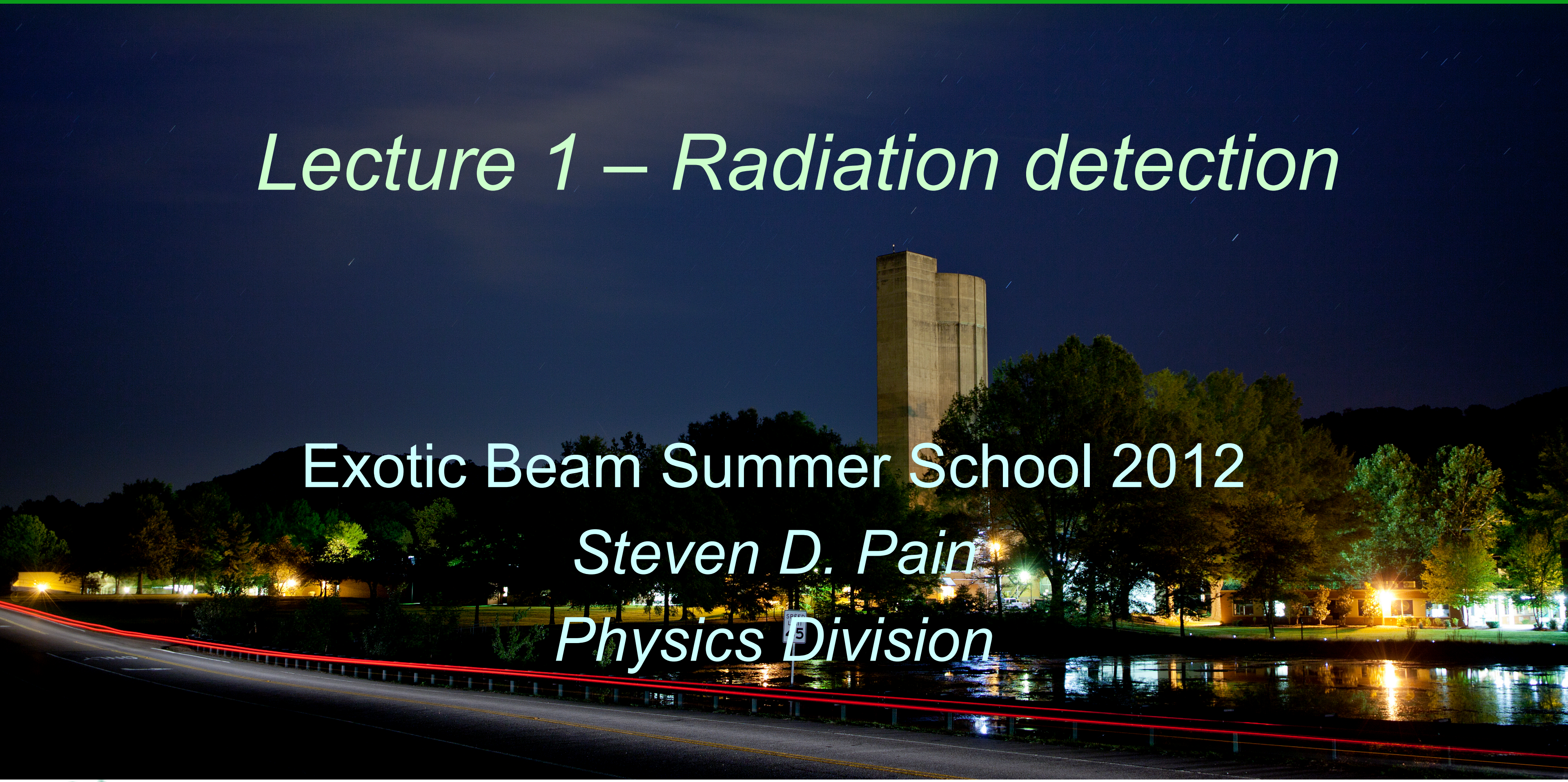
Experimental Techniques



Lecture 1 – Radiation detection

Exotic Beam Summer School 2012

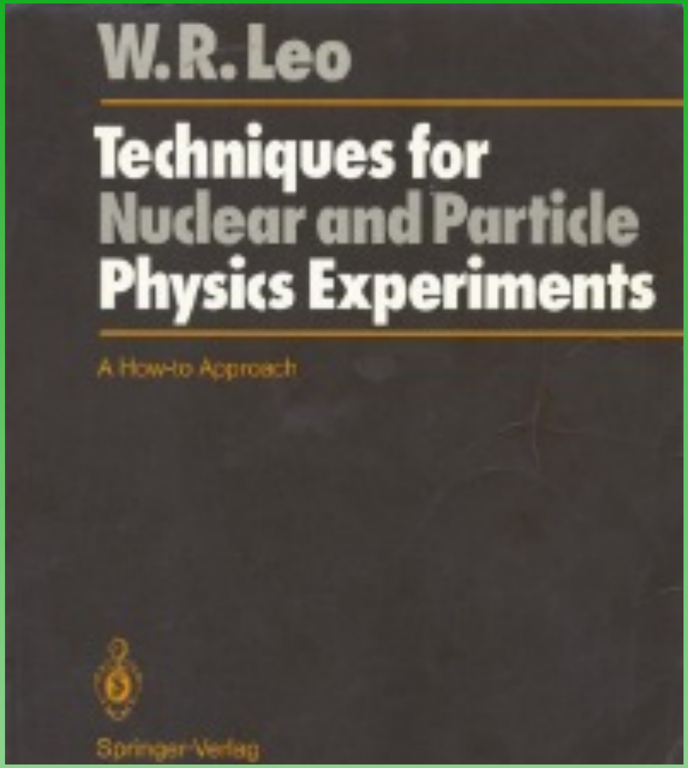
Steven D. Pain

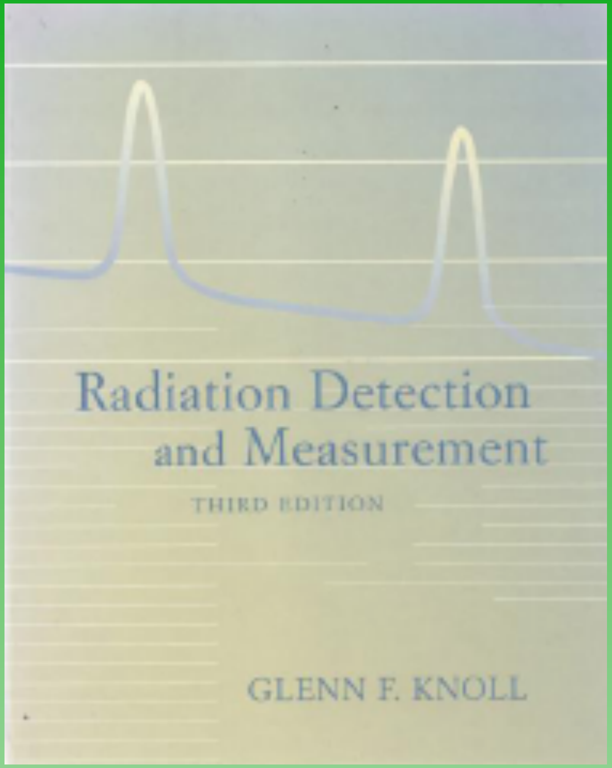
Physics Division

OAK RIDGE NATIONAL LABORATORY

Managed by UT-Battelle for the Department of Energy

References





J.B. Marion and F.C. Young

Nuclear Reaction Analysis Graphs & Tables

North Holland Publishing Company (1968)

Measurement in Nuclear Experiments

"All measurements are essentially of position, right?"

(photographic plates)

Measurement in Nuclear Experiments

"All measurements are essentially of position, right?"

(photographic plates)

Things you can measure:

- Charge (voltage, current)
- Time (frequency)
- Position
- Number

Things you can calculate:

- Energy
- Velocity
- Mass
- Momentum
- Charge (nuclear or atomic)
- Probabilities (eg cross sections)

Things to optimize:

- Resolution
- Efficiency (statistics!)
- Selectivity
- Rates

Many times, improving one of these comes at the expense of another

Things you can infer:

