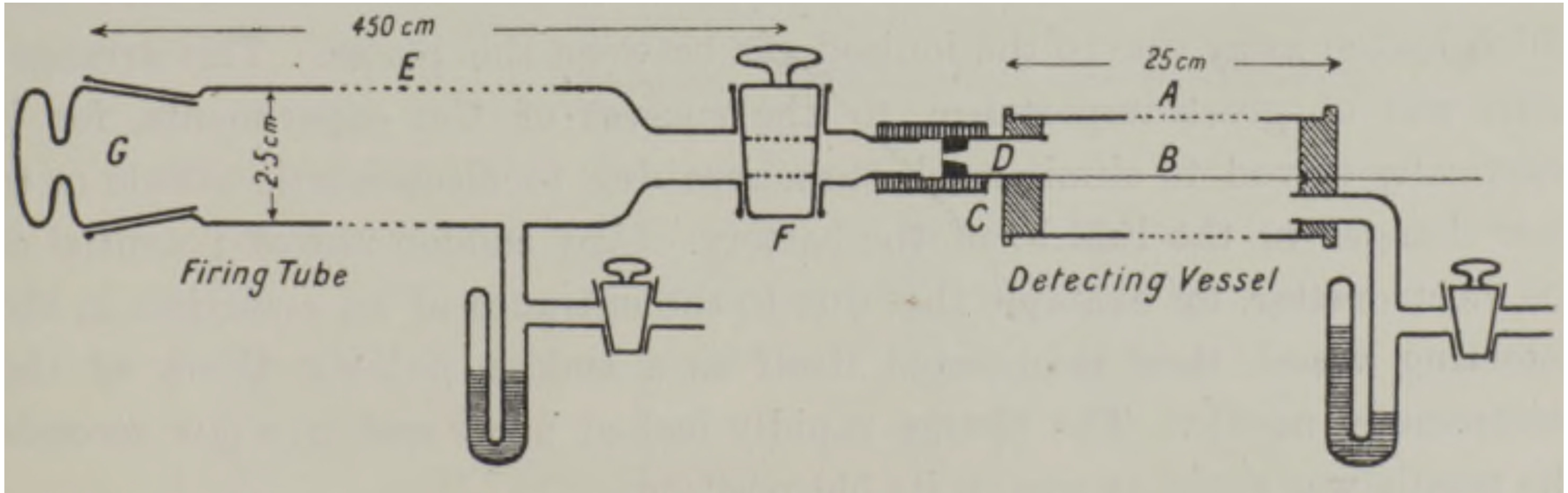
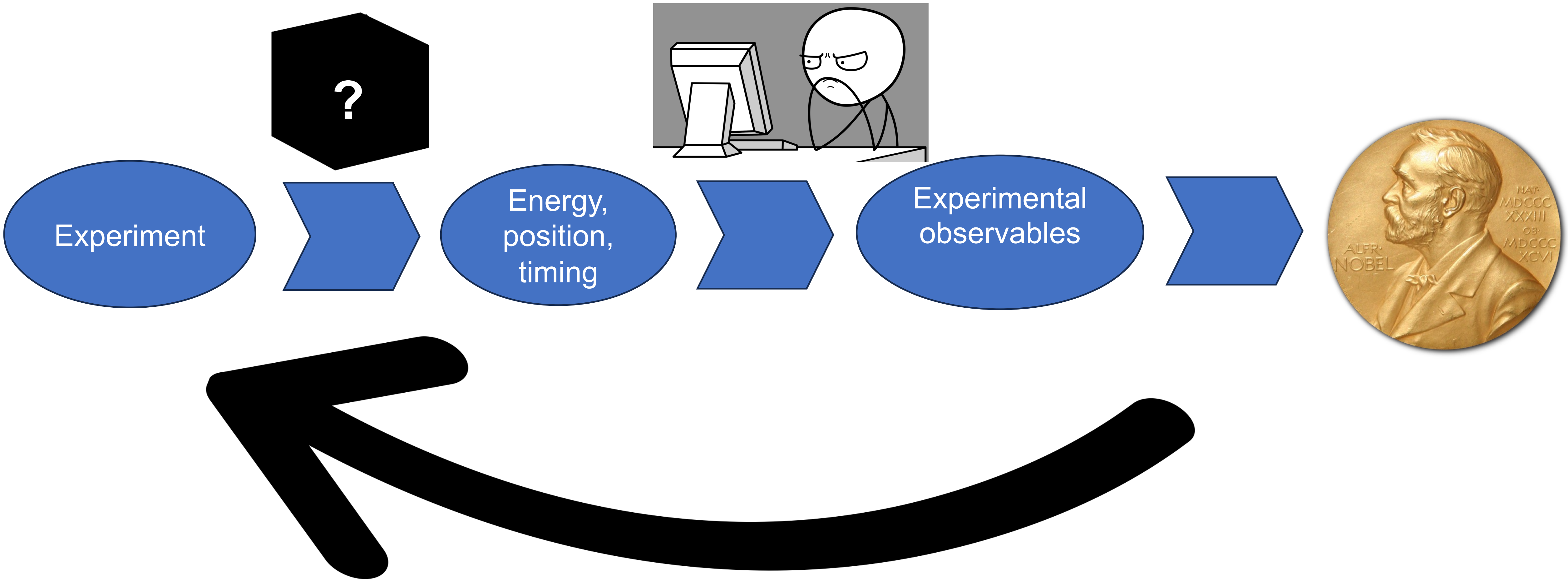


Fig. 1.

- *"In our experiments to detect a single α-particle, it was arranged that the α-particles could be fired through a gas at low pressure exposed to an electric field somewhat below the sparking value. In this way, the small ionisation produced by one α-particle in passing along the gas could be magnified several thousand times. The sudden current through the gas due to the entrance of an α-particle in the testing vessel was thus increased sufficiently to give an easily measurable movement of the needle of an ordinary electrometer."*

E. Rutherford and H. Geiger, Proceedings of the Royal Society A, **81**. 546 "An Electrical Method of Counting the Number of α-Particles from Radio-active Substances

What (exactly) are we trying to measure?



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Interactions of (heavy) *charged particles* with matter:
i.e. What do we measure?

- Mainly interact via Coulomb force (interactions with nucleus negligible) and leave behind free **electron / ion pair**
- Bethe-Bloch formula for stopping power S:

$$-\frac{dE}{dx} = K\rho \frac{Z}{A}\frac{z^2}{\beta^2}\left[ln\frac{2m_0\gamma^2v^2W_{max}}{I^2} - 2\beta^2\right]$$

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Materials with higher charge slow down particle faster

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Materials with higher mass do not slow down particle faster

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Particles with higher charge lose energy faster

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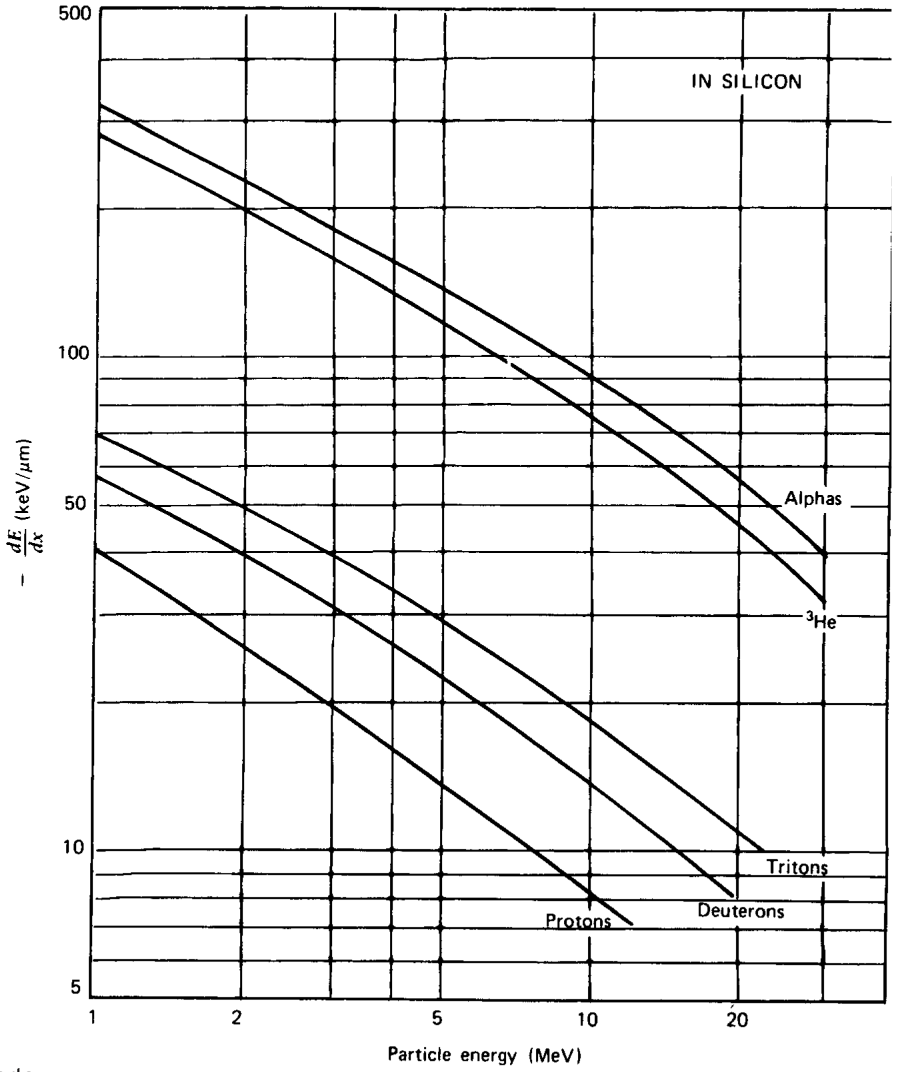
Energy loss varies inversely with particle energy

Interactions of (heavy) *charged particles* with matter

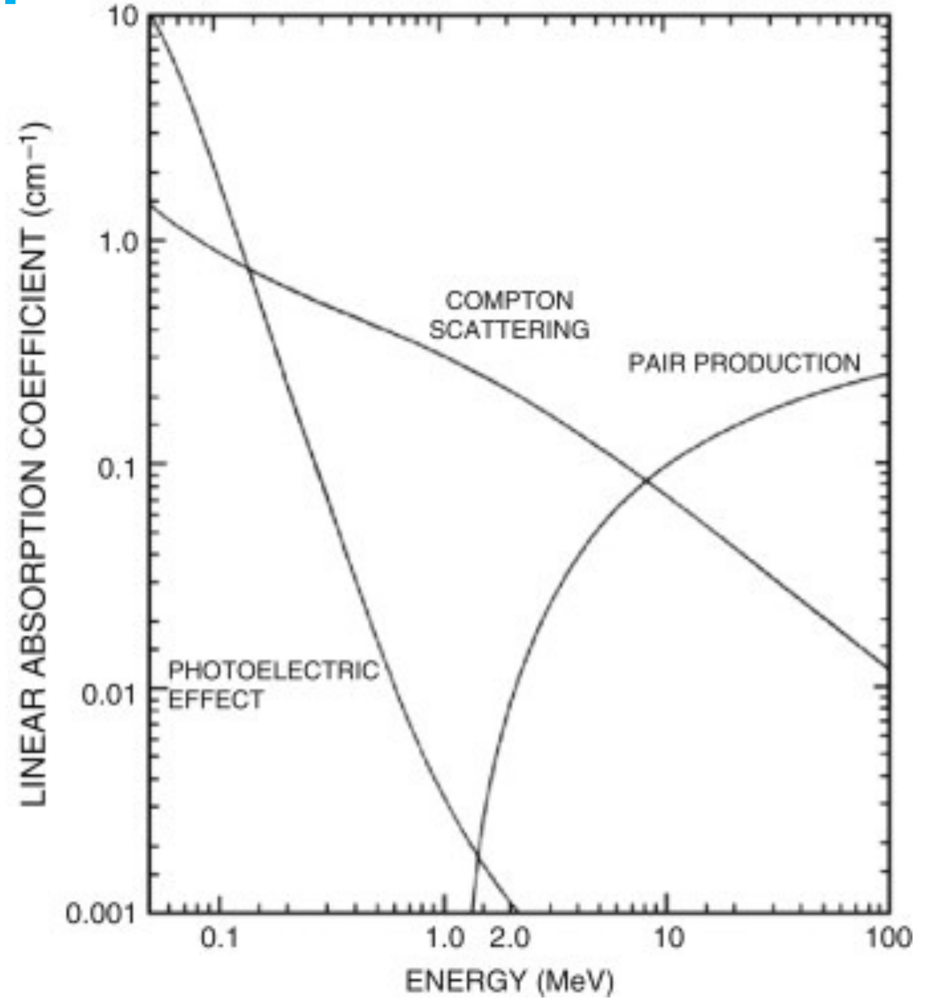
$$-\frac{dE}{dx} = K\rho\frac{Z\,z^2}{A\,\beta^2}\left[ln\frac{2m_0\gamma^2v^2W_{max}}{I^2} - 2\beta^2\right]$$

- We can use this to our advantage for particle identification!



Interactions of *gamma-rays* with matter

- Great! But, what about neutrons and gammas? No coulomb force ☹ to slow it down
  - Detect charged particle (e-) emitted via interactions
- Unlike charged particles, gamma-rays do not have continuous energy loss:
  - Photoelectric absorption-> $\propto \frac{Z^{\sim 4.5}}{E_{\gamma}^{3.5}}$ $E_{\gamma} \approx$ kicked out e-
  - Compton scattering: most common, kicks out e-, linear dependence with Z
  - Pair production: dominates > 5-10 MeV



Progress in Particle and Nuclear Physics 60 (2008) 283–337

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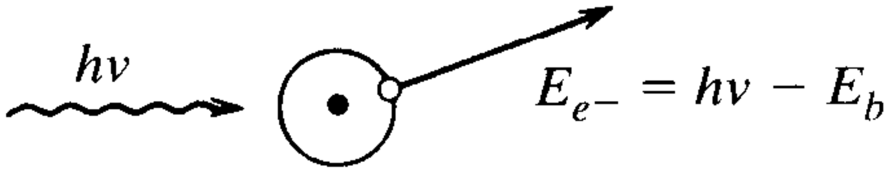

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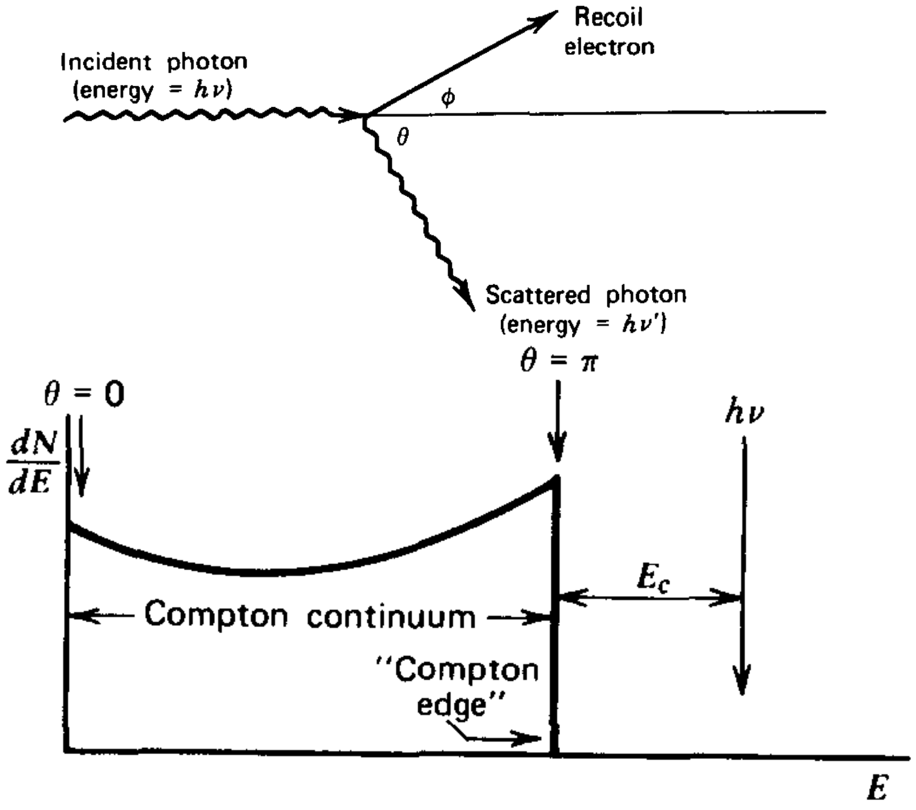

$$E_{e-}\Big|_{\theta=\pi} = h\upsilon\left(\frac{2h\upsilon/m_0c^2}{1+2h\upsilon/m_0c^2}\right) \rightarrow E_c \approxeq \frac{m_0c^2}{2}$$