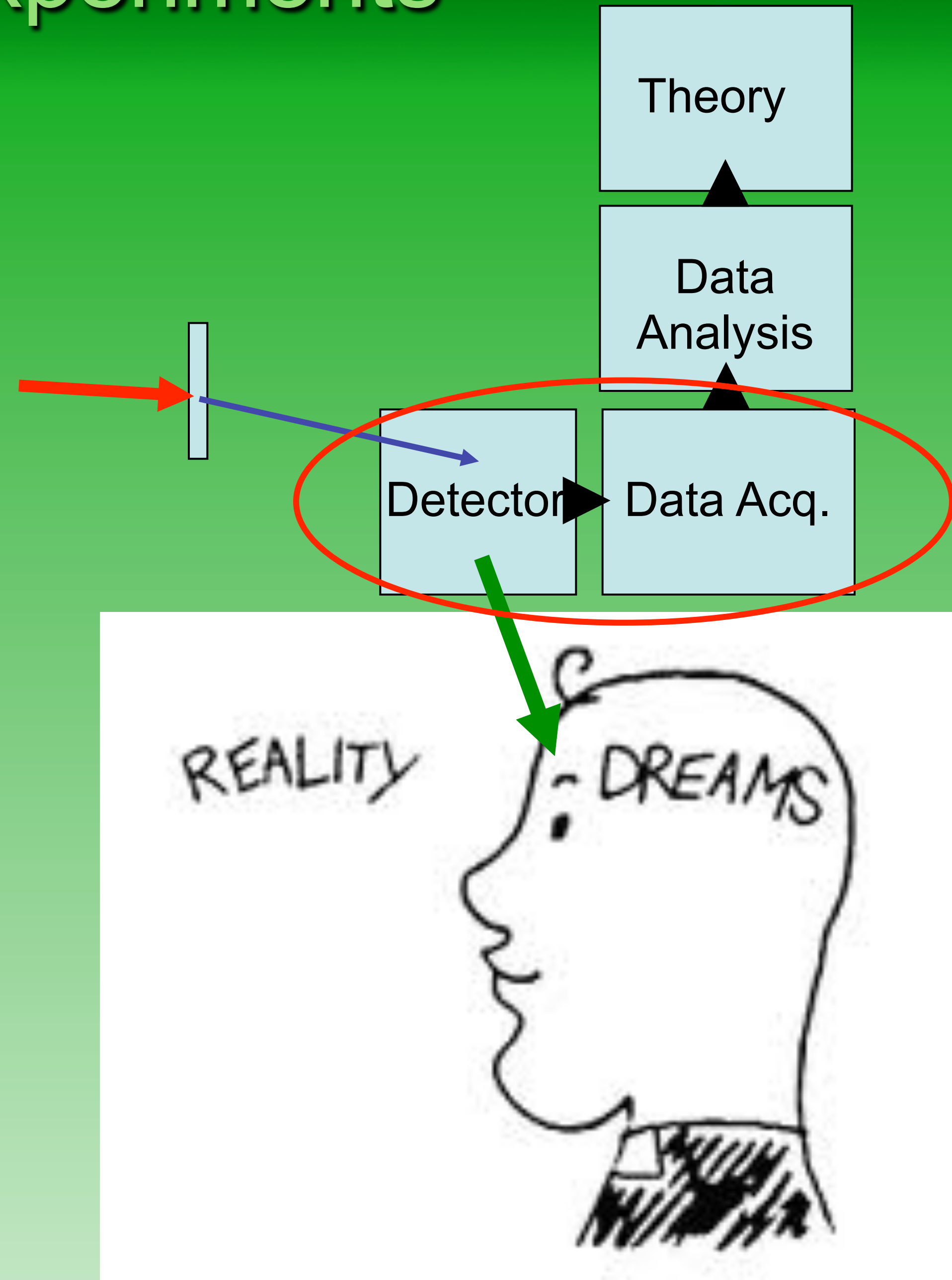
Theory

- Quantum numbers (ℓ, J, π, S...)

(discrete assignments from continuous data)

Nuclear Experiments

- Usually involve a beam and a target (sometimes just a source)
- Detectors are our eyes (all observable information comes from them)
- All detectors involve the interaction of radiation with matter
  - Different modes of interaction
  - Different detector types



Energetic charged particles in matter

- Charged particles of energy *E* lose energy in passing through material via a number of processes

- Charged (large field), so many small interactions with electrons (large-statistics behaviour)

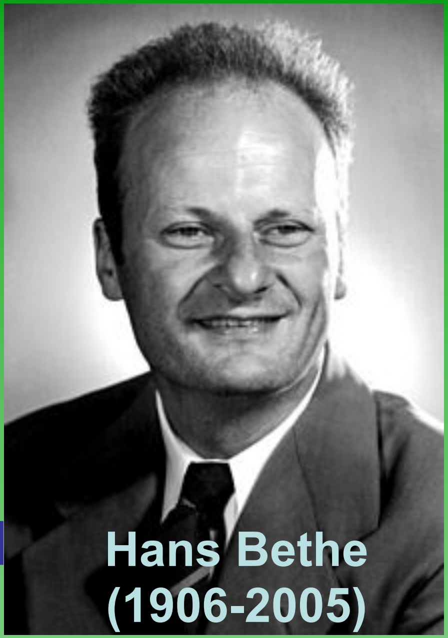
- The dominant losses are through
  - Inelastic collisions with atomic electrons
  - Nuclear elastic scattering

  (consider nucleus of 10^{-15} m, and atom of 10^{-10} m)

  - Other interaction forms (nuclear reactions, etc)

Energetic charged particles in matter

$$E = \frac{1}{2}mv^2 \qquad -\frac{dE}{dx} \propto \frac{mz^2}{E}$$



dominant in the classical limit [40 MeV/A (0.3 c) – <1% deviation]

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_0 v^2} nZ \left[\ln \frac{2m_0 v^2}{I} - \ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2} \right]$$

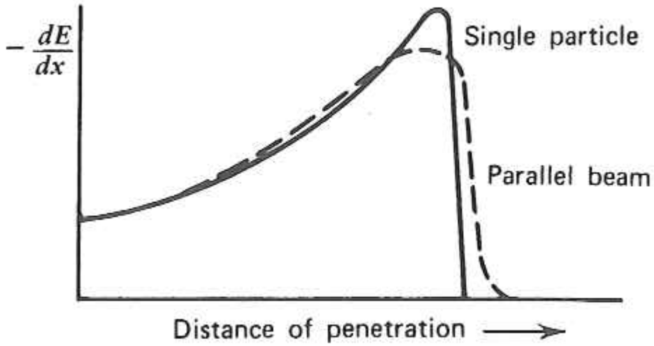
Bethe-Block formula

z – projectile atomic number
v – projectile velocity
m_0 - electron mass
e – electron charge

n – target number density
Z – target atomic number
nZ – target electron density
I – average excitation and ionization potential

Energetic charged particles in matter

Bragg curve



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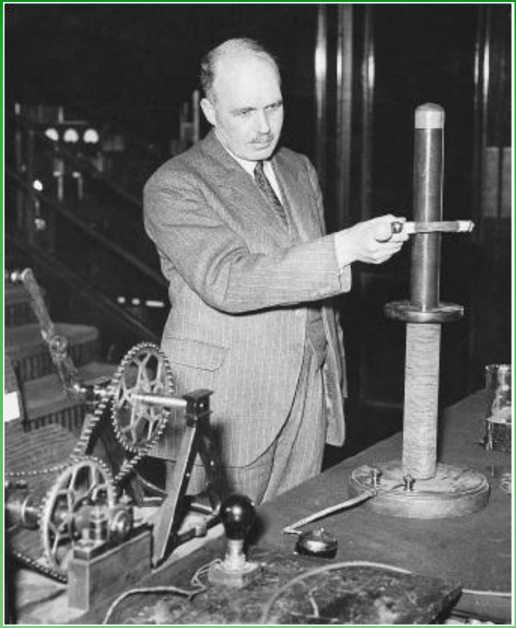

William Henry Bragg (1890-1971)

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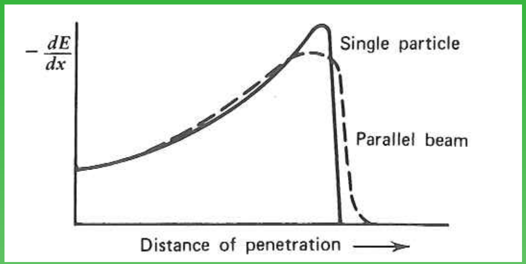

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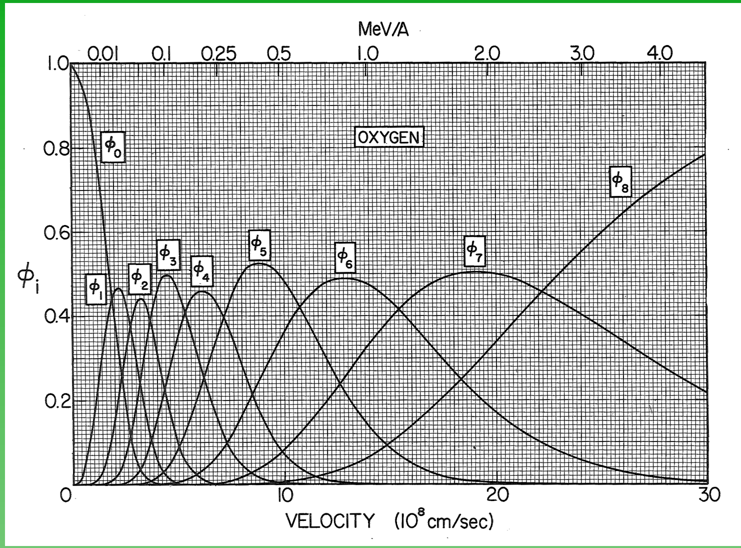
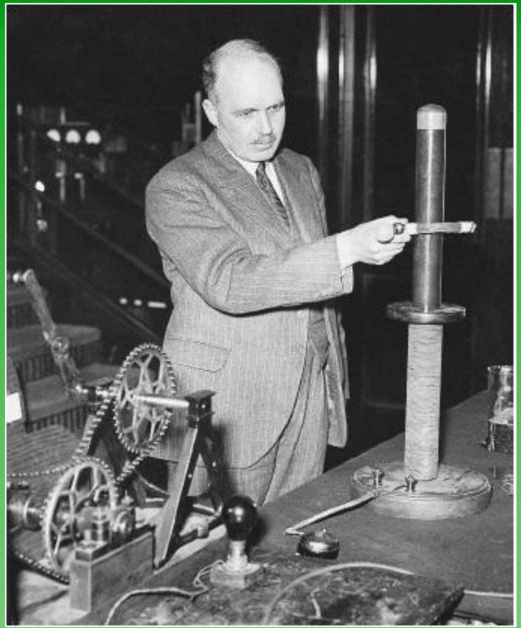


Charge state fraction



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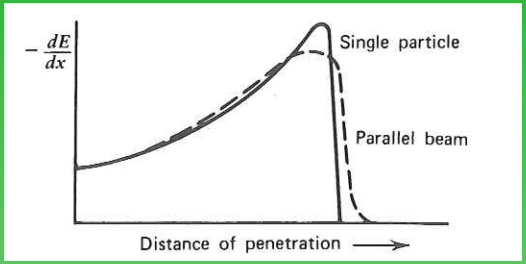

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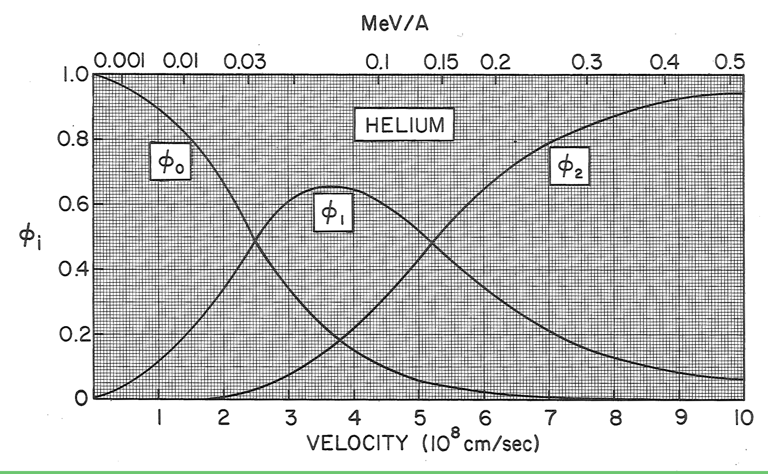

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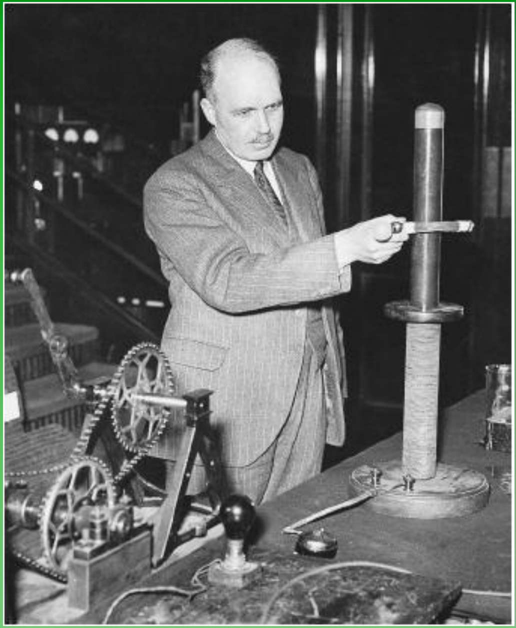
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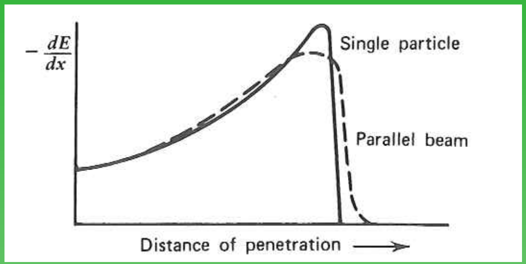

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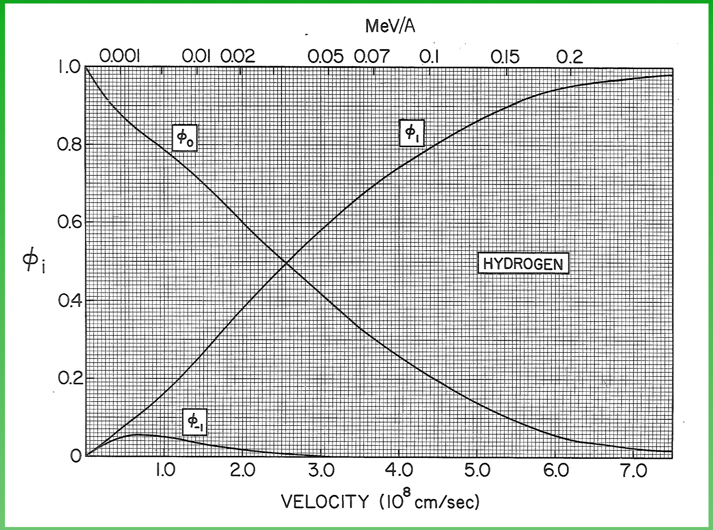

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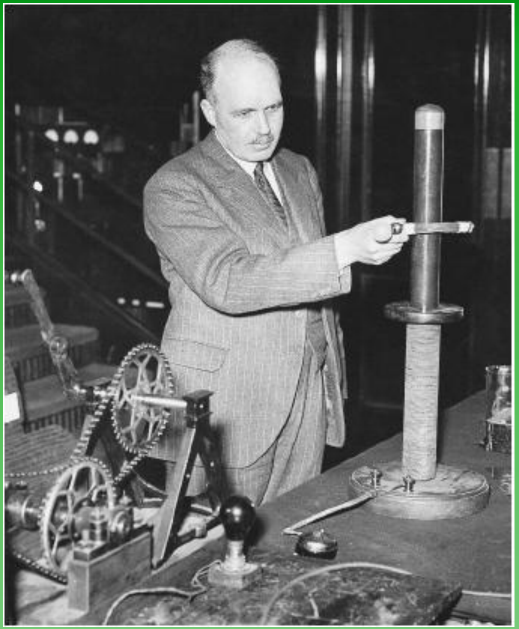

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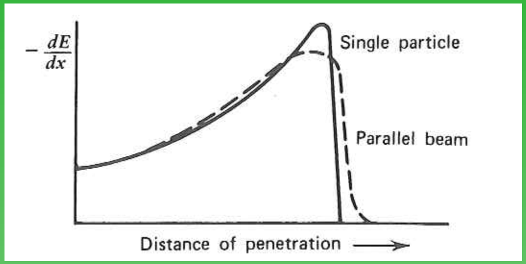


Bragg curve

Hydrogen – proton therapy

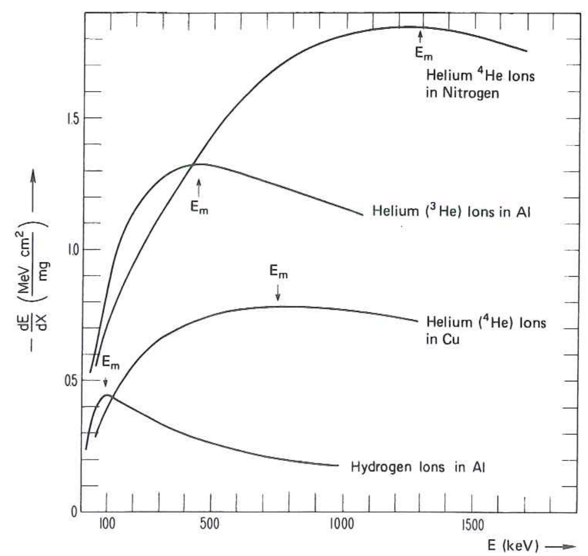
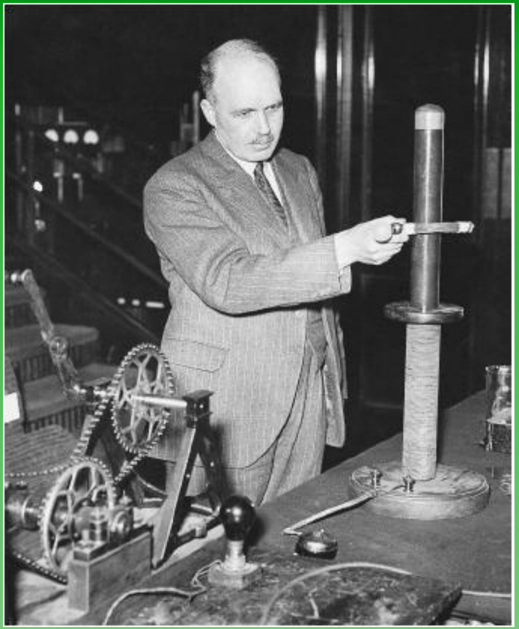


Figure 2.3 Specific energy loss as a function of energy for hydrogen and helium ions. E_m indicates the energy at which dE/dx is maximized. (From Wilken and Fritz.[3])



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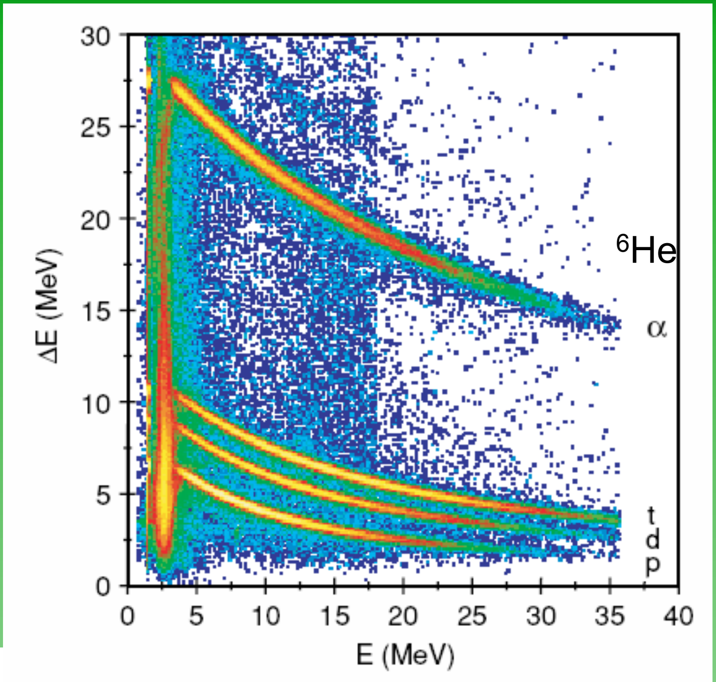