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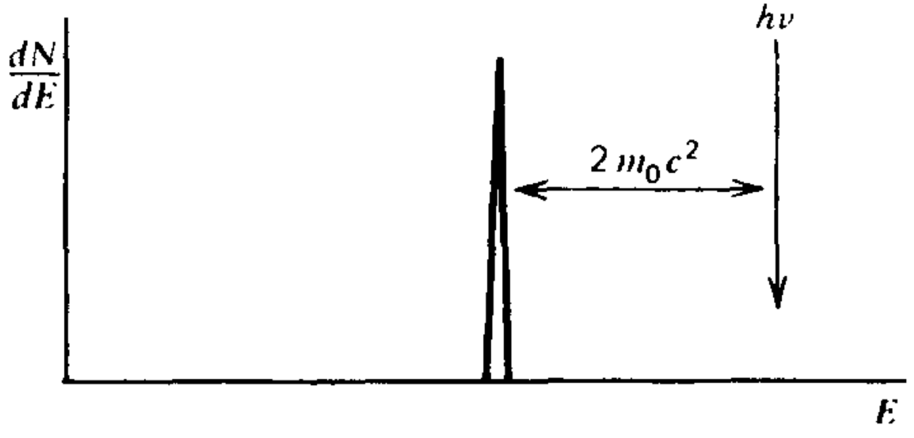
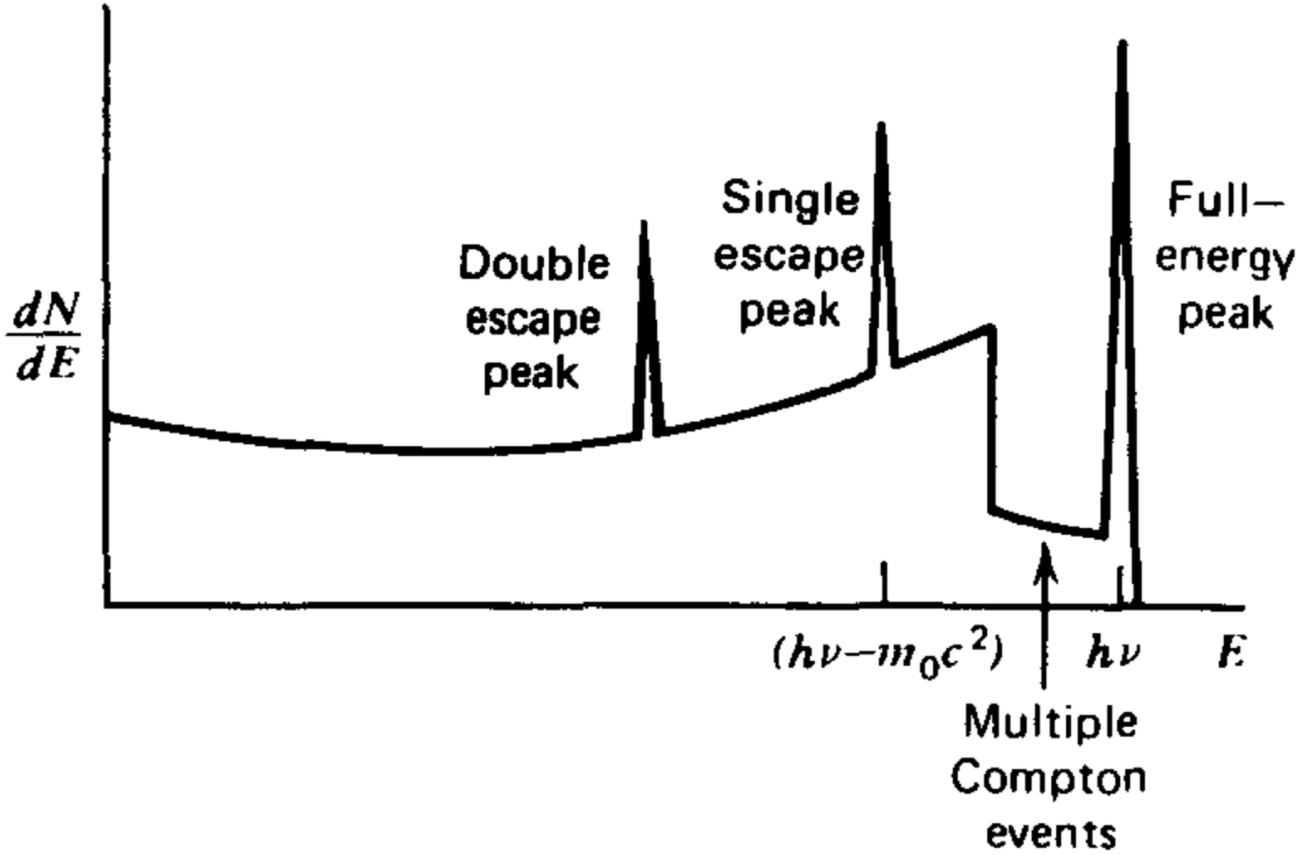
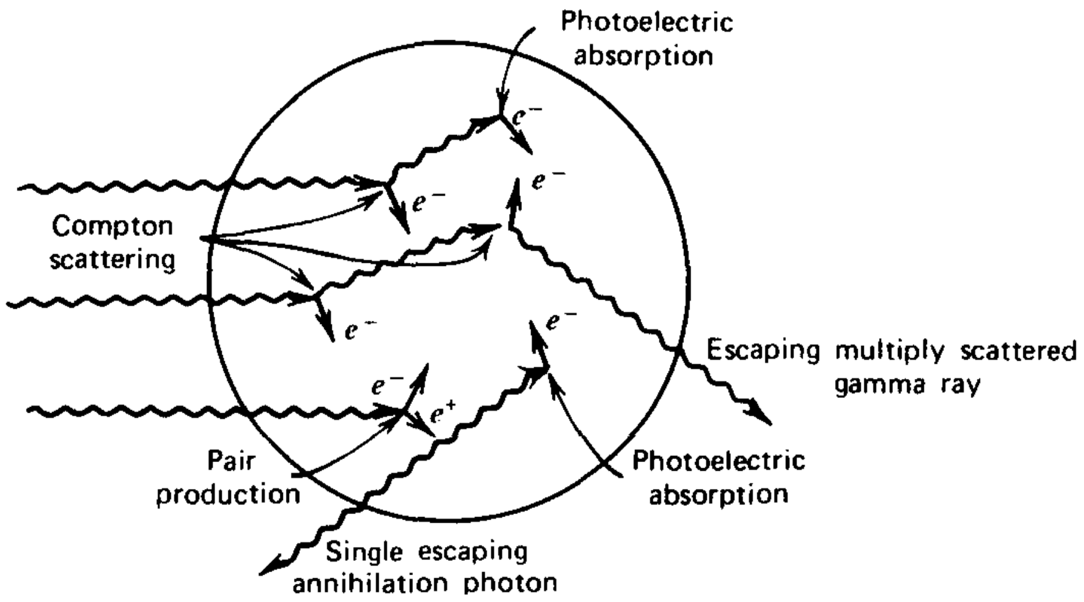
  - Photoelectric absorption-> $\propto \frac{Z^{\sim 4.5}}{E_\gamma{}^{3.5}}$

    $E_\gamma \approx$ kicked out e-
  - Compton scattering: most common, kicks out e-, linear dependence with Z
  - **Pair production: dominates at higher energies**



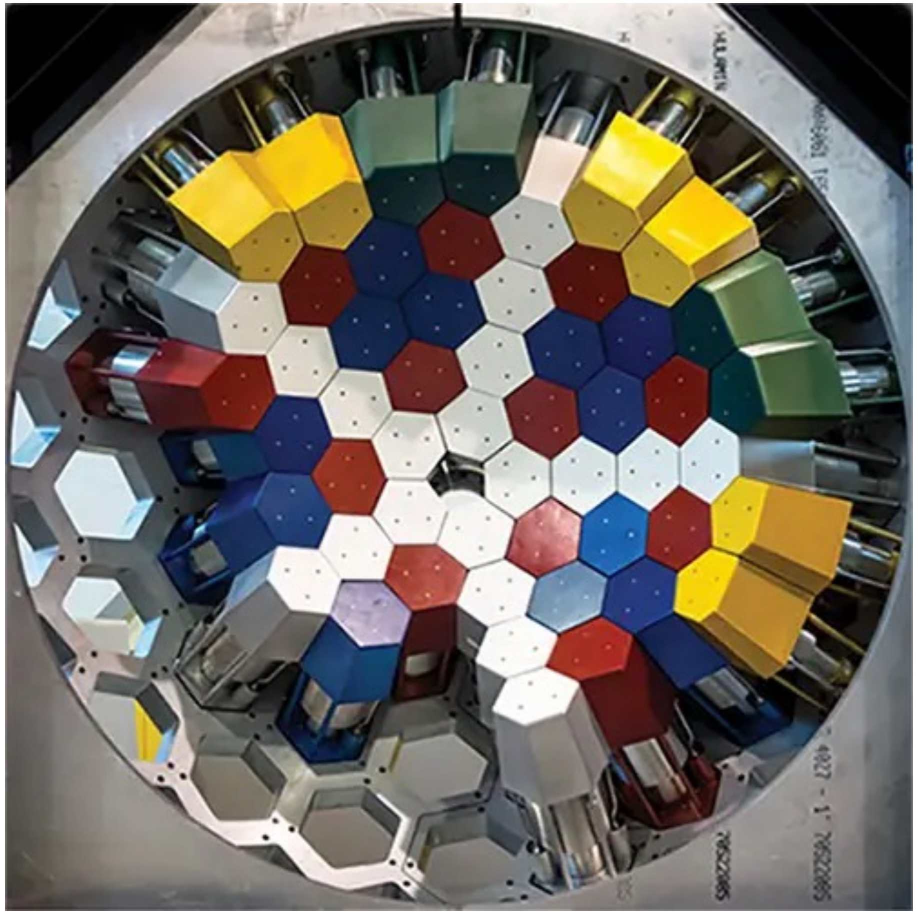
Interactions of *gamma-rays* with matter





Interactions of *neutrons* with matter

- Neutrons interact with nucleus of absorbing material-> detect secondary radiation of resulting heavy charged particles
- Proton recoil scintillators (n,p)
- Obtain energy from ToF
  - Liquid scintillators
    - **DESCANT** array
  - Plastic scintillators
    - VANDLE, MONA

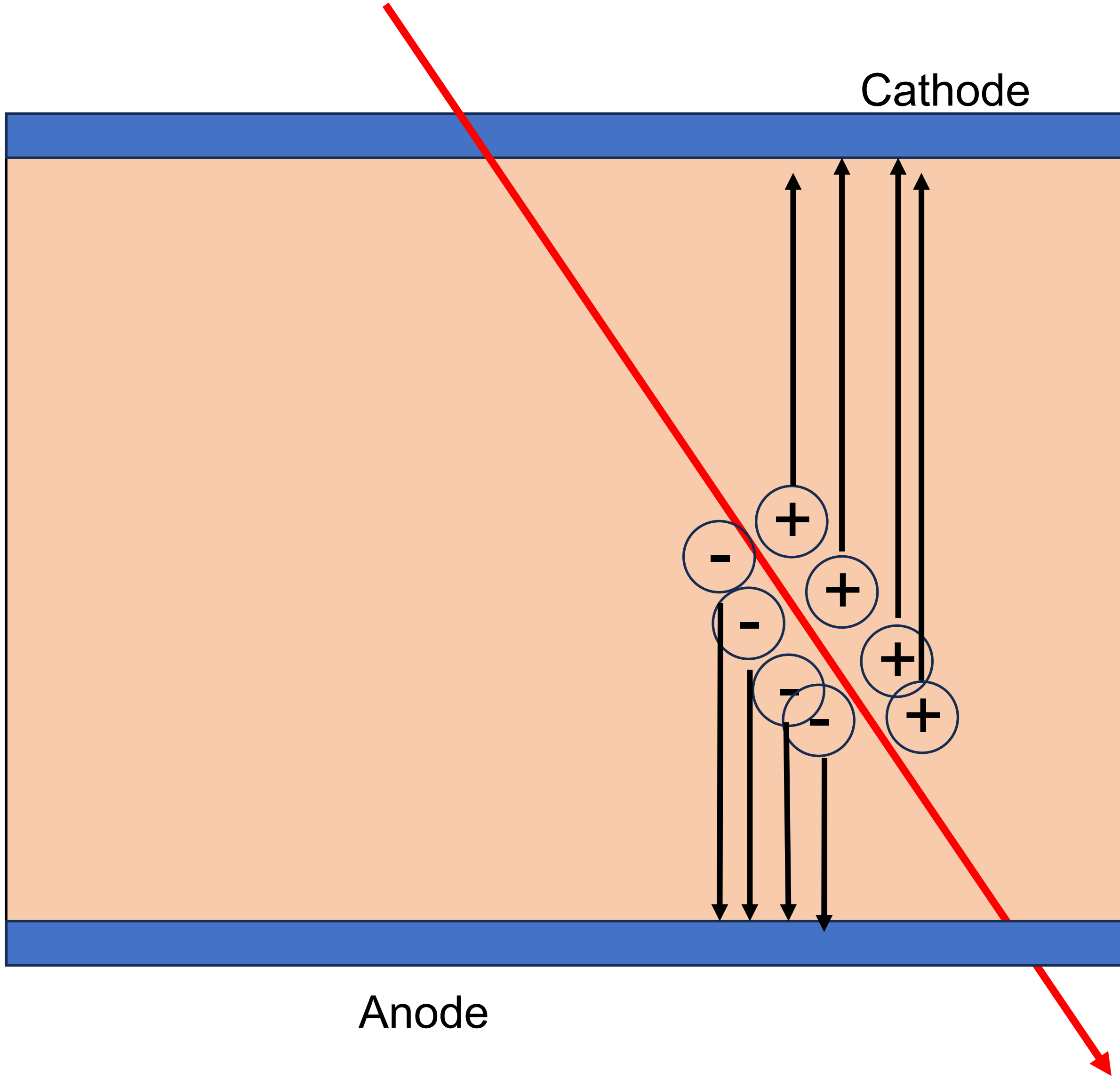


Detectors

- **Gas detectors**
  - IC, proportional counters
- **Semiconductor diodes**
  - Si (charged particle), Ge (gamma-ray)
- **Scintillation detectors**
  - light output

Gas Detectors

- Charged particle creates e-/ion pairs
  - W-value ≈ 25-35 eV
  - ~30k pairs per 1 MeV for typical gas
- Ionization chambers
  - Electrons drift to anode and induced charge seen on electrode-> signal independent of HV
- Proportional counters
  - Townsend avalanche



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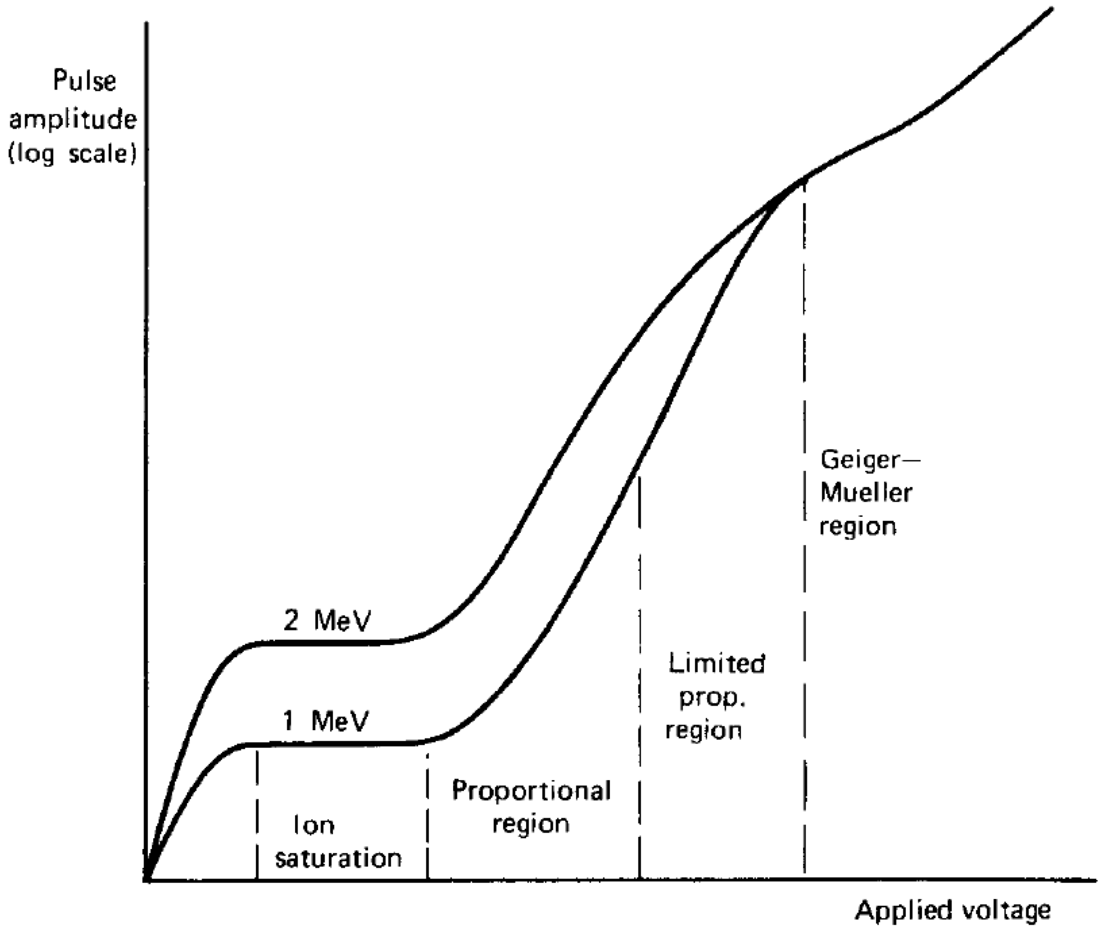
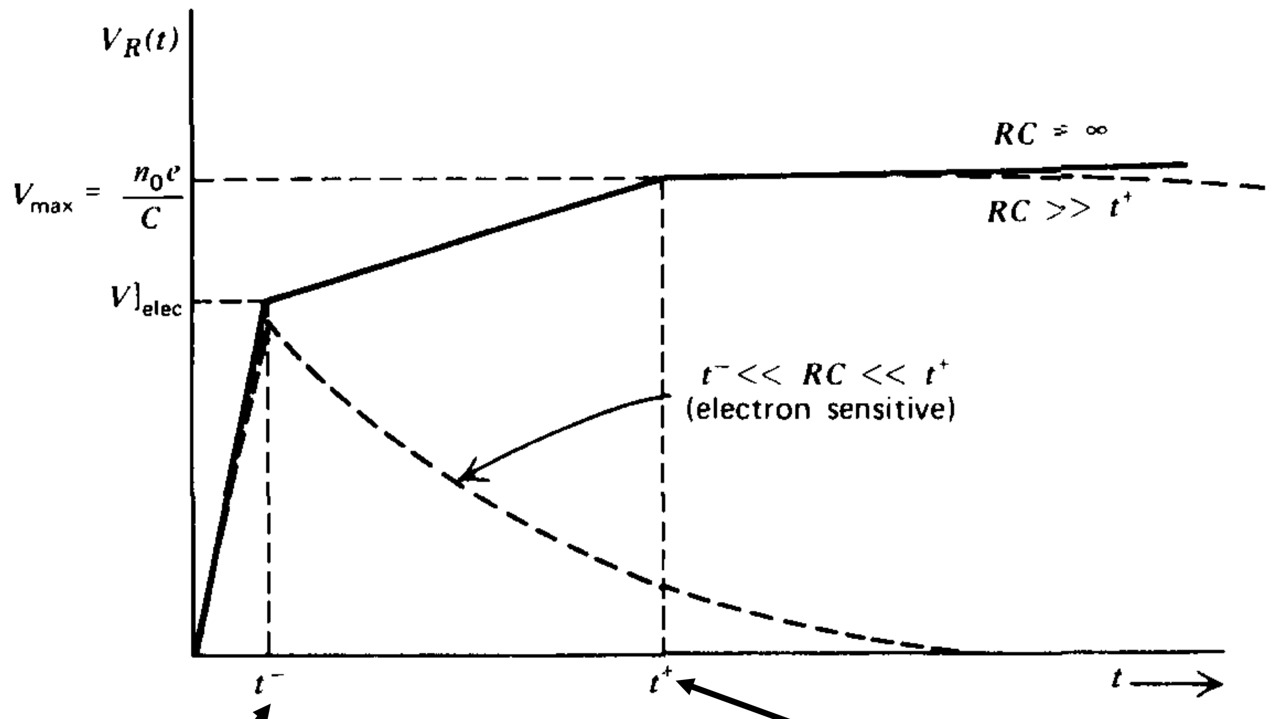


https://cds.cern.ch/record/117989/files/CERN-77-09.pdf

Gas Detectors: Ionization chambers

- Drift velocity $v = \frac{\mu E}{p}$
- ~10 ms over 1 cm for ions
  ~µs for e-



Time for e- to reach anode

Time for ions to reach cathode

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Gas Detectors: Ionization chambers