Charged particle identification with segmented or stacked detectors

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Photons in matter

Probabilistic

(few large interactions)

Material causes attenuation

Photoelectric absorption

$$E_{e^-} = E_\gamma - E_b$$

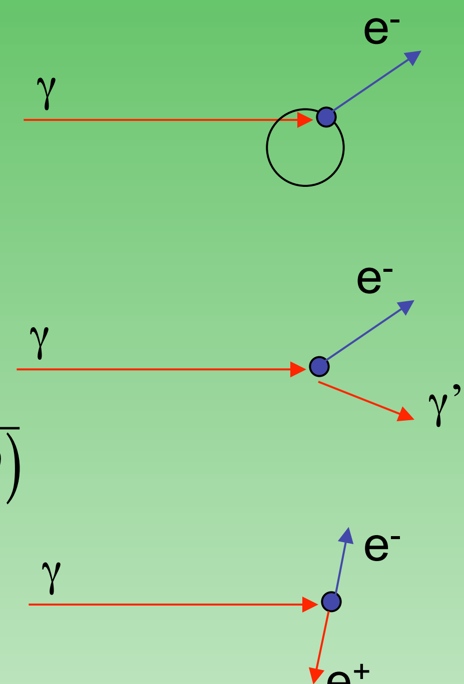
Compton scattering

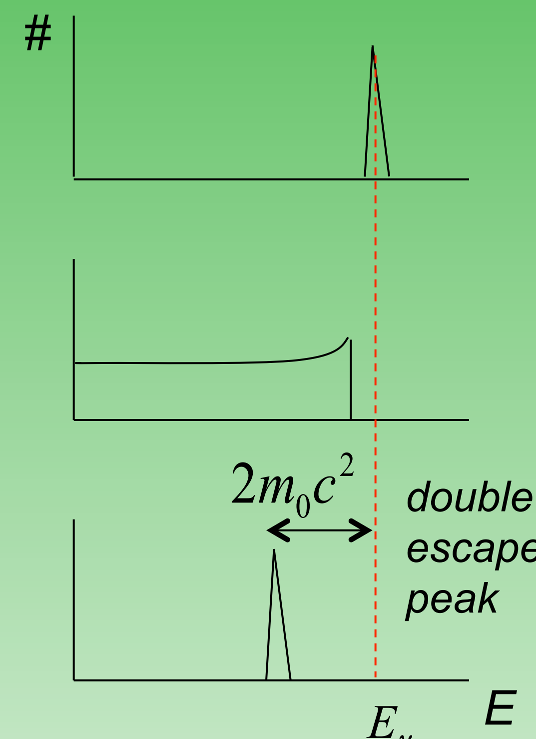
$$E_{e^-} = E_\gamma - E_{\gamma'}$$

$$E_{\gamma'} = \frac{E_\gamma}{1 + \left(h\nu / mc^2\right)\left(1 - \cos\theta\right)}$$

Pair production

$$E_{e^-} + E_{e^+} = h\nu - 2m_0c^2$$





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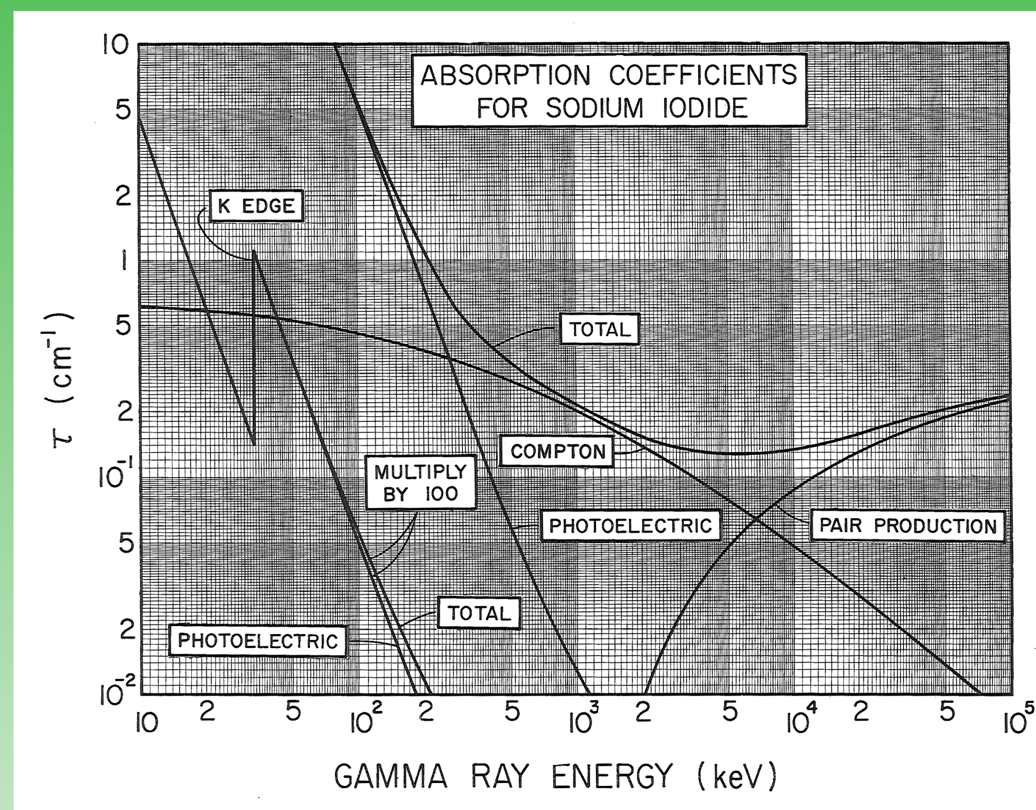


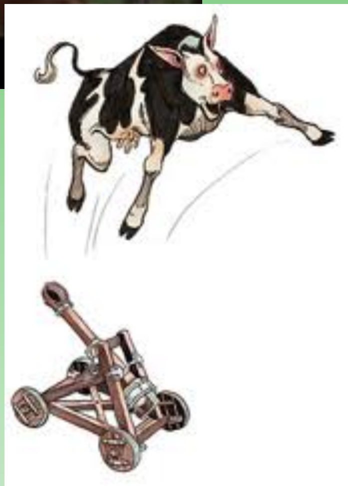
Neutrons in matter

- Most energy lost through nuclear scattering (low cross sections, signal from movement of scattered nucleus)
- Largest energy transfer for proton scattering (hydrogen content important)

- Multiple scattering to thermalize, then other reaction cross sections become significant

  (n,γ) (n,α) (n,p) (n,f)

- To detect, can use large signals/ cross section reactions (eg ^3He)
- Difficult to collect all the energy (signal not necessarily proportional to n energy)
- To get energy,use timing for ToF measurement (scintillators)



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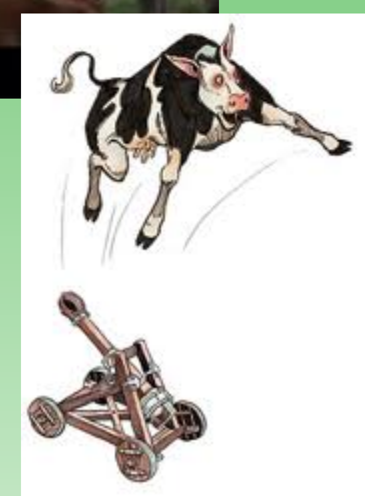


Gas detectors

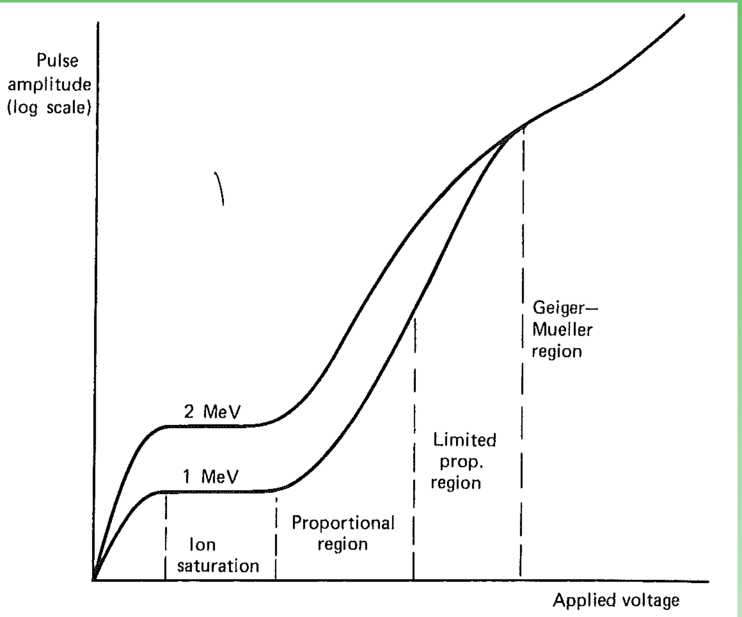
Charged particle measurements (typical)

Energy loss through ionization of the gas molecules

Voltage to separate and collect charge

Electric field (strength, shape) applied determines mode of operation (ionization chamber, proportional counter, GM)

Pulse and DC modes



Advantages

- Variable thickness (pressure, can be made thin wrt solids)
- Inexpensive and simple
- Radiation-hard

Gas detectors

Signal generation

First ionization potential (energy to remove valence electron)

w-value = average energy per e^- – ion pair (non-ionizing excitations, removal of more deeply bound electrons, etc)

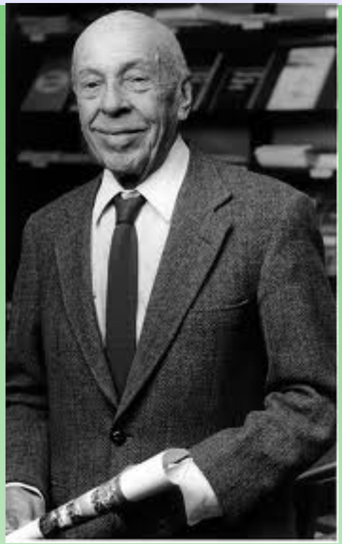
		W-value	
Gas	First ionization potential (eV)	Fast electrons (eV/ion pair)	Alphas (eV/ion pair)
Ar	15.7	26.4	26.3
He	24.5	41.3	42.7
H2	15.6	36.5	36.4
N2	15.5	34.8	36.4
Air		33.8	35.1
O2	12.5	30.8	32.2
CH4	14.5	27.3	29.1

Typically ~30 eV per e^- ion pair

Expect $\sigma = \sqrt{N} = \sqrt{\frac{E}{w}}$ Find empirically $\sigma = \sqrt{\frac{FE}{w}}$

Fano factor F accounts empirically for deviation from Poisson statistics (limited ways ions can be formed)

F ~~0.2 for gasses, ~~0.1 for semiconductors



Ugo Fano (1912-2001)

Gas Detectors

Signal collection

Diffusion (spreading of the spatial charge distribution)

Electron attachment

$e^- + M \rightarrow M^-$ *Recombination*

$e^- + M^+ \rightarrow M$

$M^- + M^+ \rightarrow M + M$

Charge transfer

$M^+ + M \rightarrow M + M^+$

$M^- + M \rightarrow M + M^-$

Matters if gas mixture is used

Ionization Chambers

Drift velocity for ions $v = \frac{\mu E}{p}$

μ = mobility (gas dependent quantity)

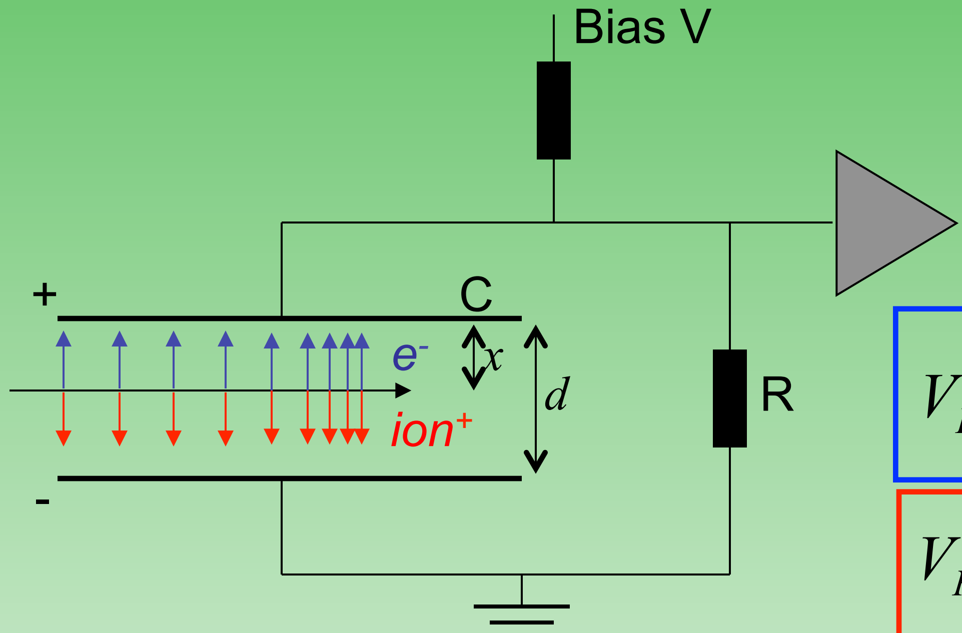
E = electric field strength (~10^4 V/m)

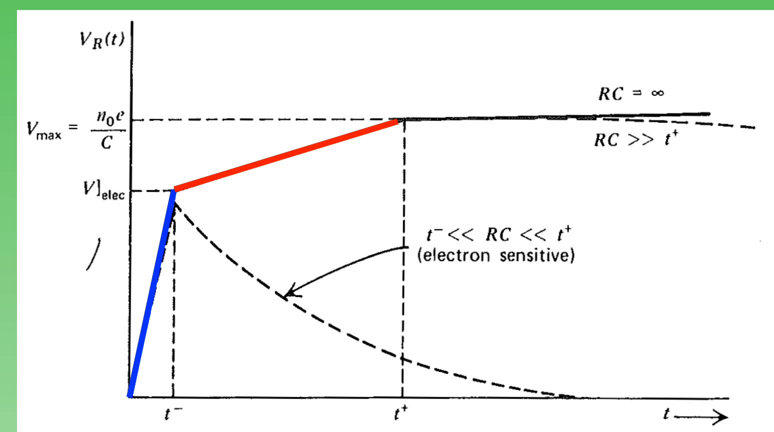
p = gas pressure

$\mu \sim 1\times10^{-4}$ m^2 atm/V.s for ions of most gasses

Electrons are typically faster by a factor of ~1000

Signal induced by movement of charge in E





$$V_R = \frac{n_0 e}{dC}\left(v^- + v^+\right)t$$

$$V_{elec} = \frac{n_0 e}{dC}x$$

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$$V_{max} = \frac{n_0 e}{C}$$

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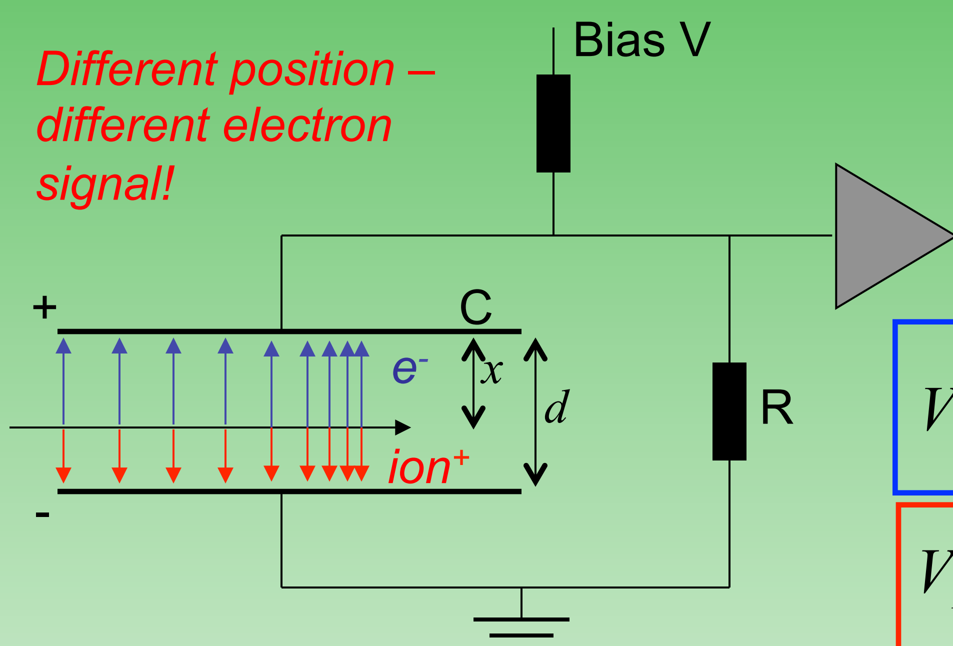
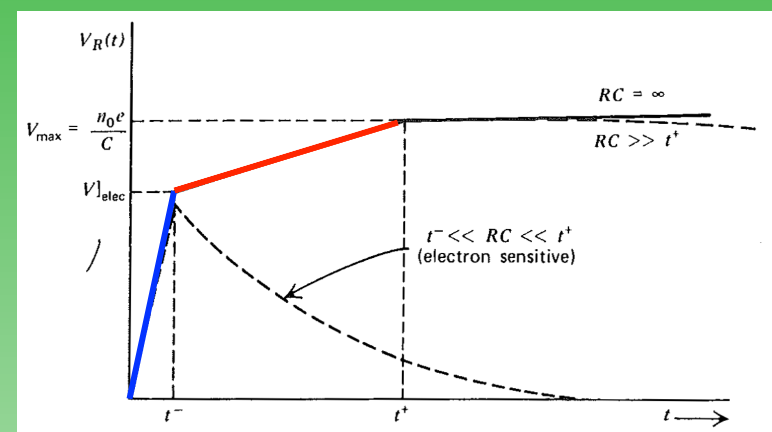
Different position – different electron signal!