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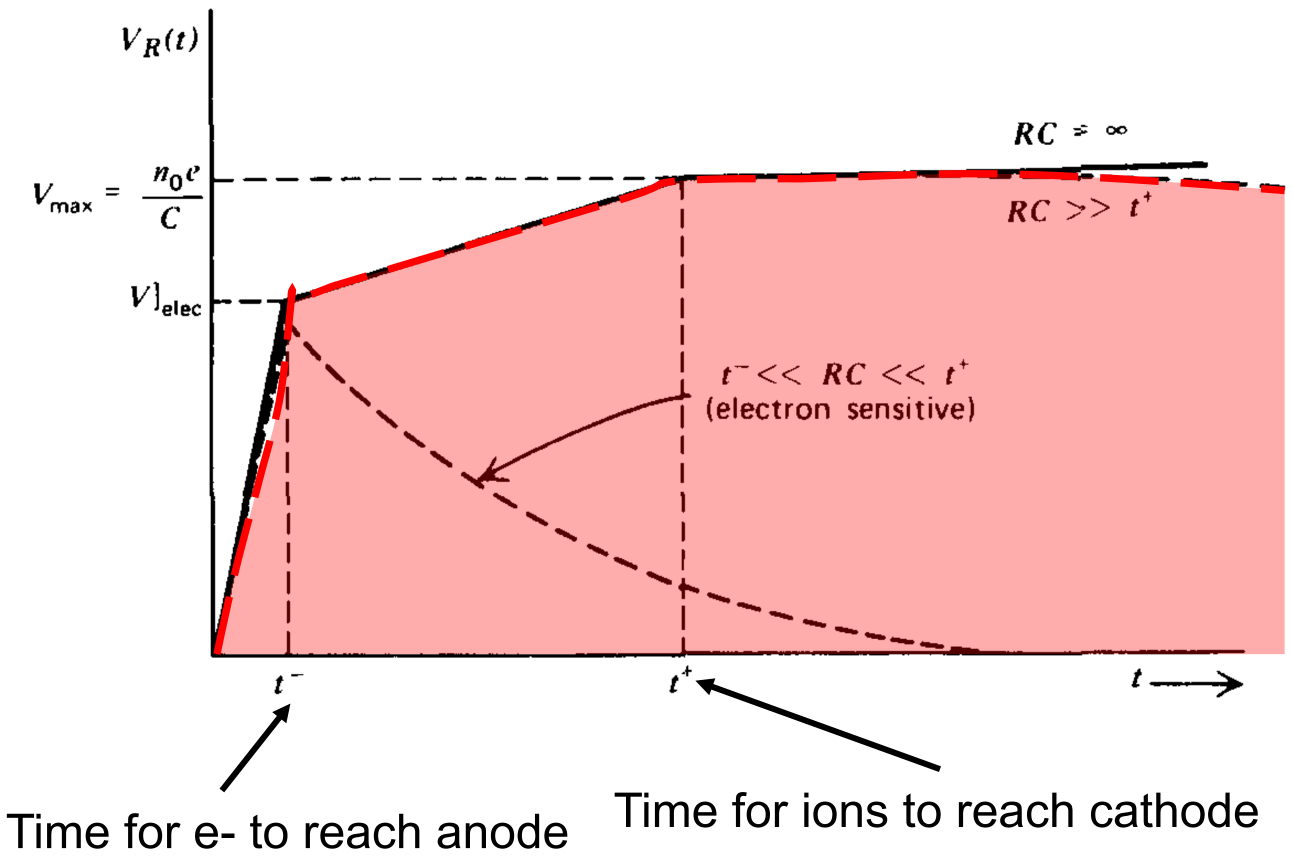
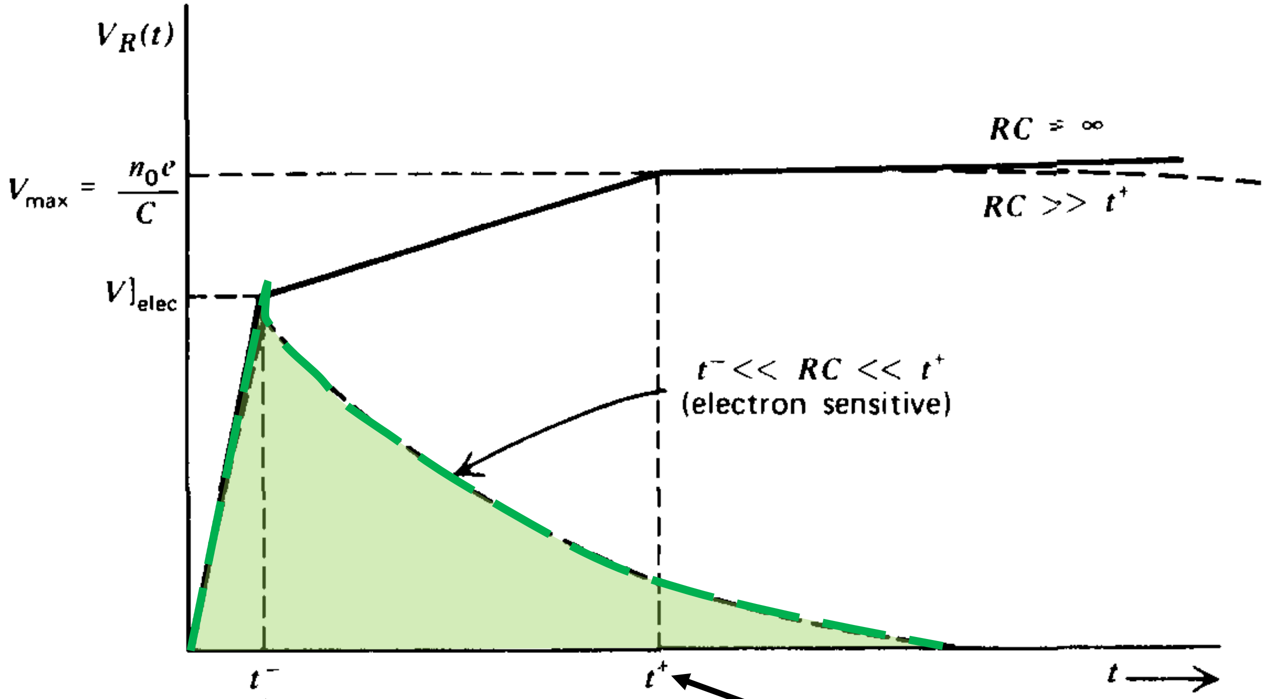


Gas Detectors: Ionization chambers

- Drift velocity $v = \frac{\mu E}{p}$
- ~10 ms over 1 cm for ions
  ~μs for e-
- Use the "fast" signal to count beam
  - Lose portion of pulse derived from ion drift
  - Amplitude now dependent on where electrons formed
    - $V|_{elec} = \frac{n_0 e}{C} \cdot \frac{x}{d}$



Time for e- to reach anode

Time for ions to reach cathode

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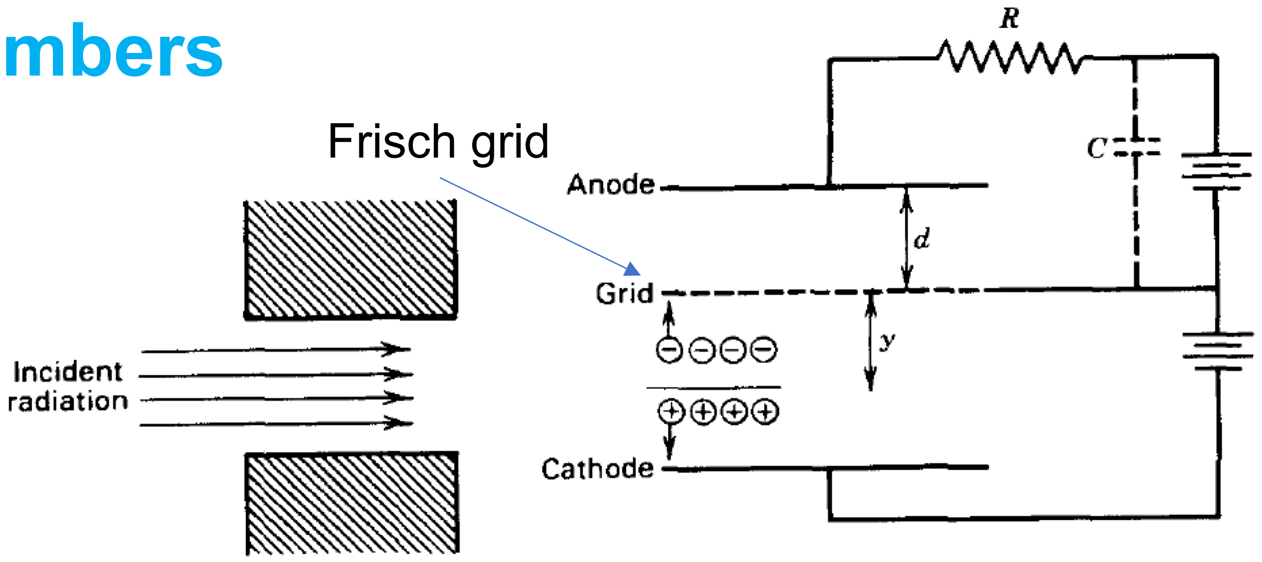
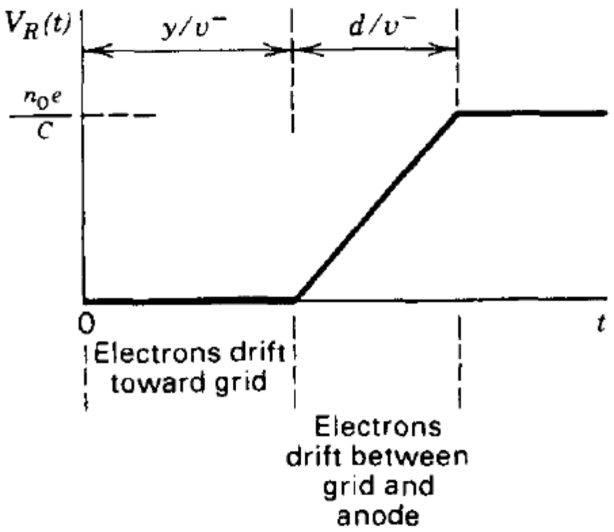
Gas Detectors: Ionization chambers

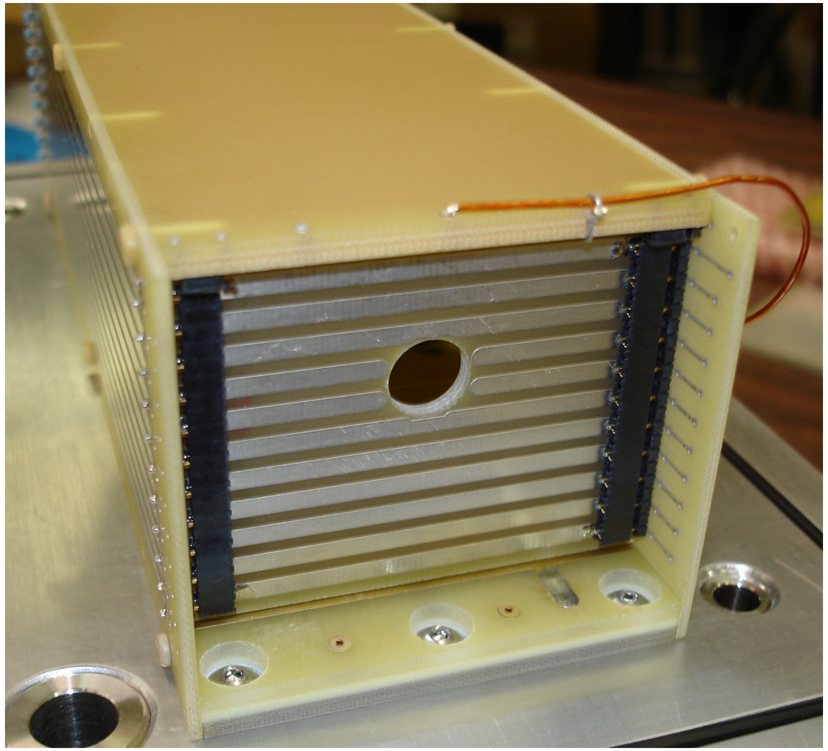
- Frisch grid removes position dependence of signal on "y"
- Signal derived only from the drift of the electrons
  - Held at intermediate potential (must be transparent to e-)





Gas Detectors: Ionization chambers

- Using e- signal allows for fast counting; can also identify contaminants ($\Delta E \propto Z^2$)
- Tilted electrodes to reduce response time
  - 500 kHz, 5% energy resolution



IRIS (TRIUMF) transmission IC

Nuclear Inst. and Methods in Physics Research, A 890 (2018) 119–125
Nuclear Inst. and Methods in Physics Research, A 751 (2014) 6-10

Gas Detectors: Proportional counteres

- Same principle as IC, increase HV (~10^6 V/m), create additional e-/ion pair-> avalanche
- PPAC/PGAC:
  - Position sensitive PPAC/PGAC often used to determine (x,y) coordinate of beam (e.g. FP detector in spectrometers)

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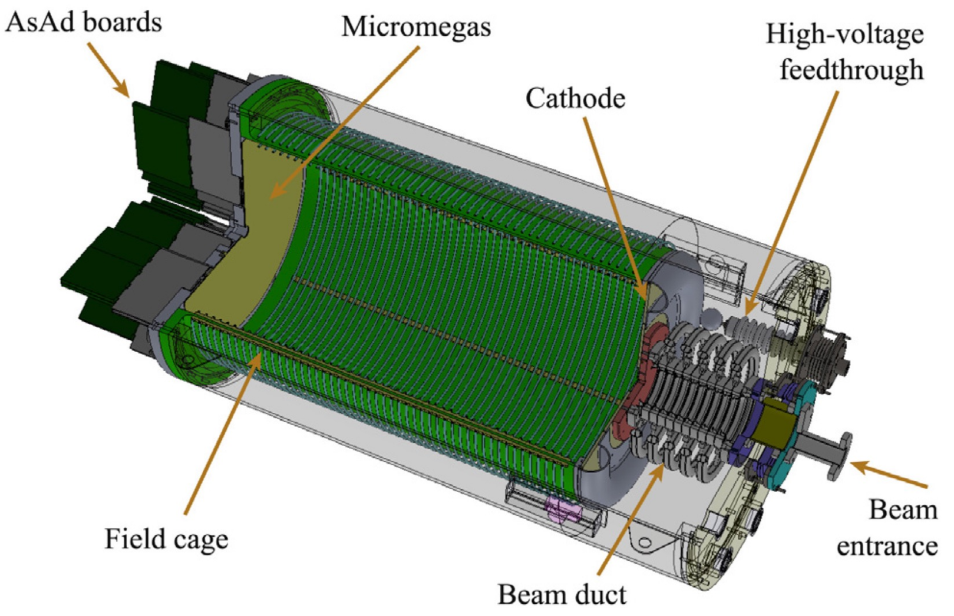
Gas Detectors: Proportional counters

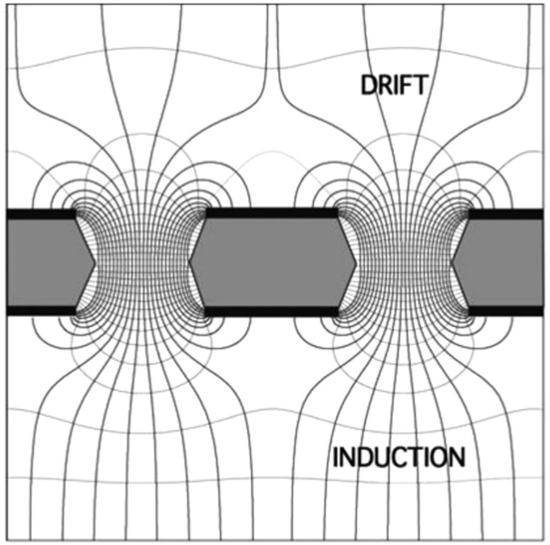
- Time projection chambers (TPC)
  - 3d tracking using drift time to determine position
- Active targets
  - Counter gas acts as target and detectors
- AT-TPC, TexAT, ACTAR, ANASEN
- Employ GEMs, Micromegas
- Many of these use auxiliary detectors (e.g. Si) to fully stop light ions

AT-TPC

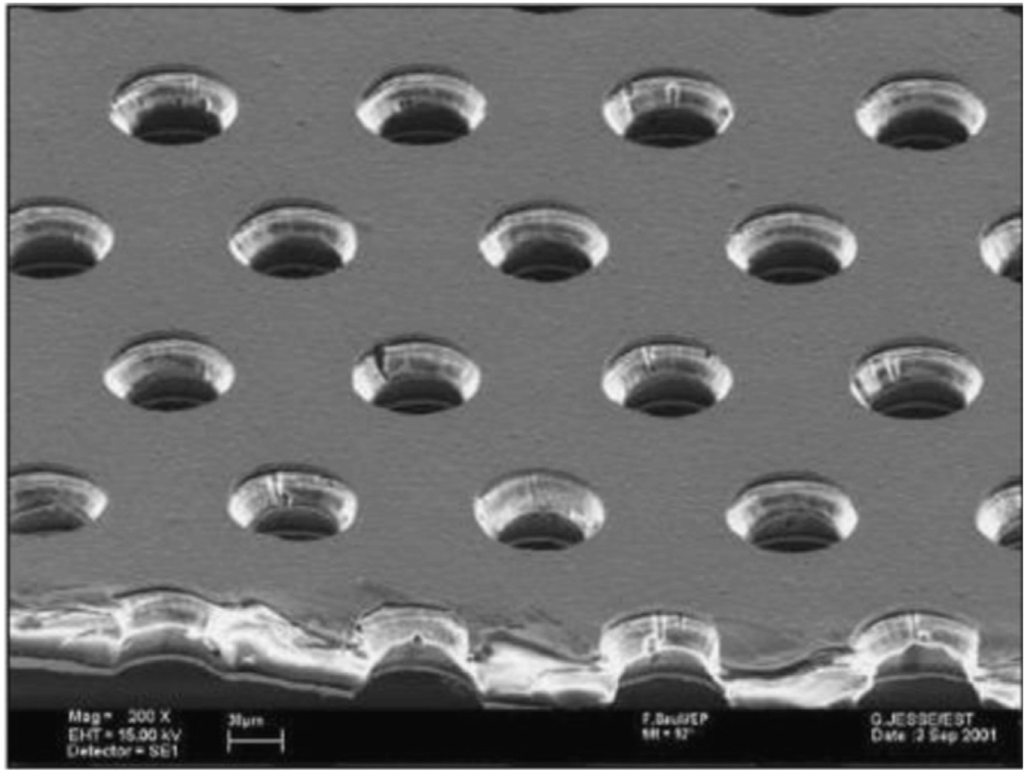


Nuclear Inst. and Methods in Physics Research, A 954 (2020) 161341

Gas Detectors: GEMS



- Gas electron multiplier (GEM)
  - Excellent spatial resolution
  - HV applied between faces of foil results in very high field -> gas multiplication
  - Can be combined to increase multiplication factor
    - Analogous to dynode stages of PMT

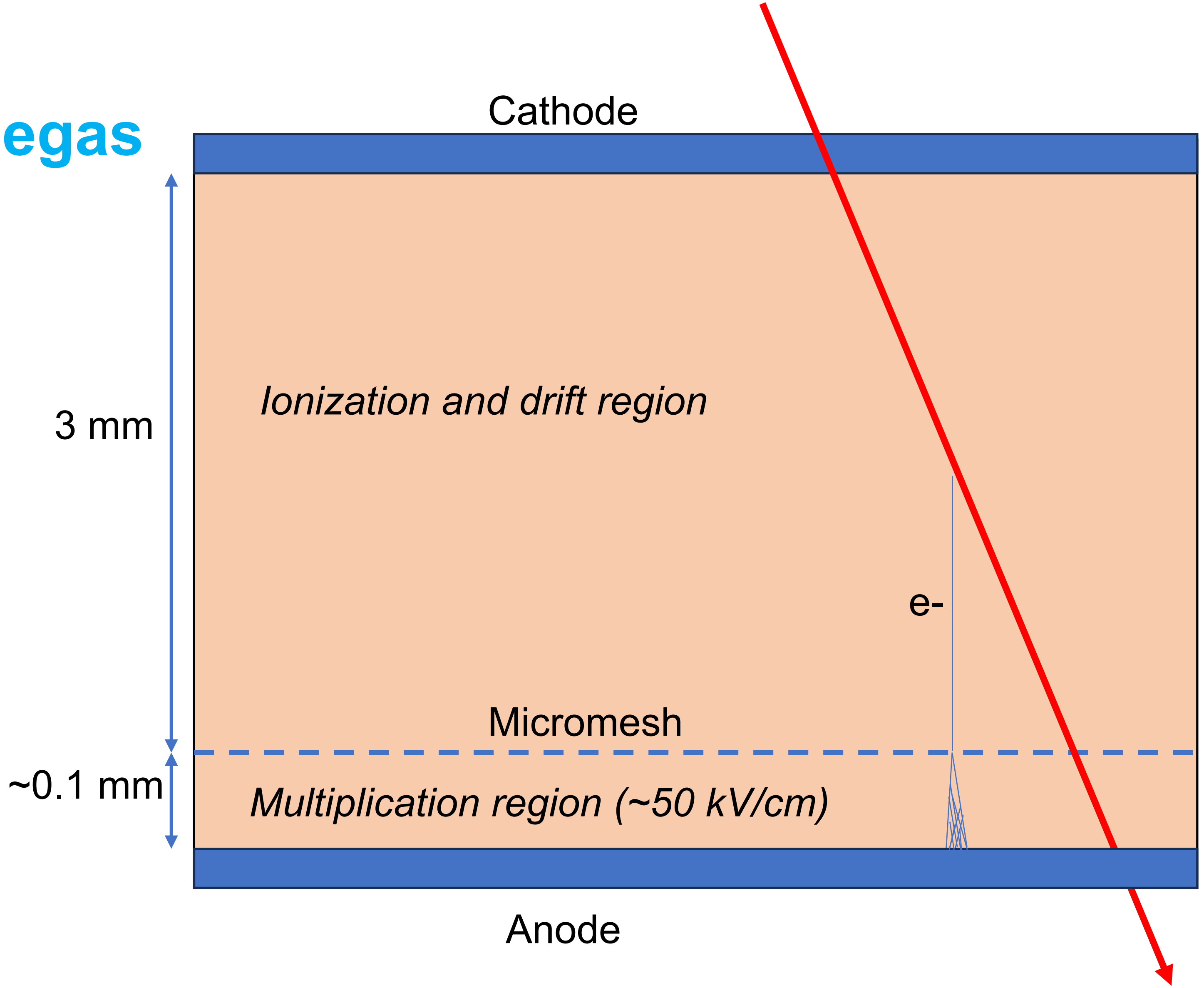


Pitch is 140 μm, diameter 70 μm

F. Sauli / Nuclear Instruments and Methods in Physics Research A 805 (2016) 2–24 3

Gas Detectors: Micromegas

- Micro-mesh gaseous structure
  - Drift region between Cathode and micromesh
  - Avalanche occurs between micromesh and anode



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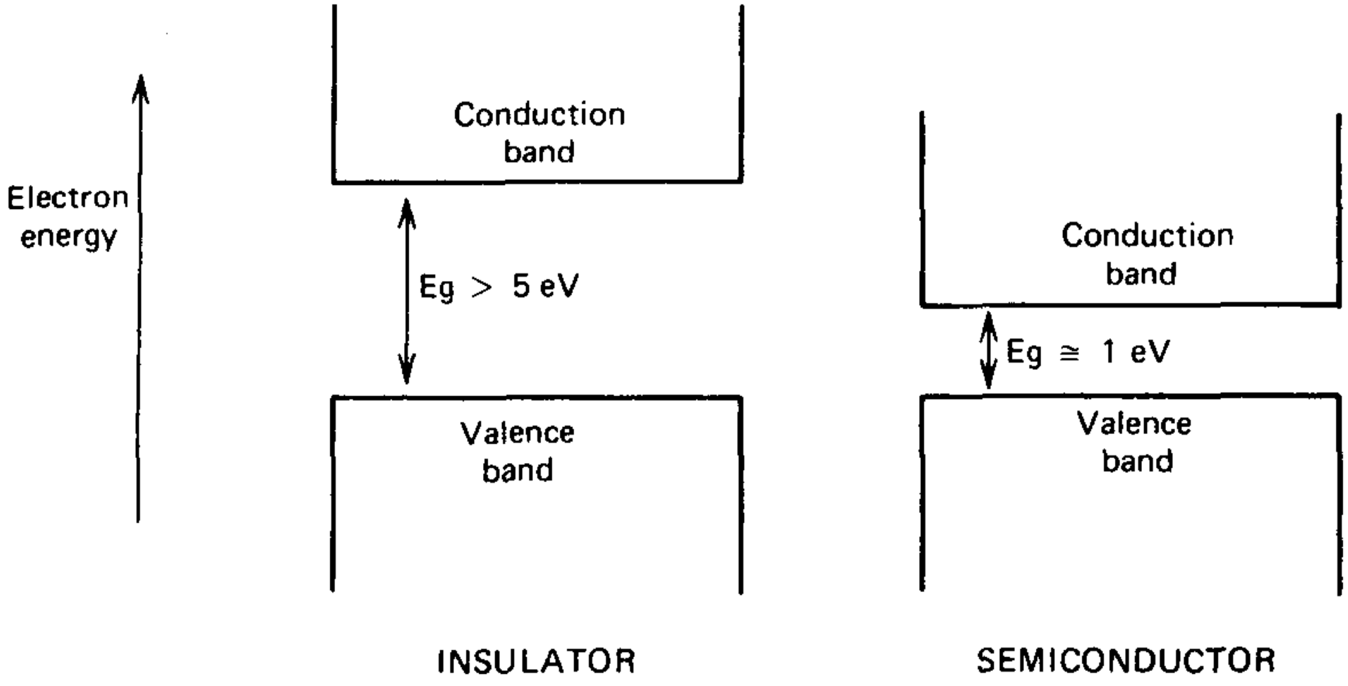
Semiconductor detectors

- Semiconductors have small band gap ~1 eV
  - Some valence electrons kicked into conduction band thermal excitations (leaves behind hole)



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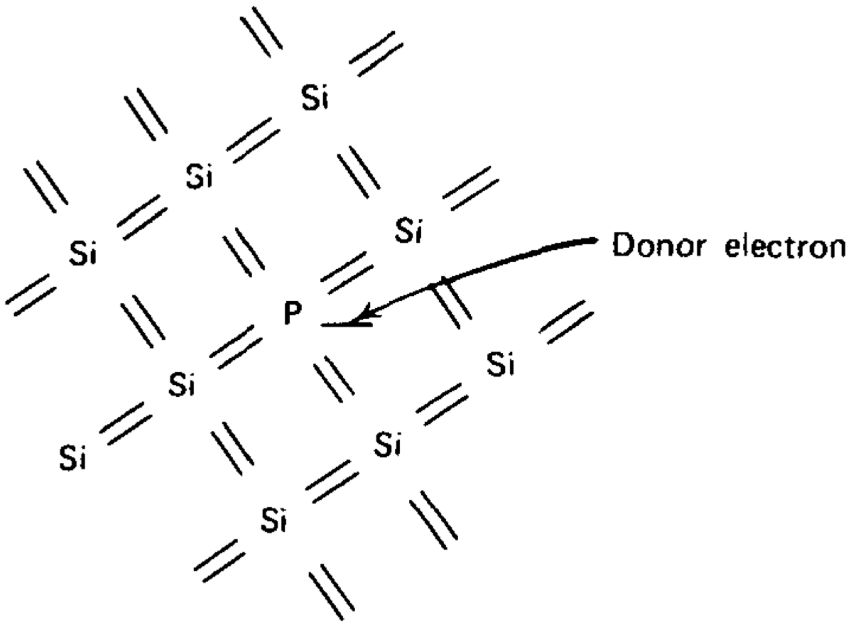
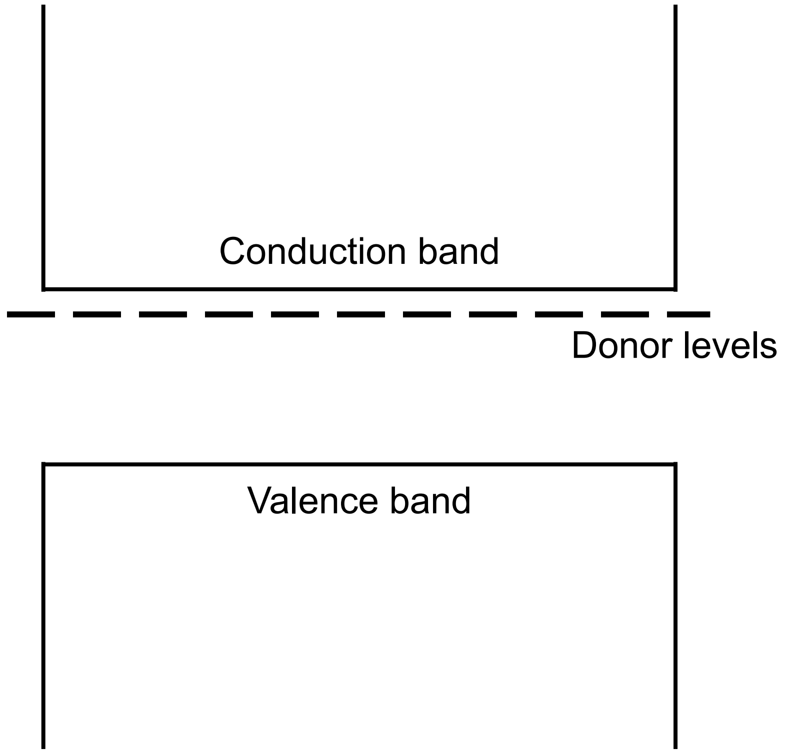
Semiconductor detectors

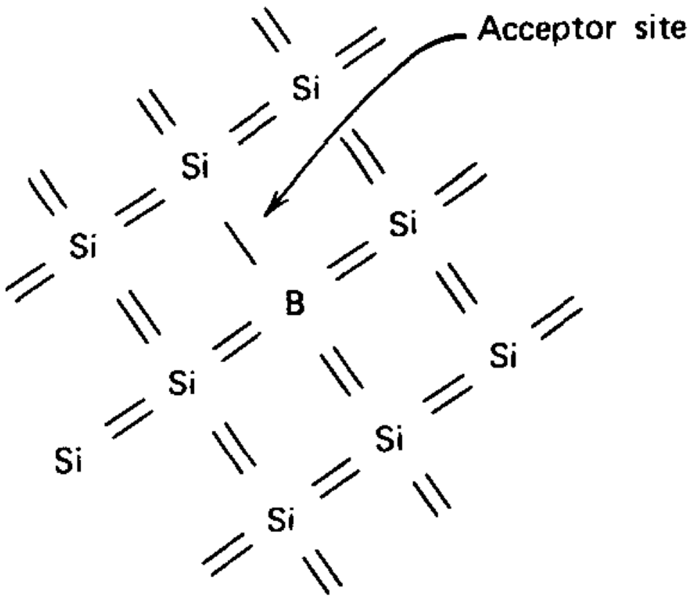
- Can dope with either
  - n-type (donor): Group 5A, 5 valence e- (P)

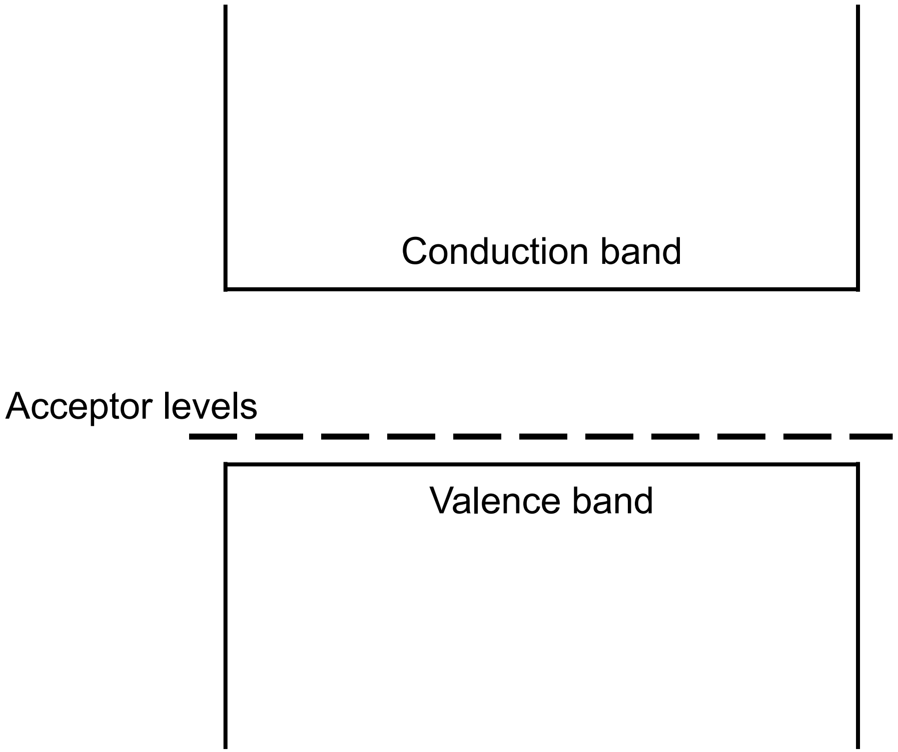




Semiconductor detectors

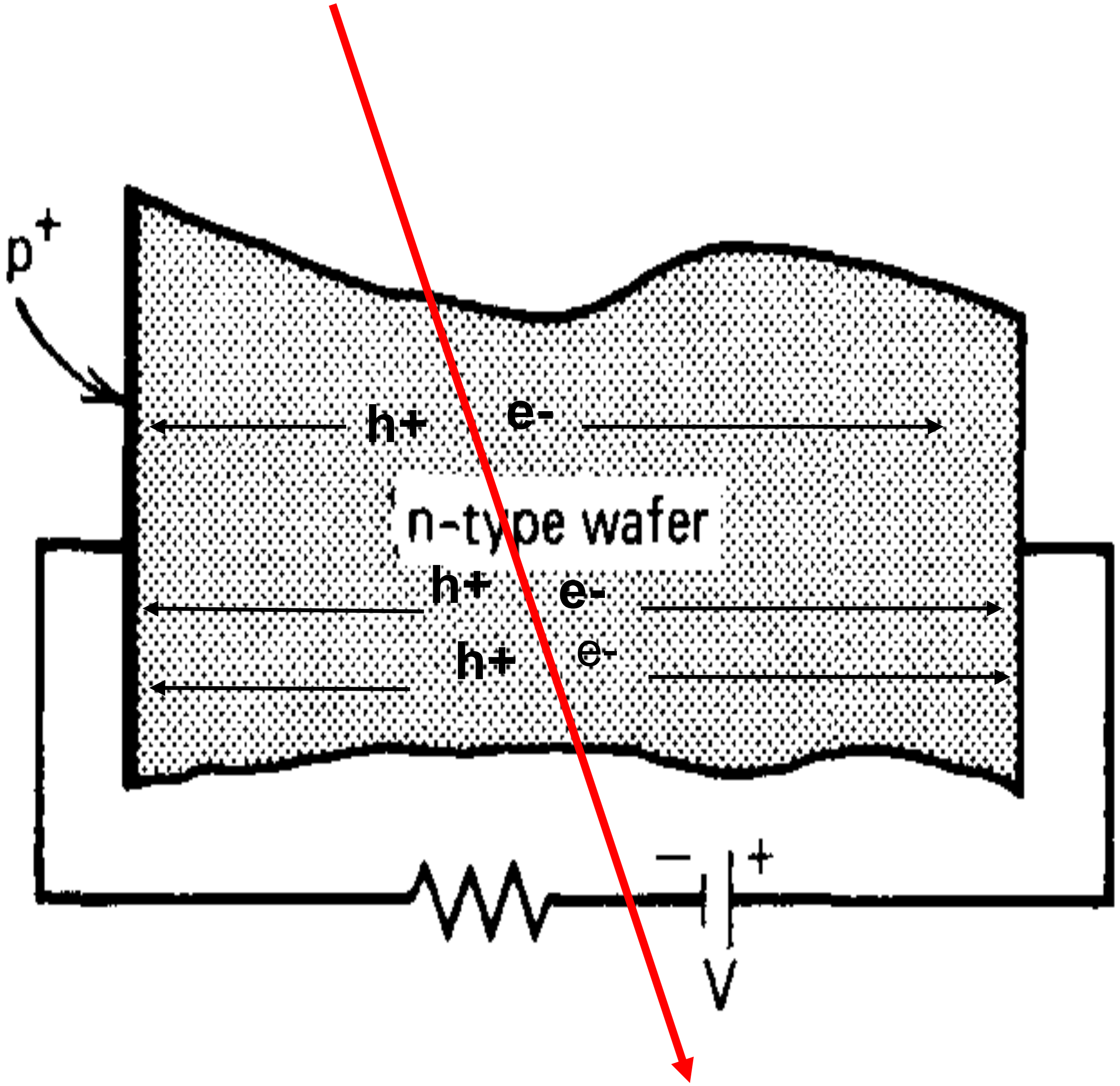
- Can dope with either
  - p-type (acceptor): Group 3A, 3 valence e- (B)





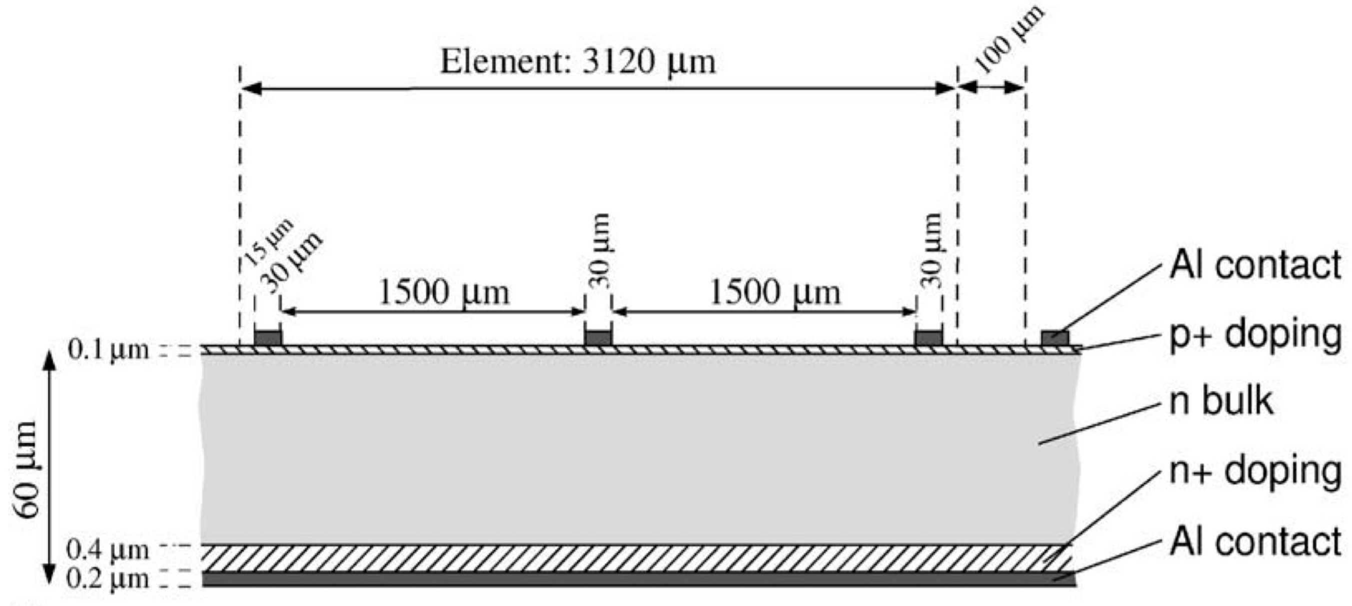
Semiconductor detectors

- P-n diode junction, **reverse** bias to increase depletion region
  - i.e. V<0 on p-side
  - Tries to move e- from p to n side
  - Very little current flow (only minority carriers)
  - “Fully depleted detector”
- Incoming particle creates e- hole pairs (analogous to e- ion pairs in gas)
- Good resolution
  - ~3 eV ionization energy for Si/Ge vs 30 eV gas