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Gridded Ionization Chambers

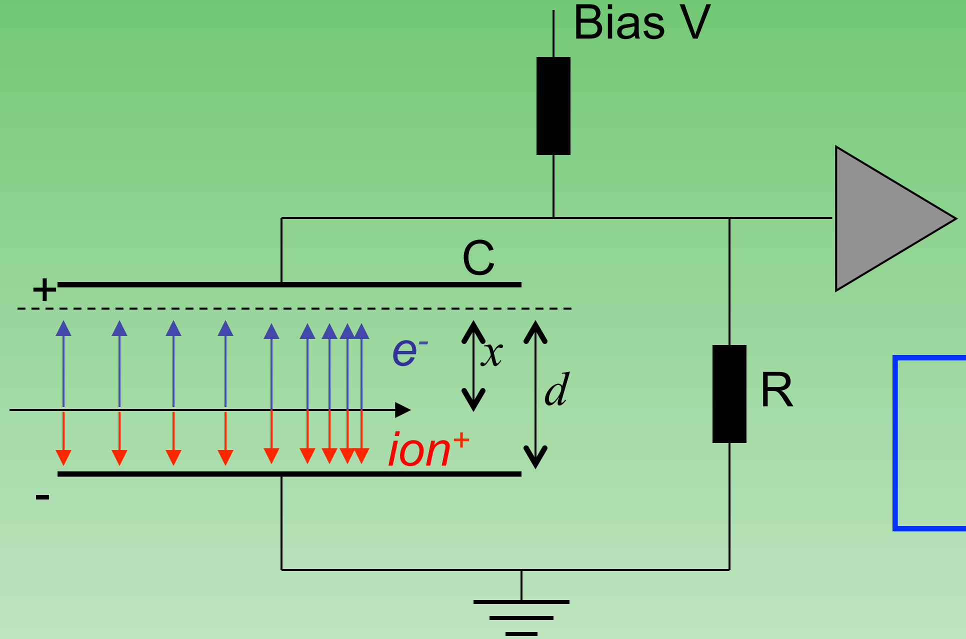
Otto Robert Frisch (1904-1979)

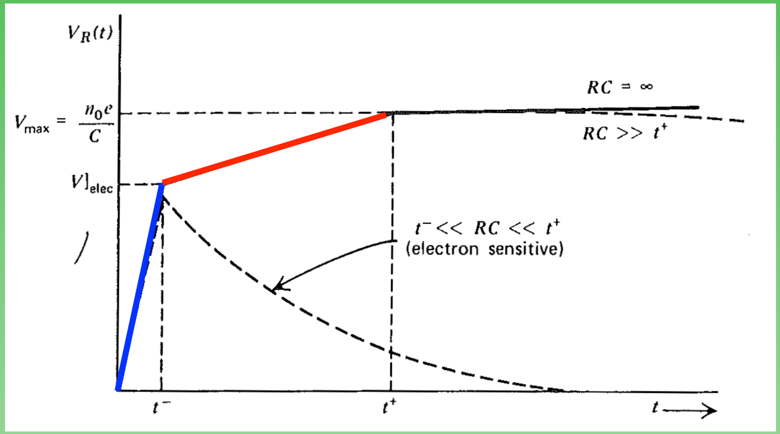
Frisch grid incorporated to shield anode from the moving electrons until they get close

Anode is sensitive to movement of charge over a fixed distance

Removes position dependence of electron signal

Short τ – high rate





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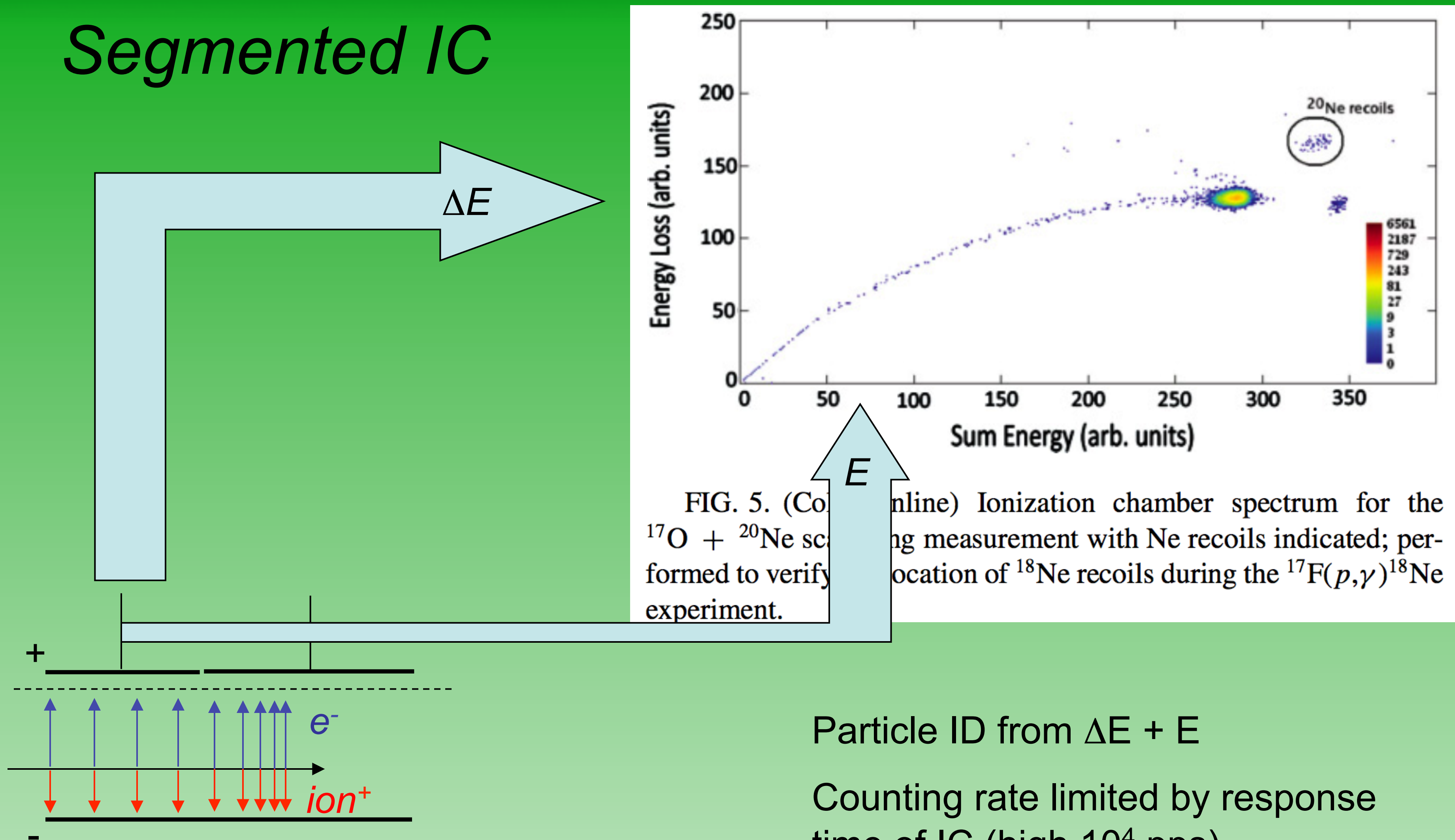
Ionization Chambers