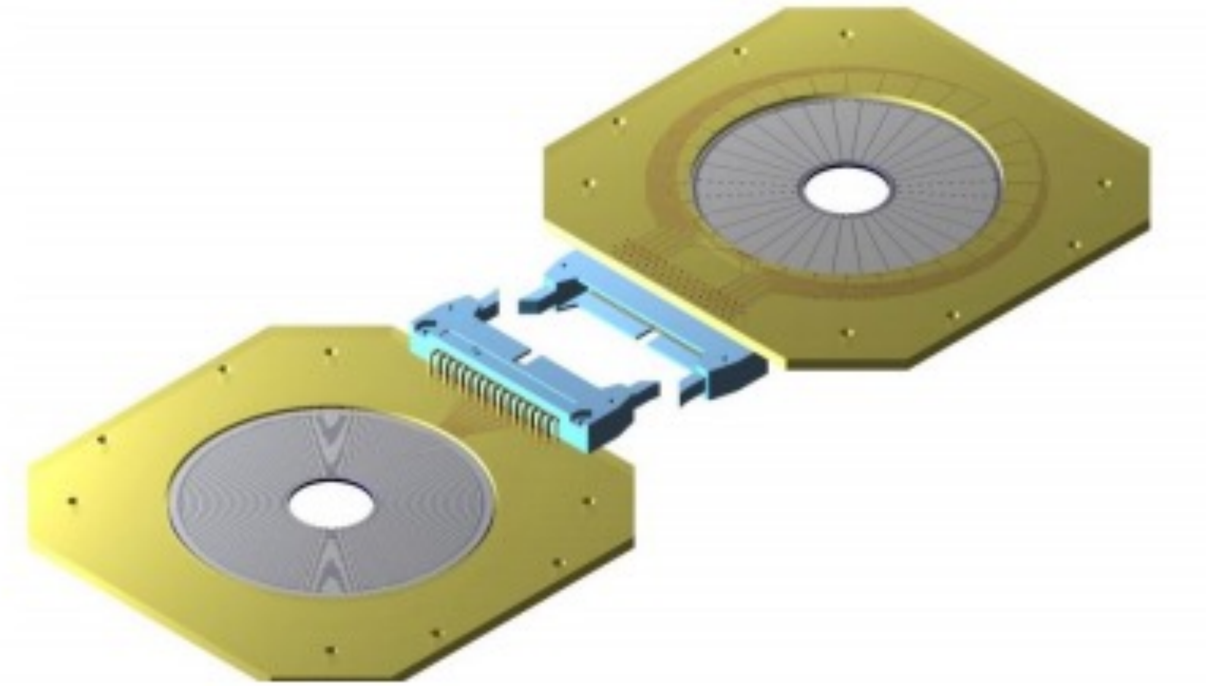
Semiconductor detectors: Si

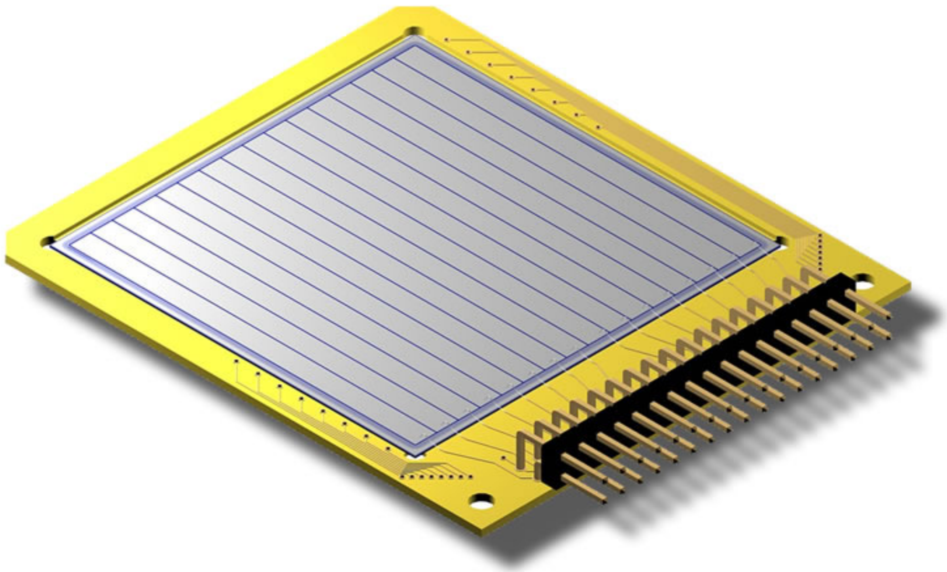
- Si strip detectors
  - Use segmentation on both sides of detector for better position resolution
  - Minimize deadlayers



Tengblad *et al*, NIMA 525 (2004) 458–464

Semiconductor detectors: Si





http://www.micronsemiconductor.co.uk/

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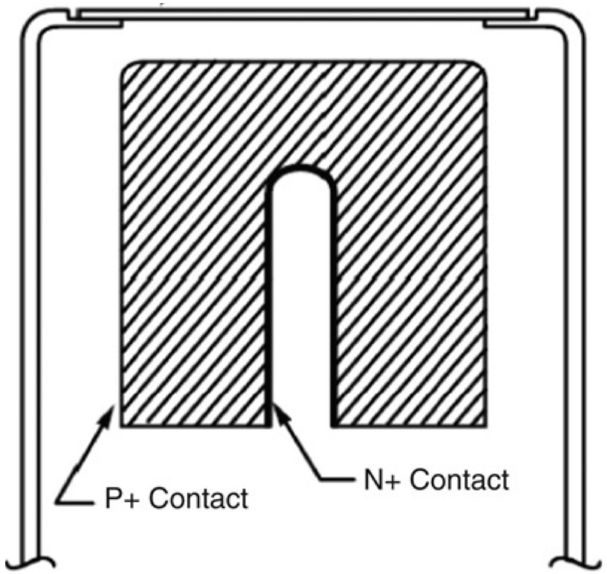
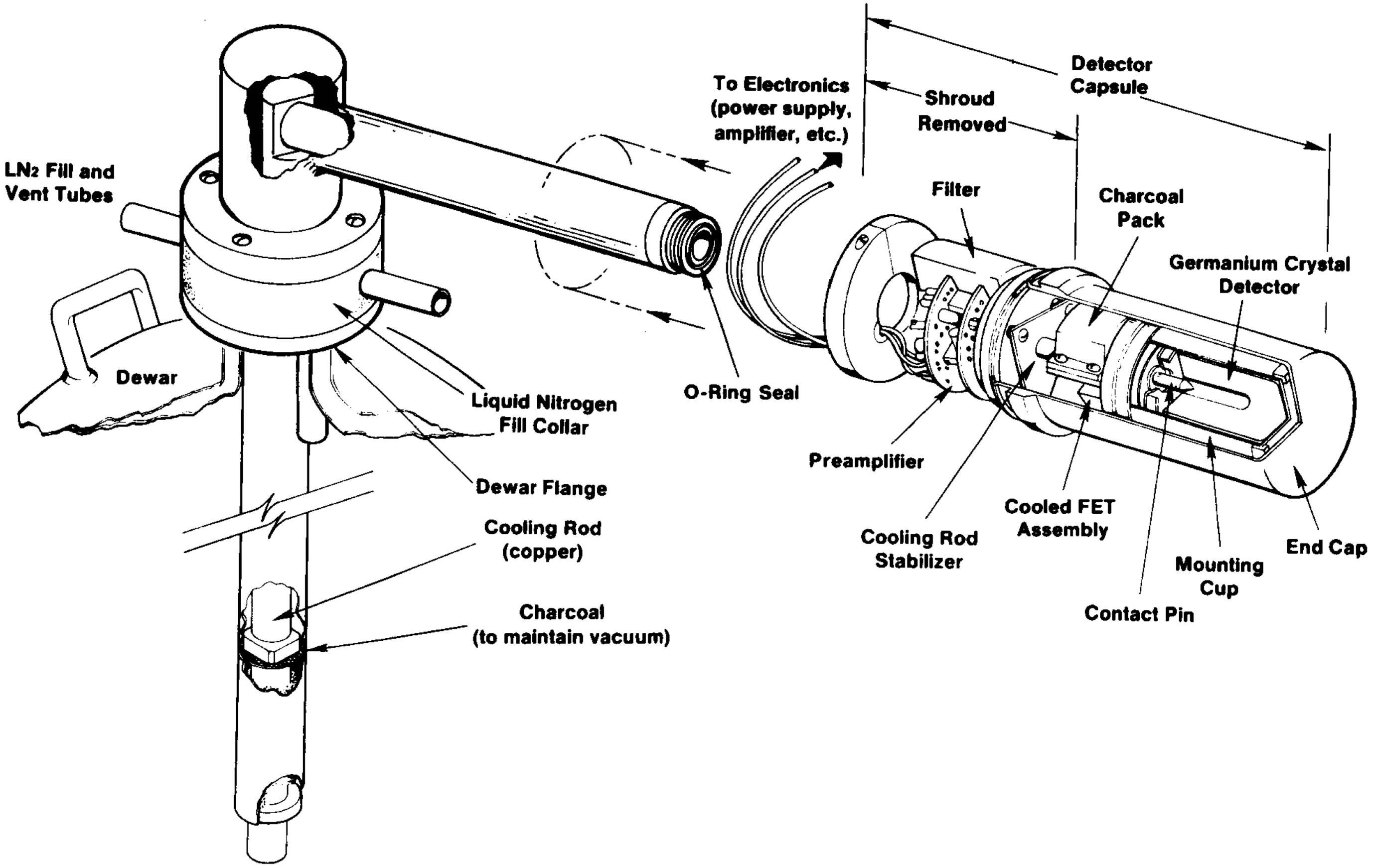
Semiconductor detectors: Ge

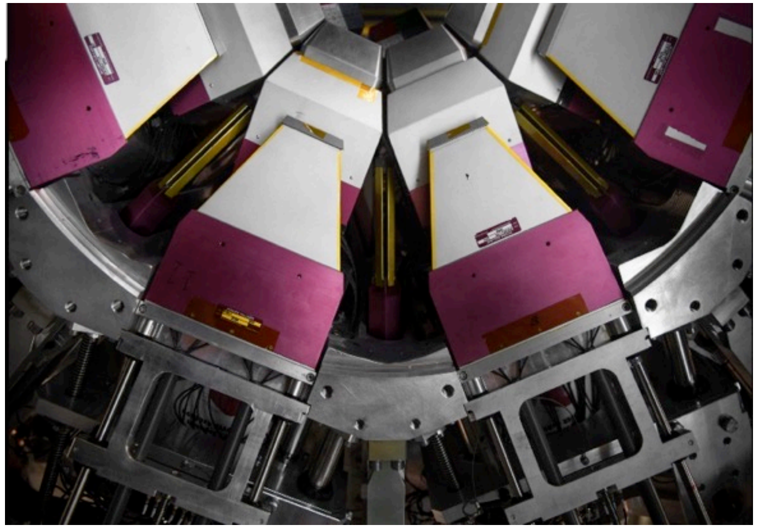
- HPGe ~0.1% resolution (~2 keV FWHM)
  - Coaxial type most common
- Must be cooled with LN2 to reduce thermal excitation





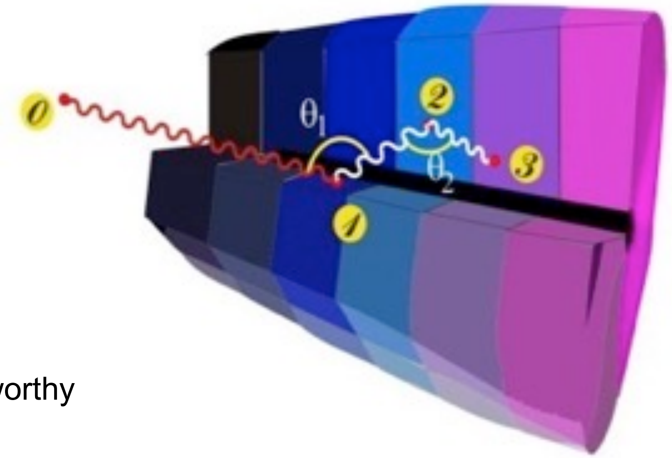
Semiconductor detectors: Ge

- Recall that gamma-rays primarily interact via Compton scattering at relevant energies
  - Large Compton background
- Typical solution is to surround Ge detectors with BGO (high efficiency) and use as anti-coincidence (Compton suppressors)
  - Gammasphere, Euroball, TIGRESS



Semiconductor detectors: Ge

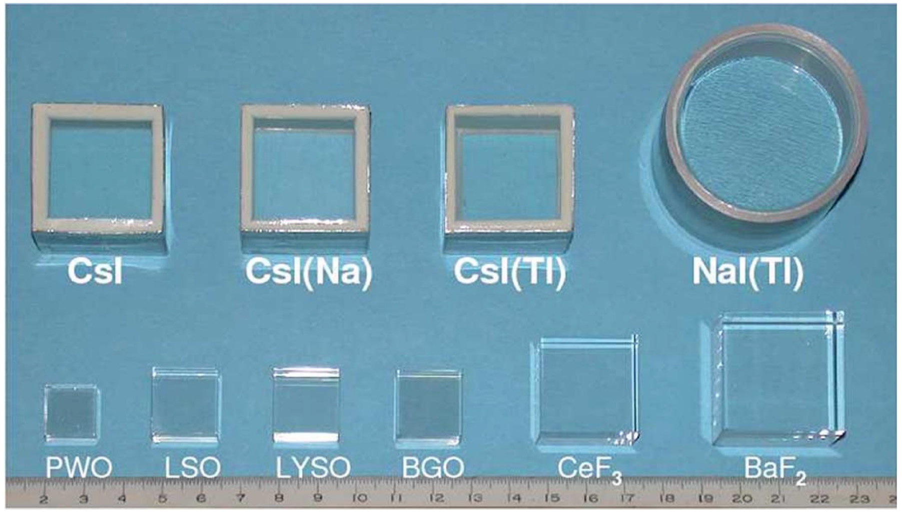
- New generation of tracking arrays
  - **GRETINA**, AGATA
- Combination of segmented detectors, digital electronics, and pulse processing
- Extract: Energy, time, position, N_{int}



Courtsey A. Garnsworthy

Detectors: scintillators

- A scintillator detector consists of two basic elements, the scintillator material which produces the light and a photodetector which detects the light
  - Inorganic   Organic: plastics   liquids   crystals



IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 55, NO. 4, AUGUST 2008 2425

https://scionix.nl/

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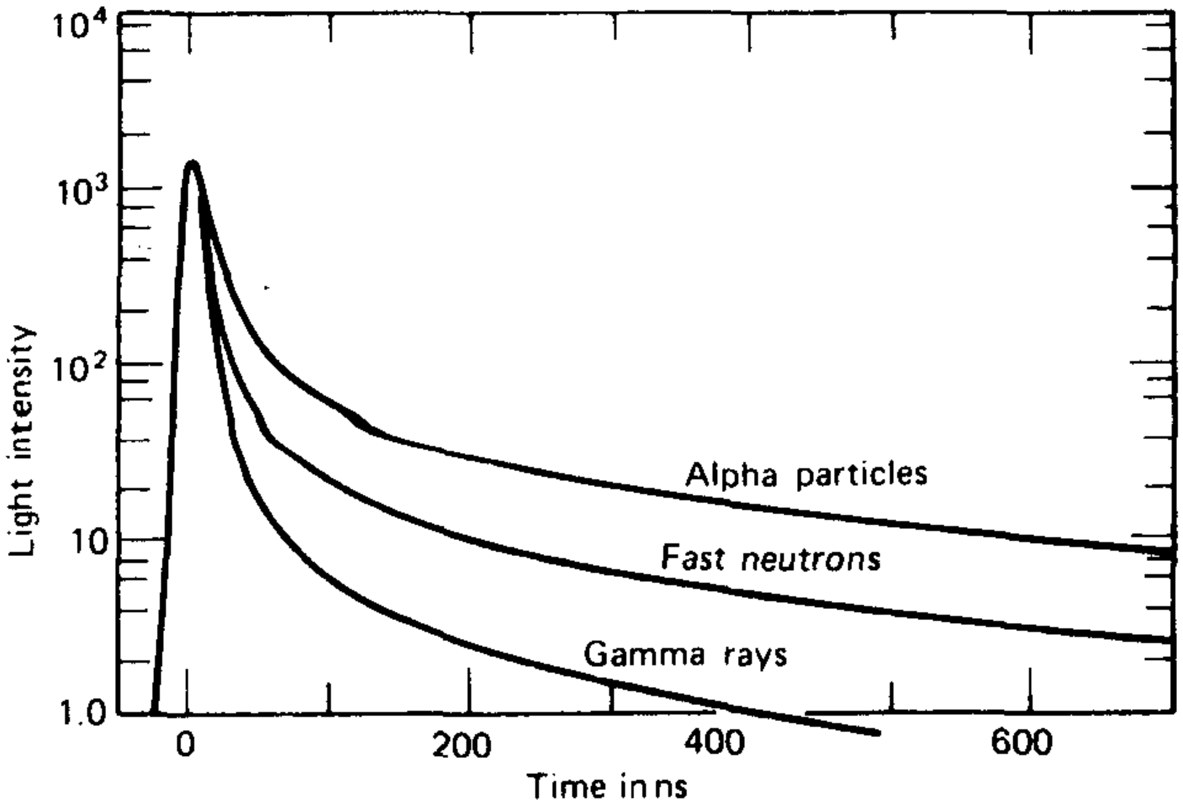
Detectors: scintillators

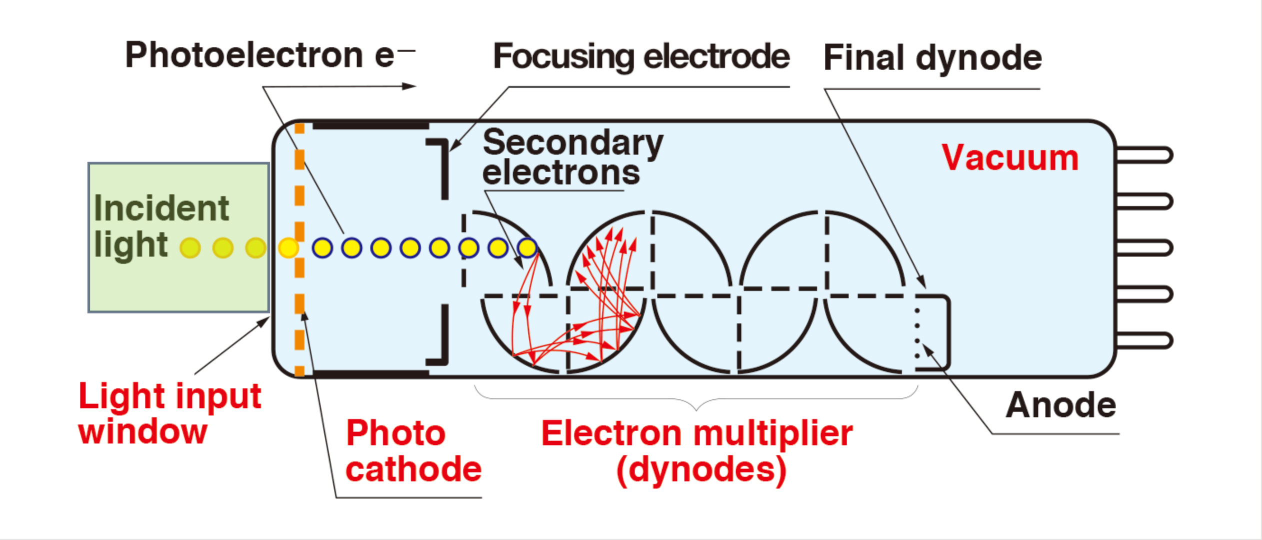
- Light produced via fluorescence: **prompt** emission of visible radiation
  - Absorption of KE from charged particle emitted in de-excitation
  - Can use slow component of response for **pulse shape discrimination** (e.g. differentiate gamma-rays from neutrons)