Segmented IC

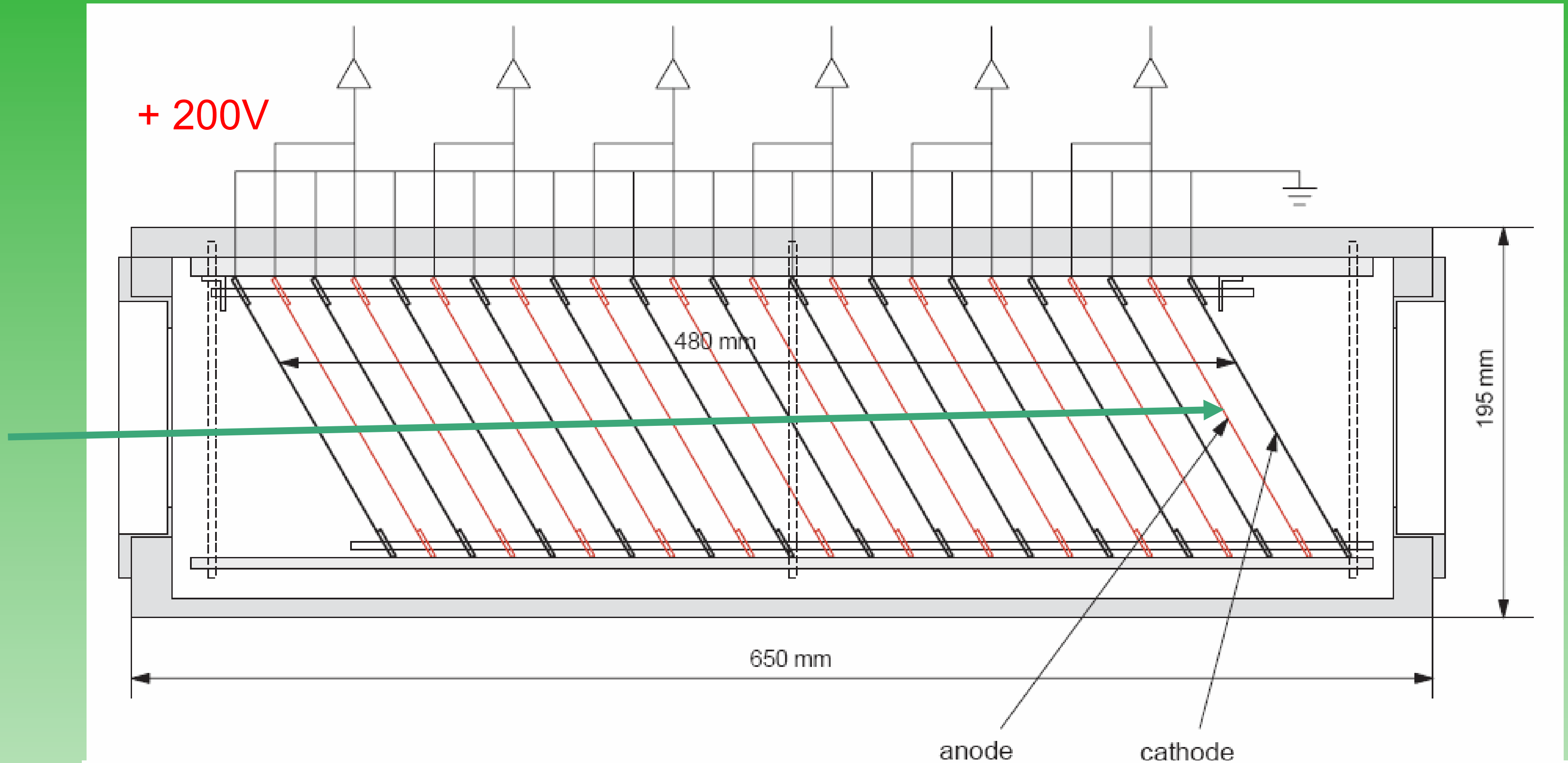


Particle ID from ΔE + E

Counting rate limited by response time of IC (high 10^4 pps)

Ionization Chambers

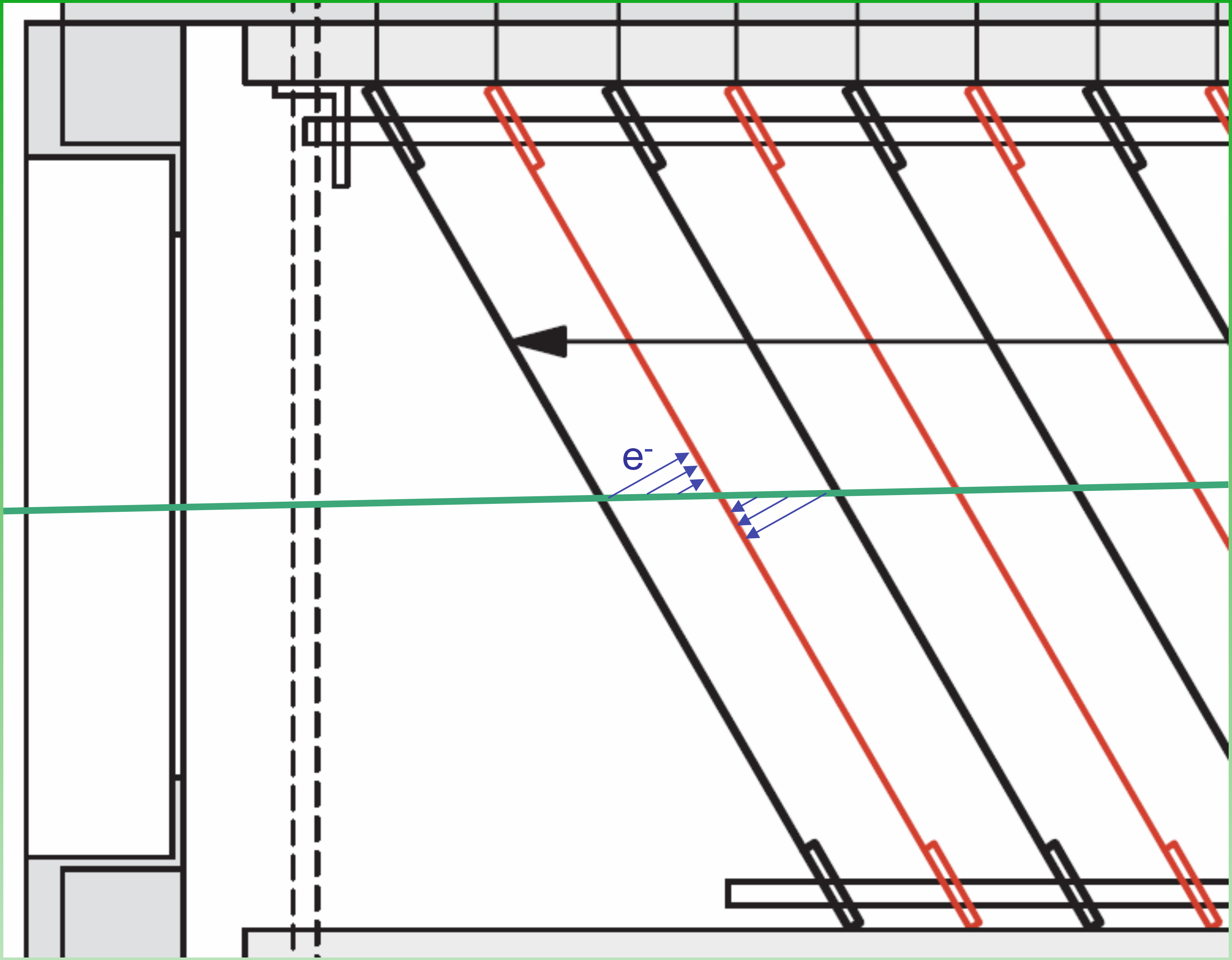
Tilted Electrode Gas Ionization Chamber



K. Kimura et al. / Nuclear Instruments and Methods in Physics Research A 538 (2005) 608–614

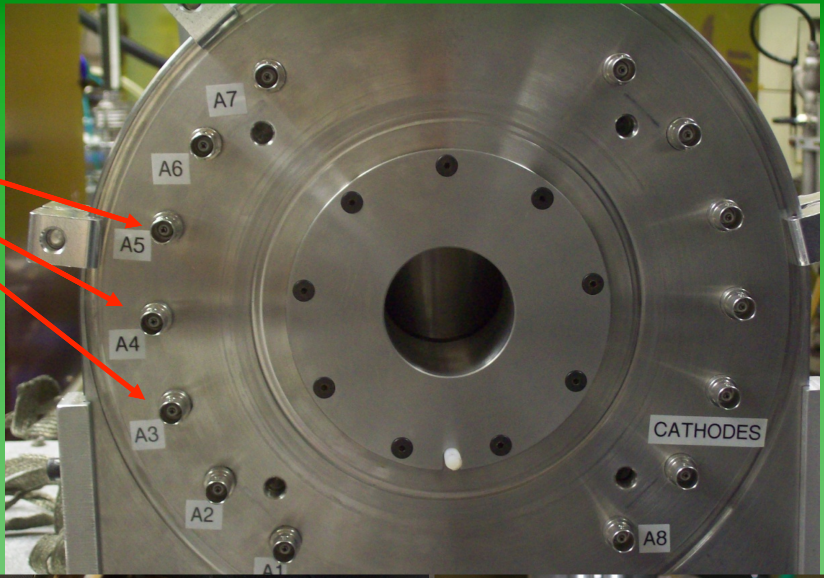
Ionization Chambers

- Position dependence minimized
- Small distance – fast collection times
- Replace foils with wire grids – reduced straggling, low energy beams
- Easy to adjust anode combinations to optimize ΔE -E