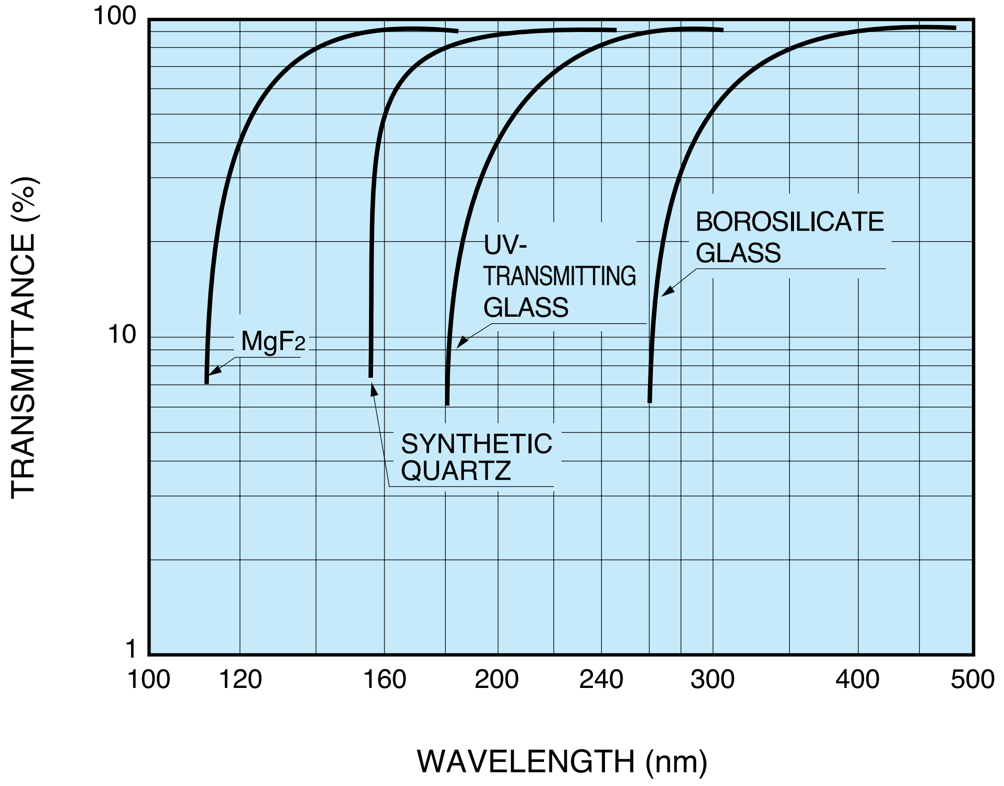


TRIUMF

Detectors: scintillators

- Not a very efficient method of detection
  - Low efficiency to convert particle to light
  - Couple to PMT via optical grease (ε↓)
  - Must match wavelength of PMT (ε↓)





https://www.hamamatsu.com/eu/en.html

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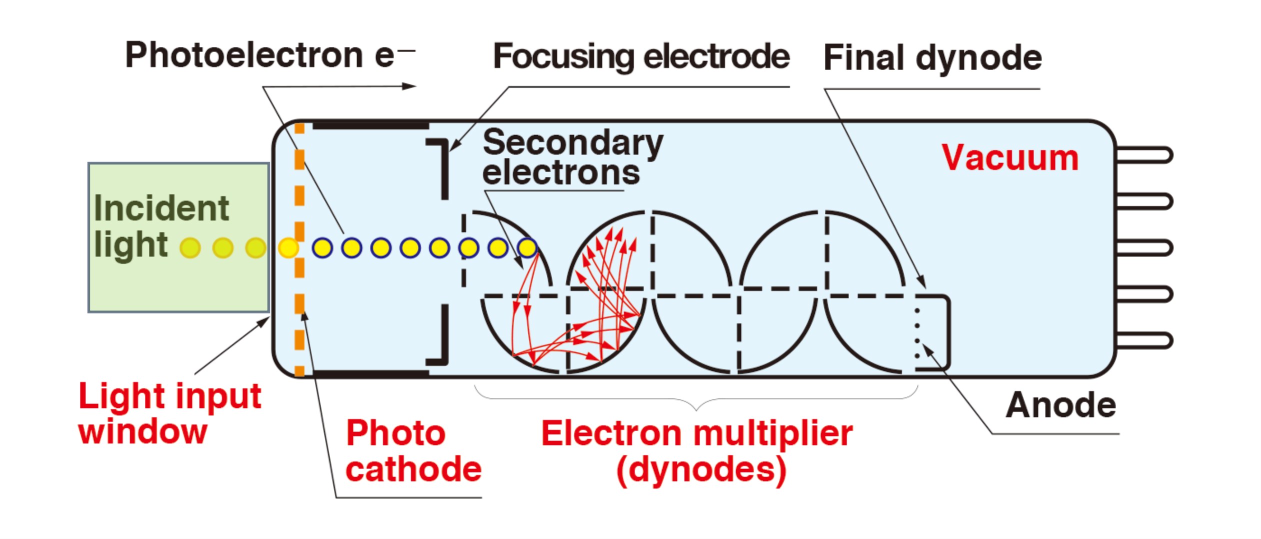

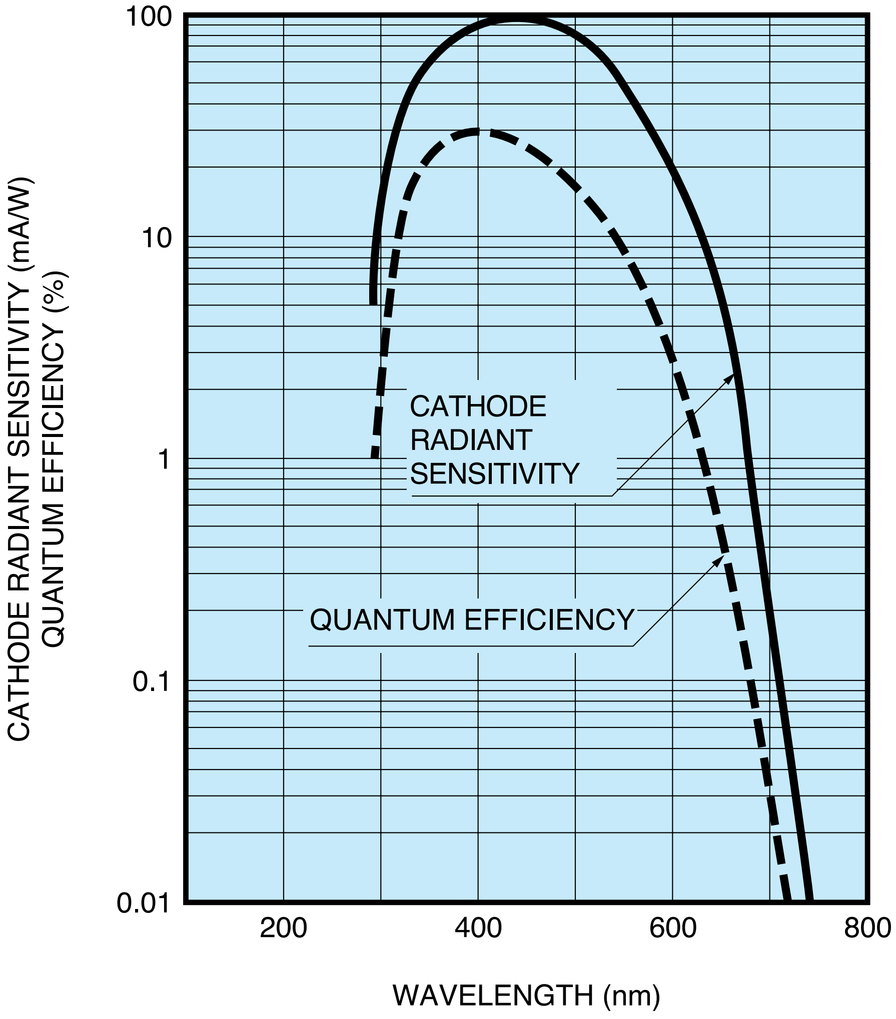

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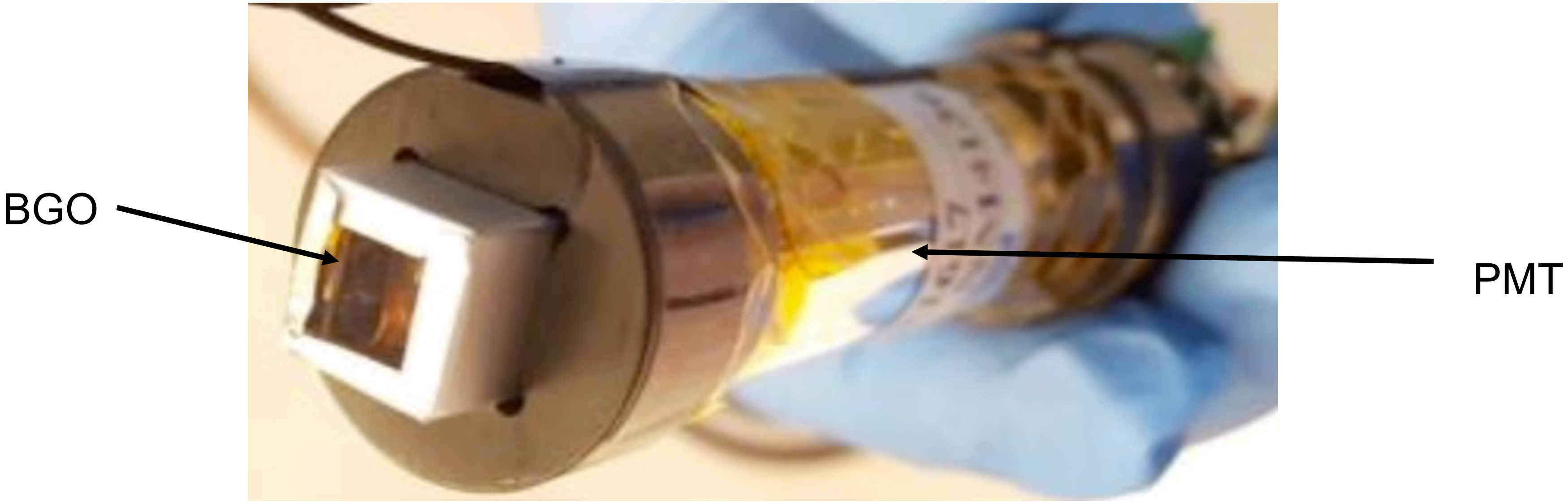
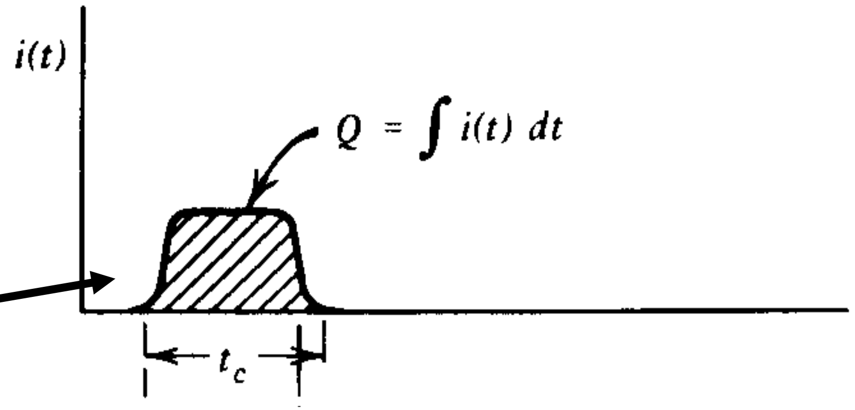


Signal processing

- Fundamental output of all radiation detectors is a burst charge Q proportional to energy

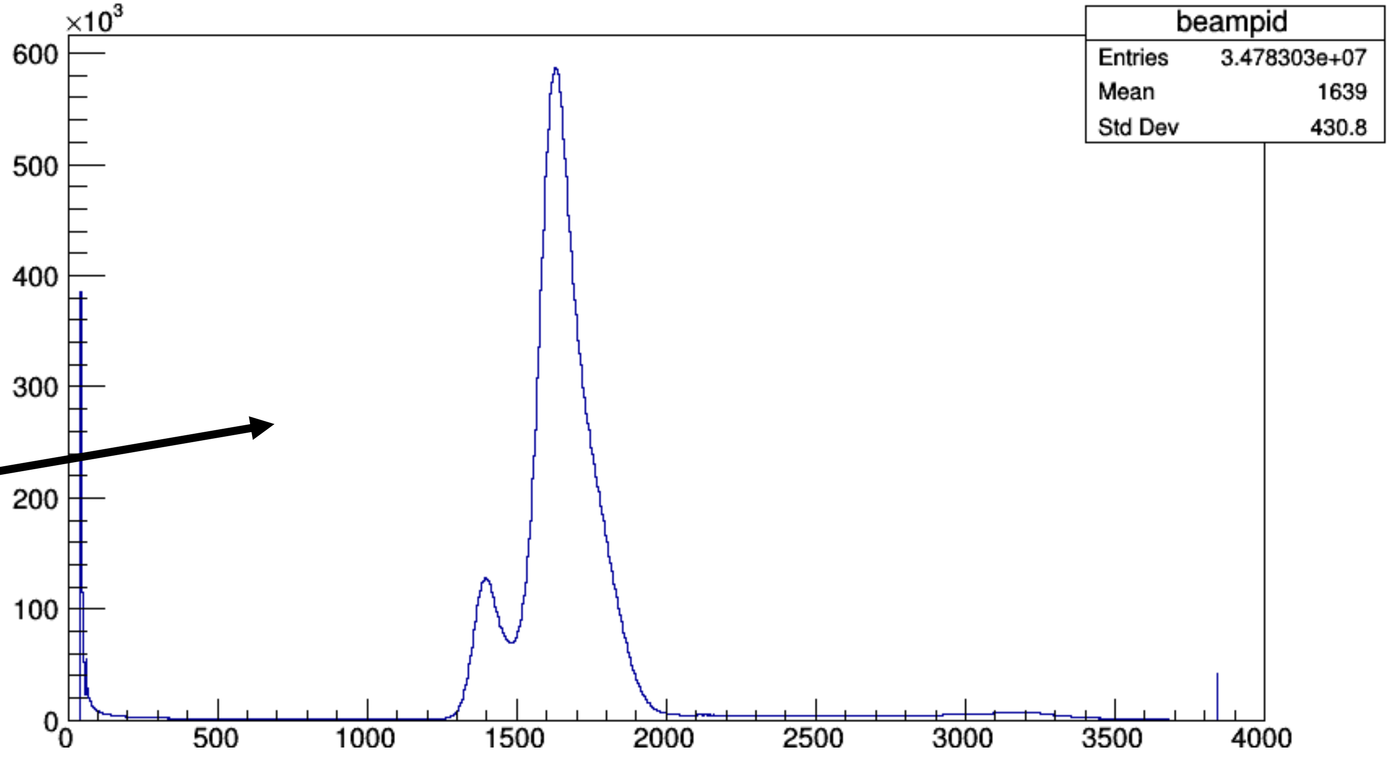
  How to go from this



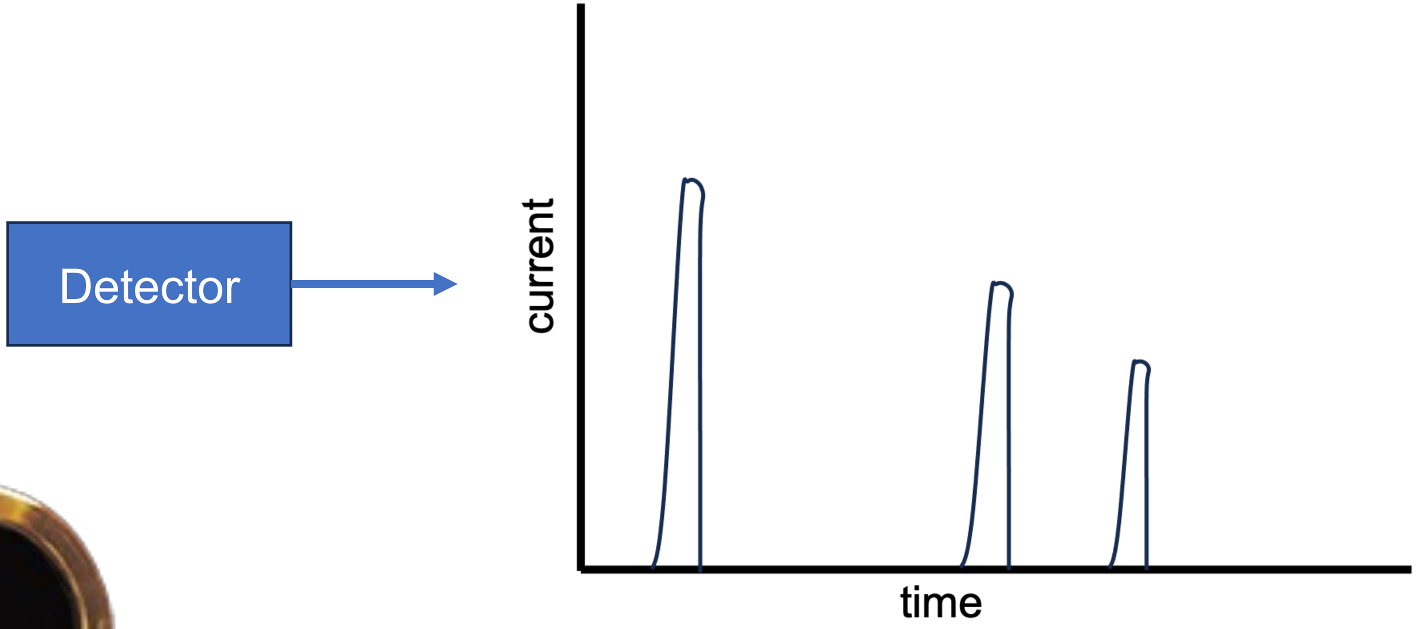
Signal processing

- Recall: Fundamental output of all radiation detectors is a burst charge Q proportional to energy

To this



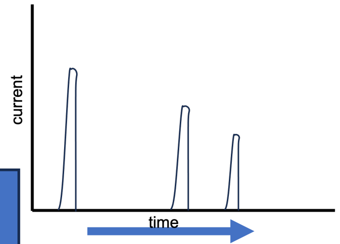
Signal processing



https://www.ortec-online.com/products/radiation-detectors/silicon-charged-particle-radiation-detectors

Signal processing

Detector

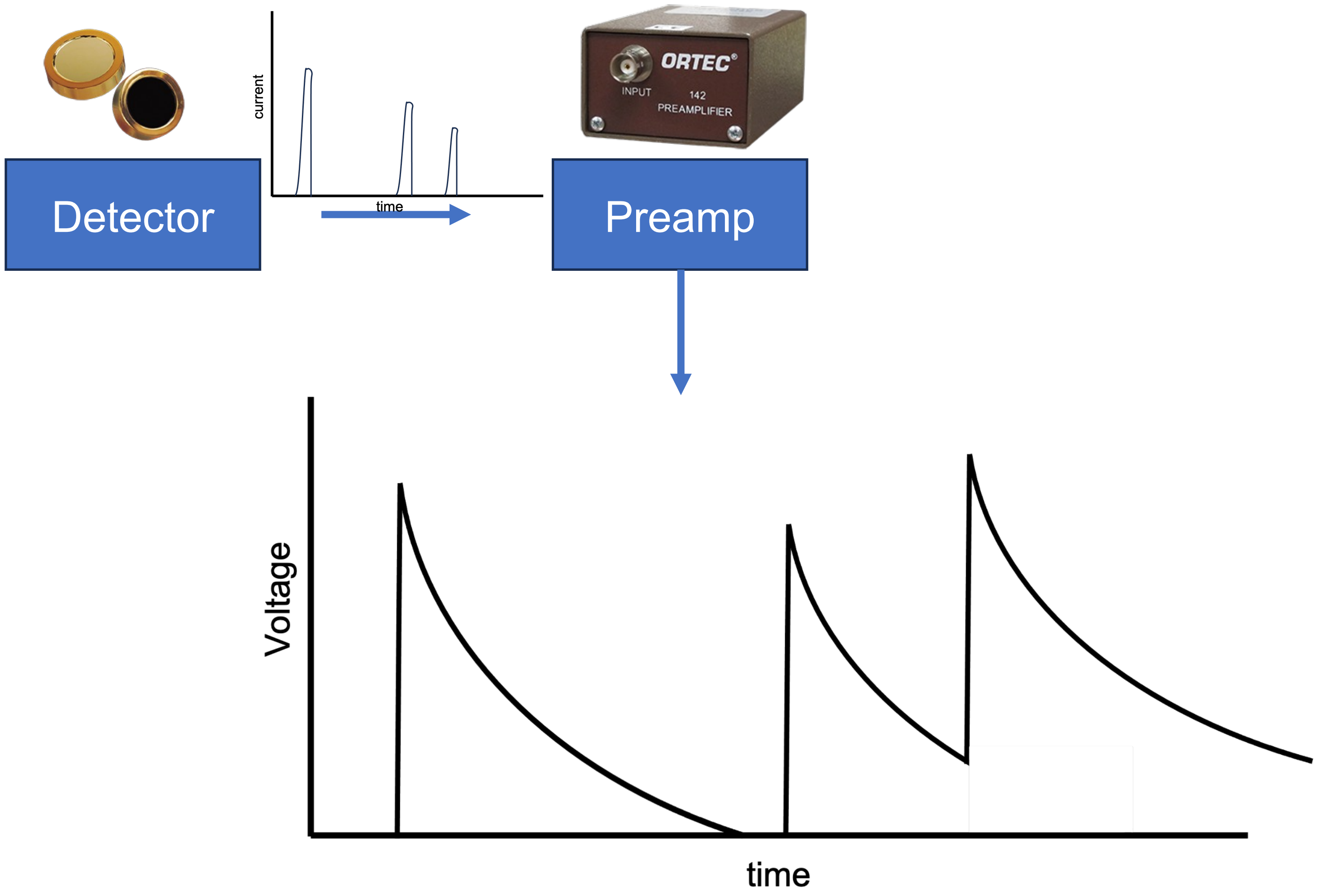


Preamp

https://www.ortec-online.com/products/electronics/preamplifiers

TRIUMF

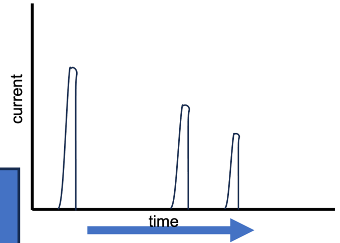
Signal processing



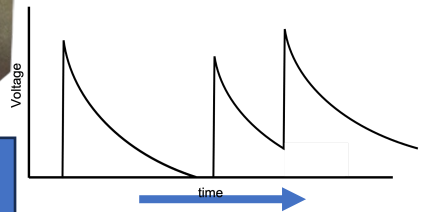
- Rise time is proportional to the charge collection time
- Amplitude is proportional to the charge Q

Signal processing

Detector



Preamp

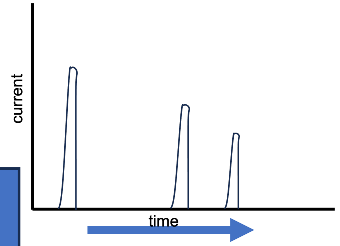


Shaping amplifier

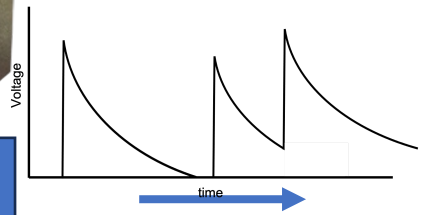
https://www.ortec-online.com/products/electronics/amplifiers

Signal processing

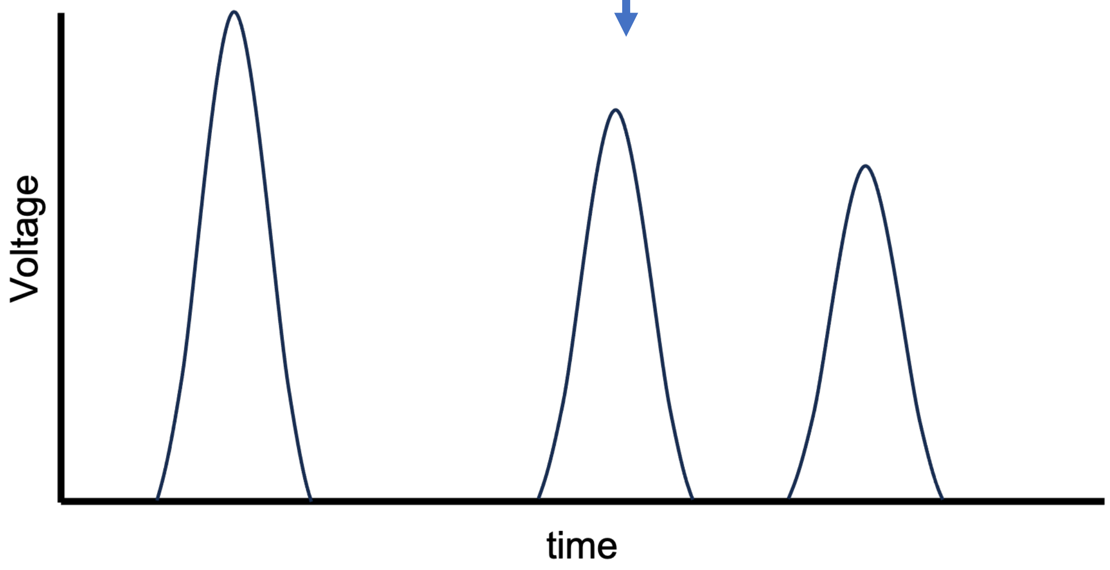
Detector



Preamp

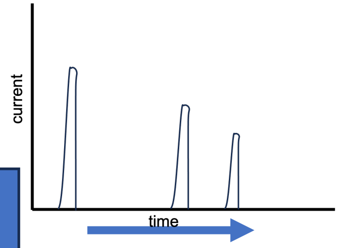


Shaping amplifier

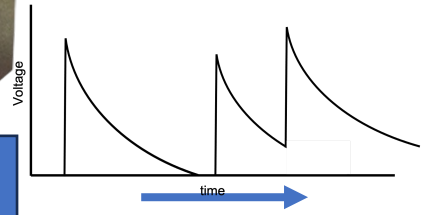


Signal processing (analog)

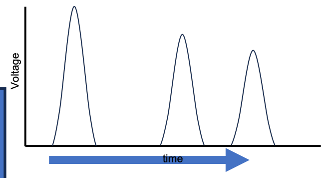
Detector



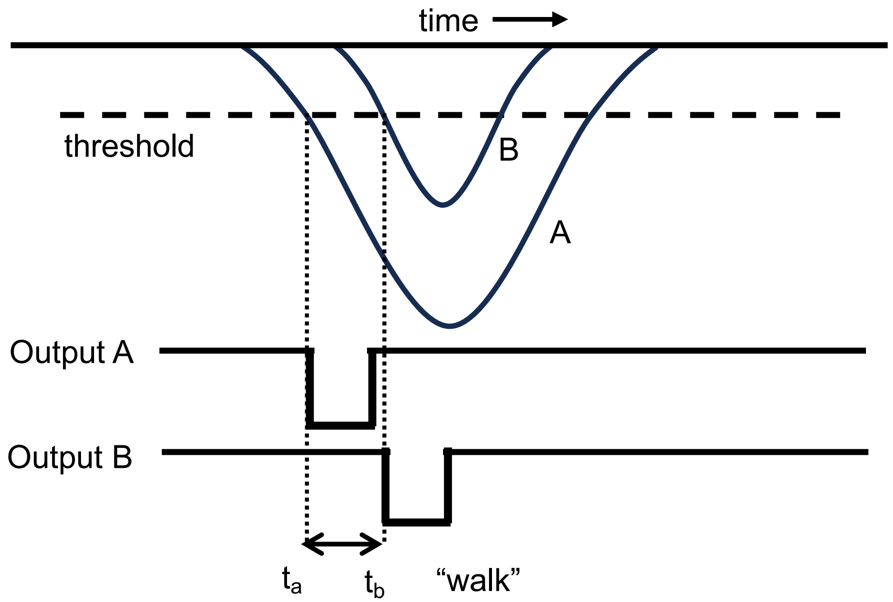
Preamp



Shaping amplifier



Discriminator



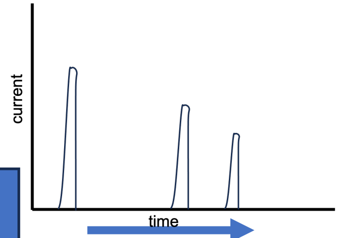
Leading edge

- Fast, but can introduce "walk" with different pulse heights

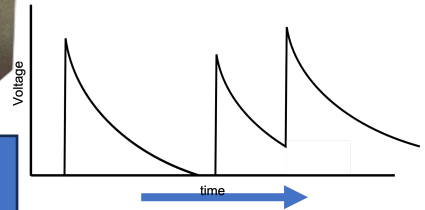
TRIUMF

Signal processing (analog)

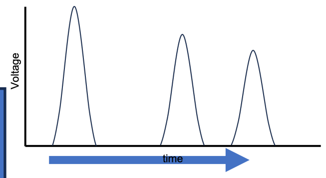
Detector



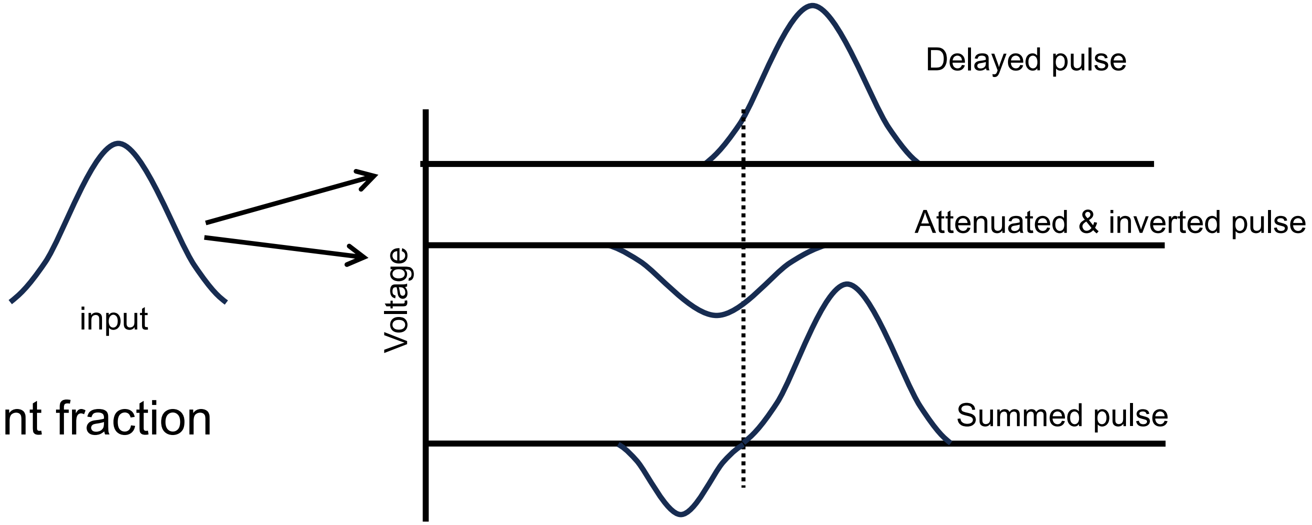
Preamp



Shaping amplifier

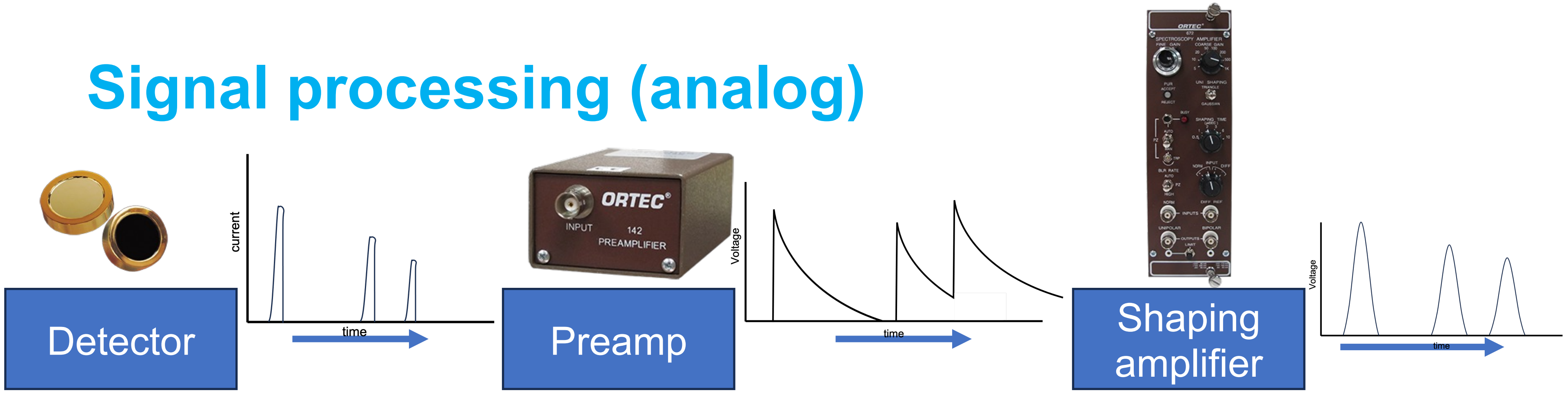


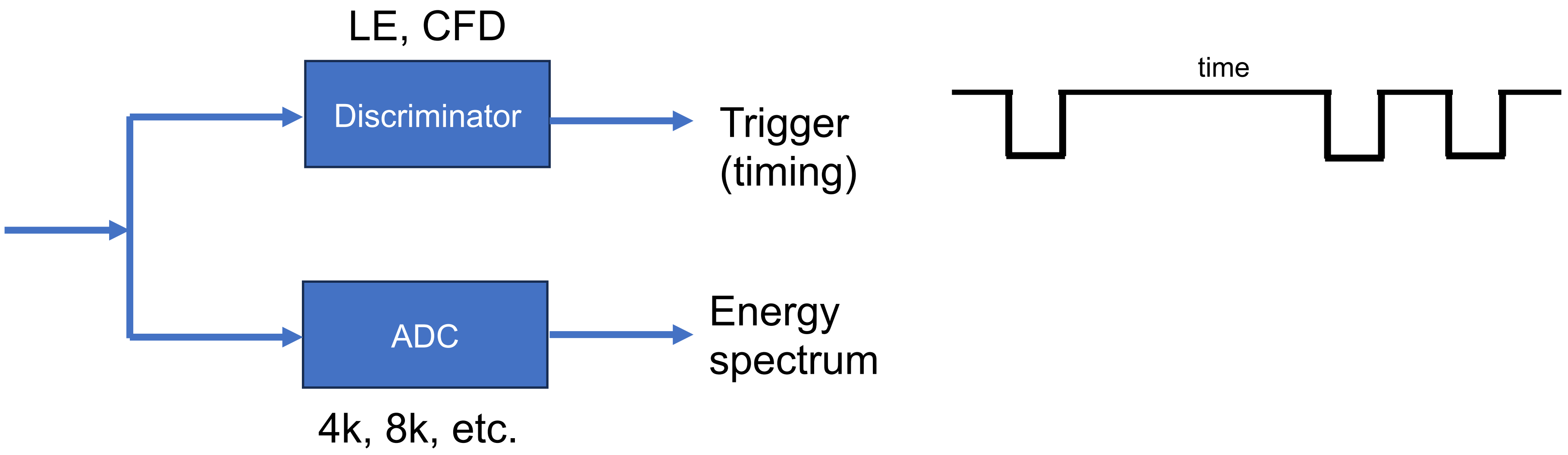
Discriminator



Constant fraction

Signal processing (analog)

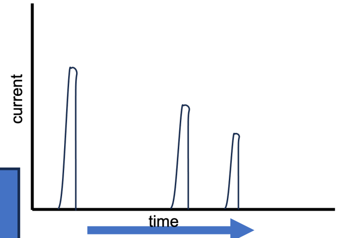




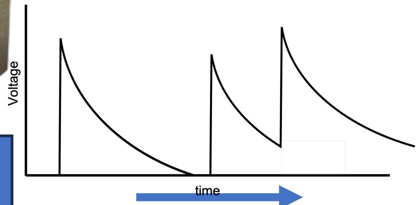
TRIUMF

Signal processing (analog)

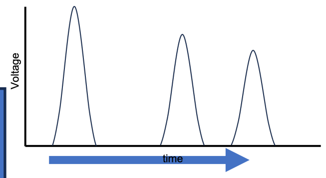
Detector



Preamp



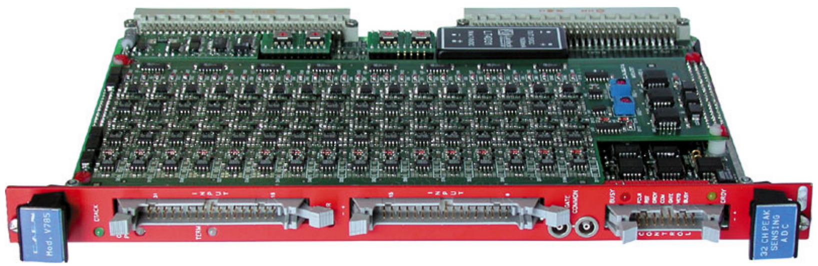
Shaping amplifier



Discriminator → Trigger (timing)

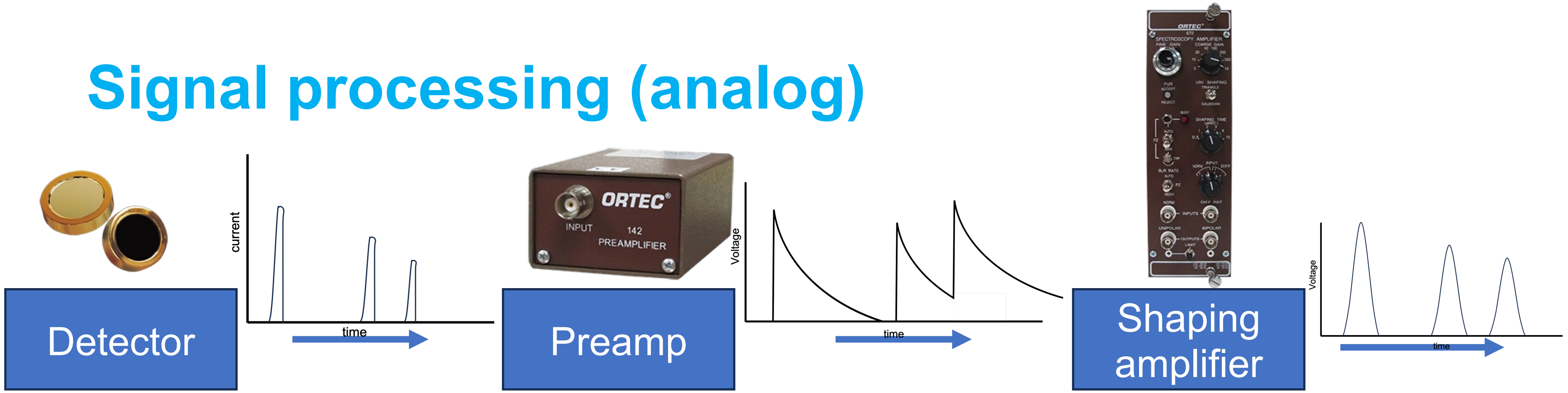
ADC → Energy spectrum

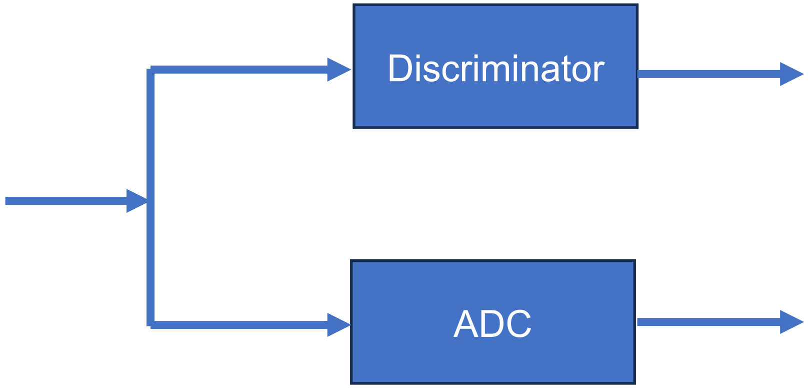
4k, 8k, etc.



Caen 32ch peak sensing ADC

Signal processing (analog)





Trigger (timing)

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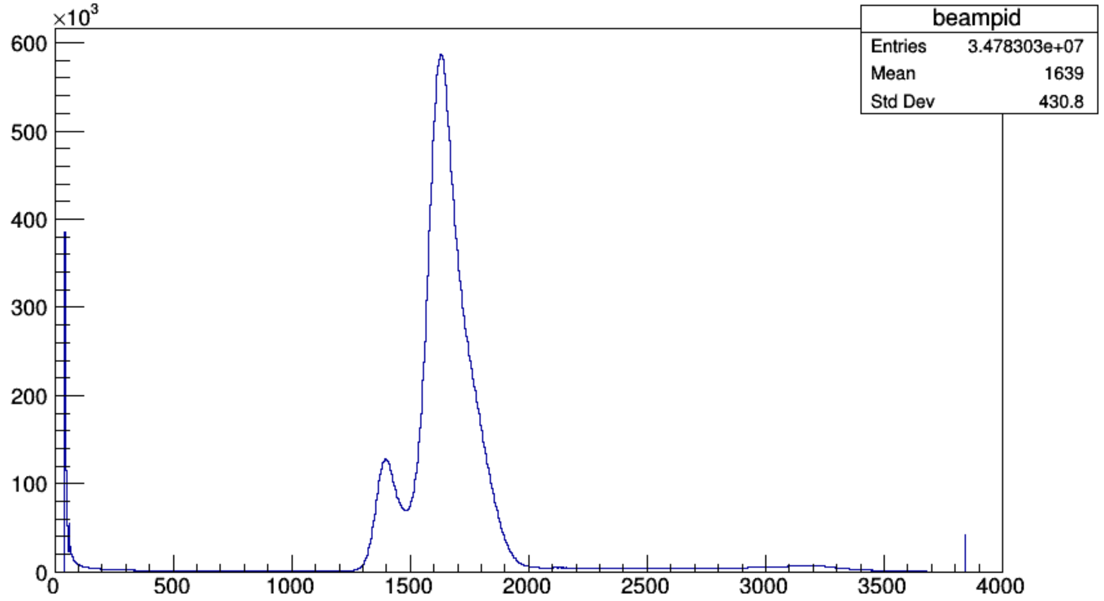
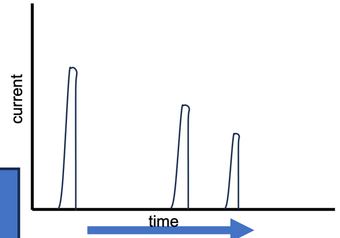
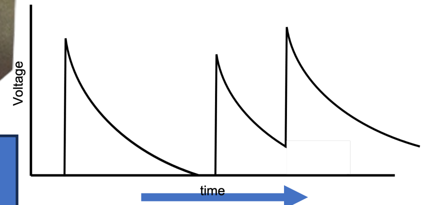


Signal processing (analog)

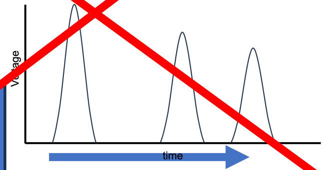
Detector



Preamp



Shaping amplifier



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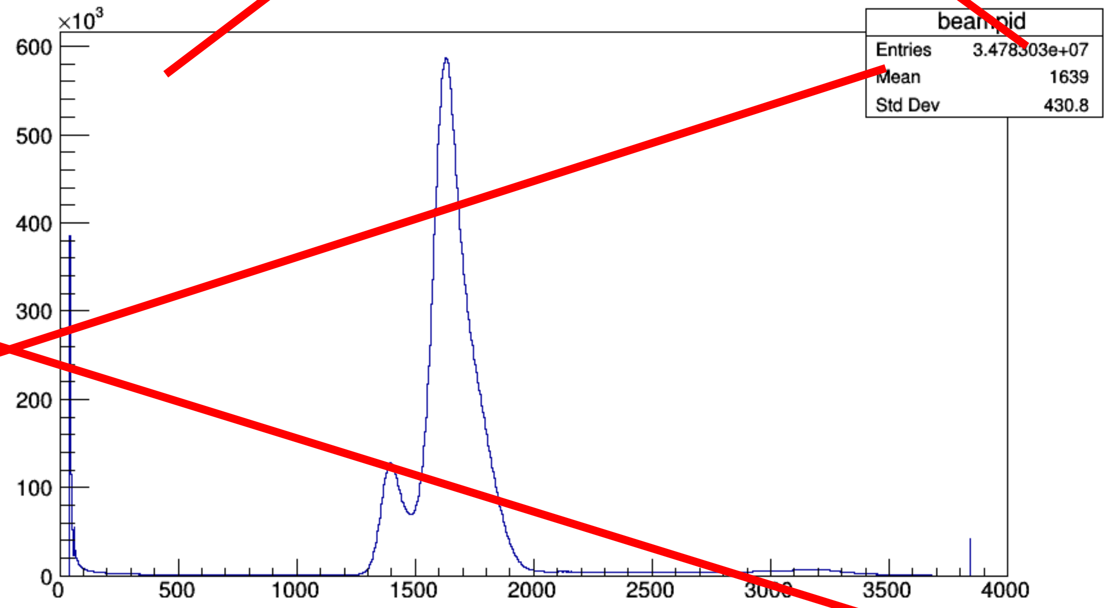
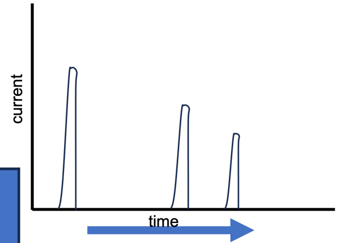
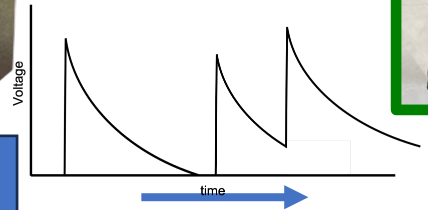


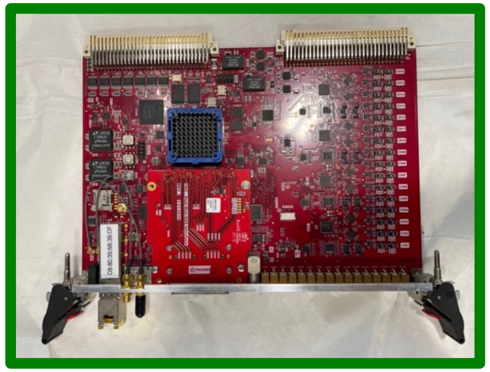
Signal processing (digital)

Detector



Preamp

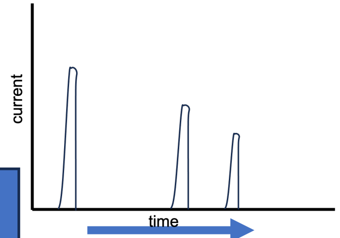


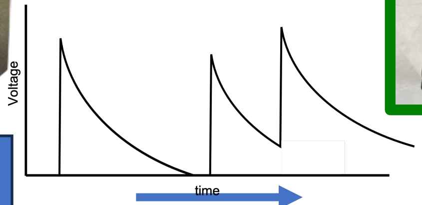


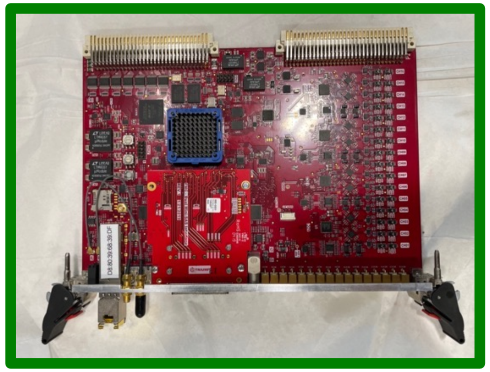
Digitizer

https://griffin.triumf.ca/daq.html

Signal processing (digital)







Detector

Preamp

Digitizer

(FPGA)

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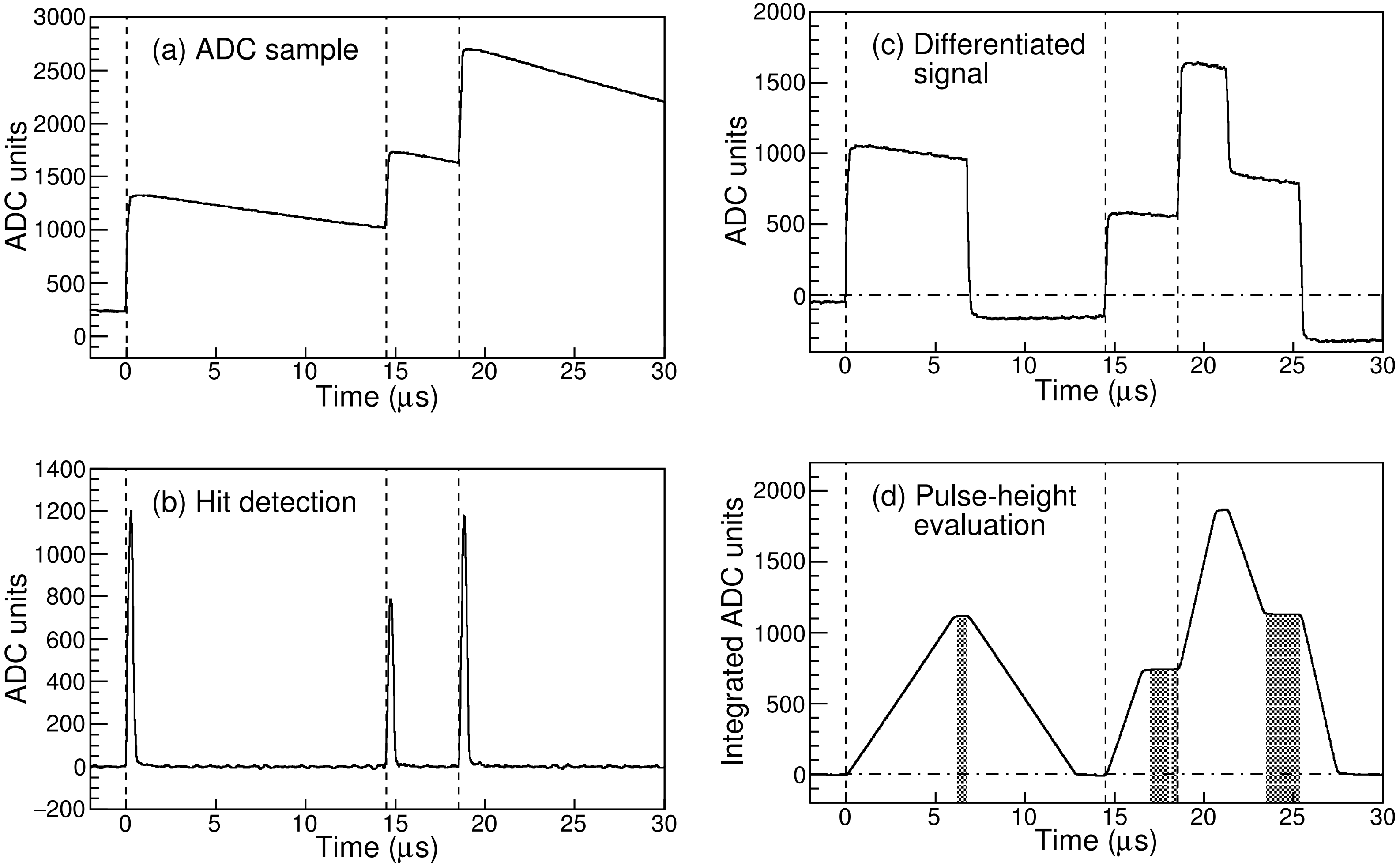
Signal processing (digital)



- GRIF16 module
  - 16 ch, 14 bit, 100 MHz sampling
  - Output is energy, time

Courtsey A. Garnsworthy

Signal processing (digital)

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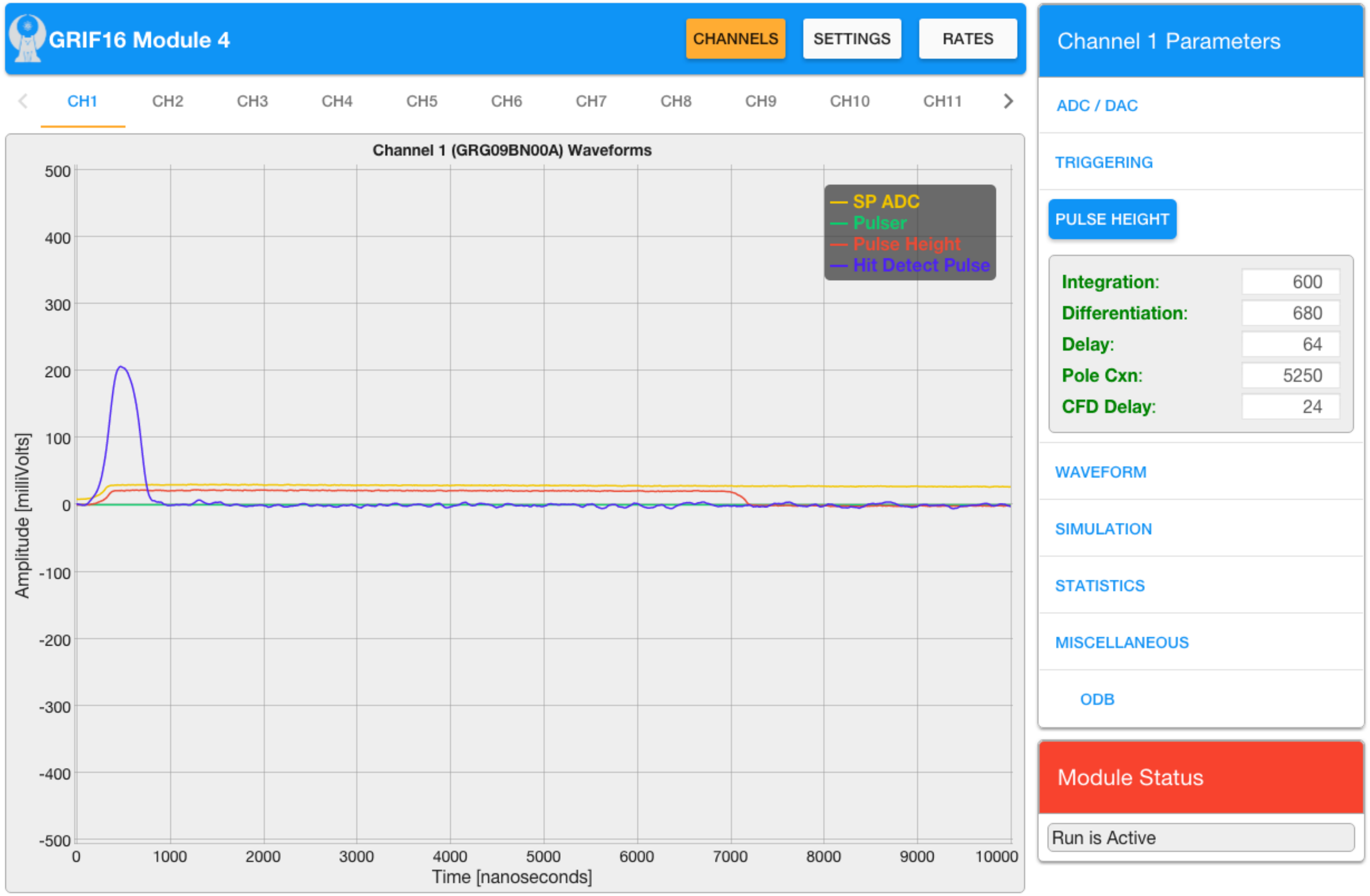
  - Output is energy, time



Courtsey A. Garnsworthy

TRIUMF

Summary

- Three main types of detectors
  - Gas detectors (IC, proportional counters)
  - Scintillators
  - Semiconductors (Si, Ge)
- Essentially, output of all detectors is a small current proportional to energy of incident radiation
- Remember to always look at the big picture: What variables are you trying to measure/extract from the experiment?
- Understanding how your detector(s) works goes a long way when inevitably something goes wrong
- Spend time in the lab and play around with detectors/electronics. A scope is your friend!
- Get out of your comfort zone and try to get some hands on experience with detector systems from other colleagues/groups