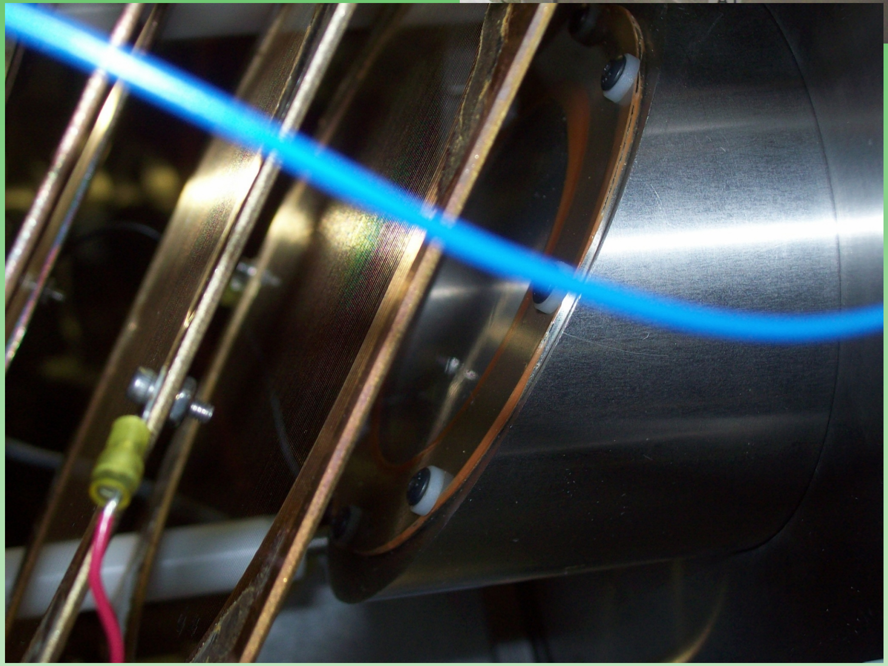


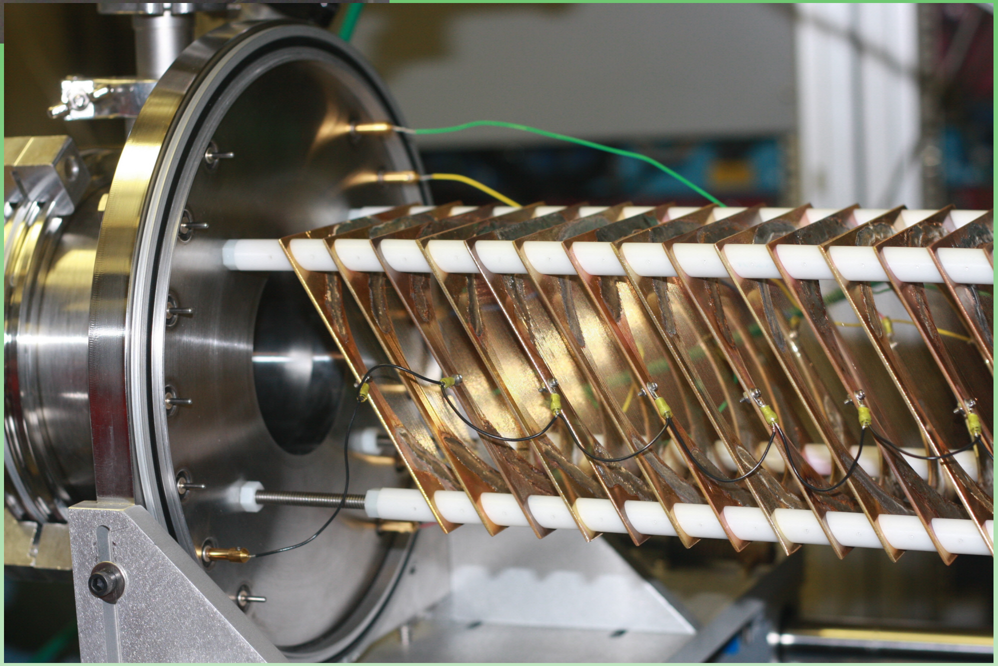
Ionization Chambers

Signal per anode grid



Angled, re-entrant window





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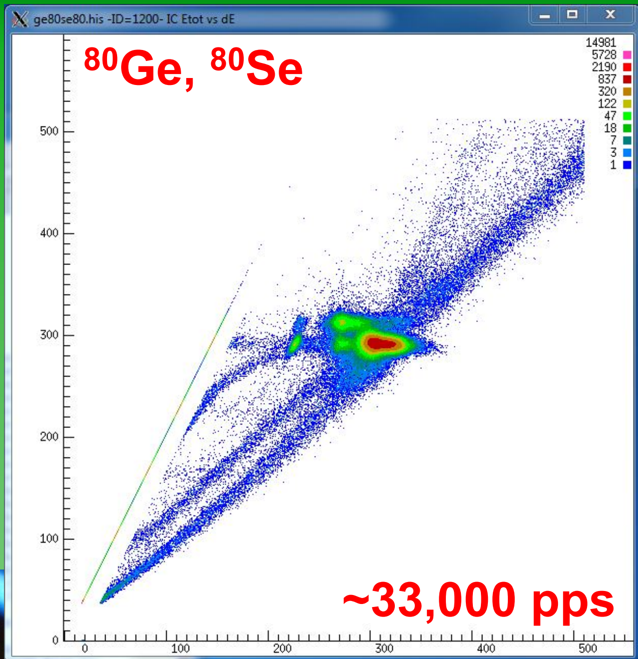
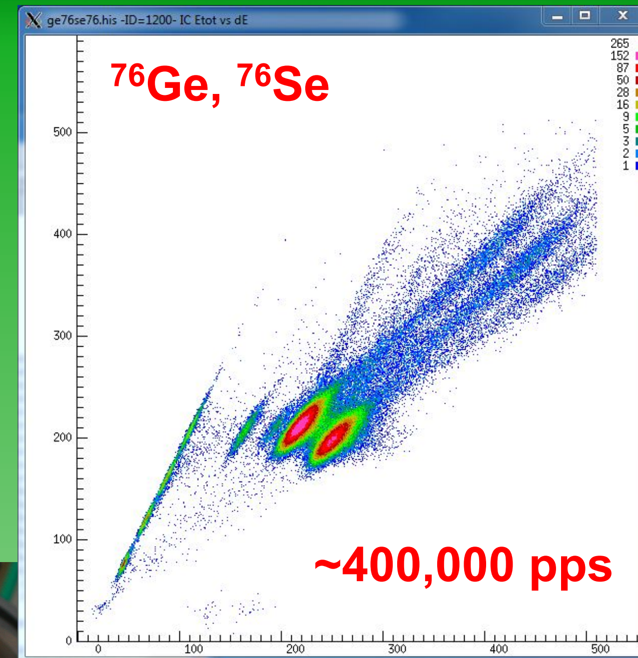
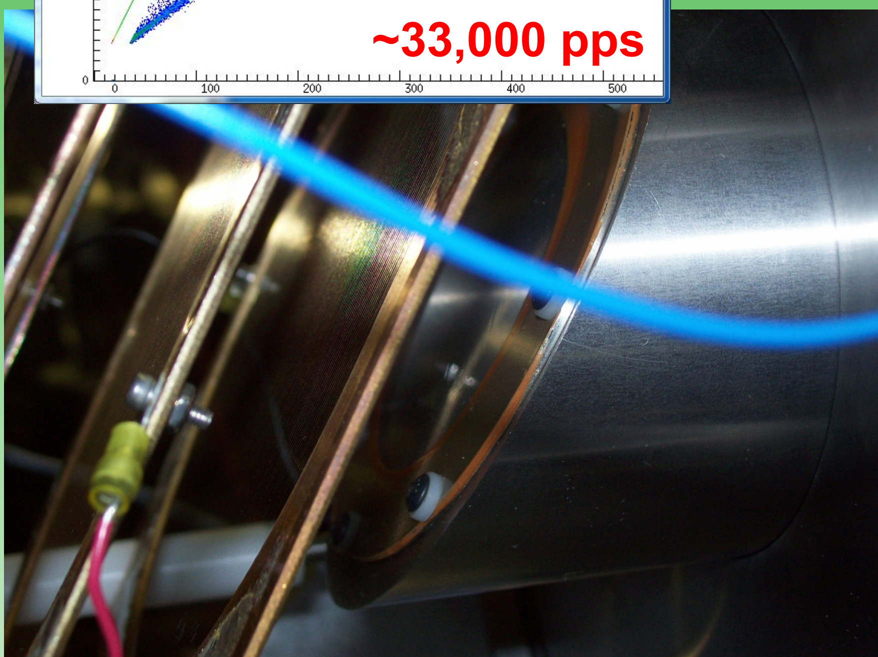
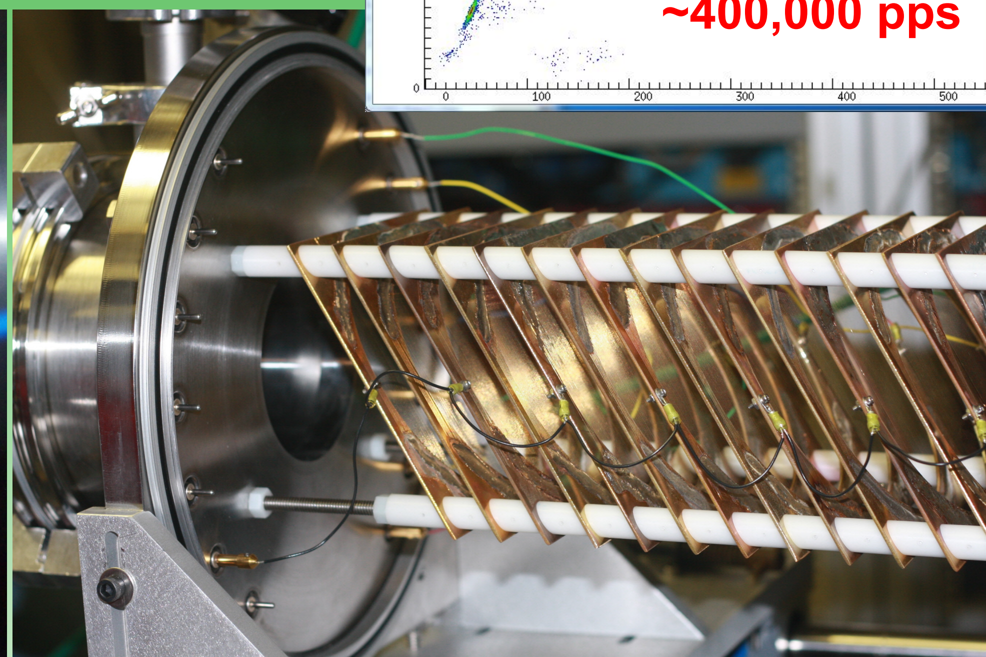


Cocktail beam tests

Mid 10^5 pps limit







Proportional Counters

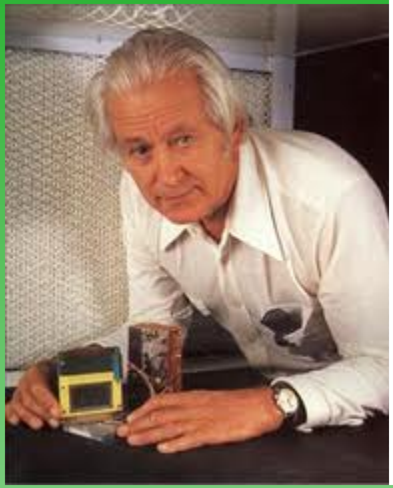
Sufficient voltage to cause secondary ionization (10^6 V/m)

Amplification of signal

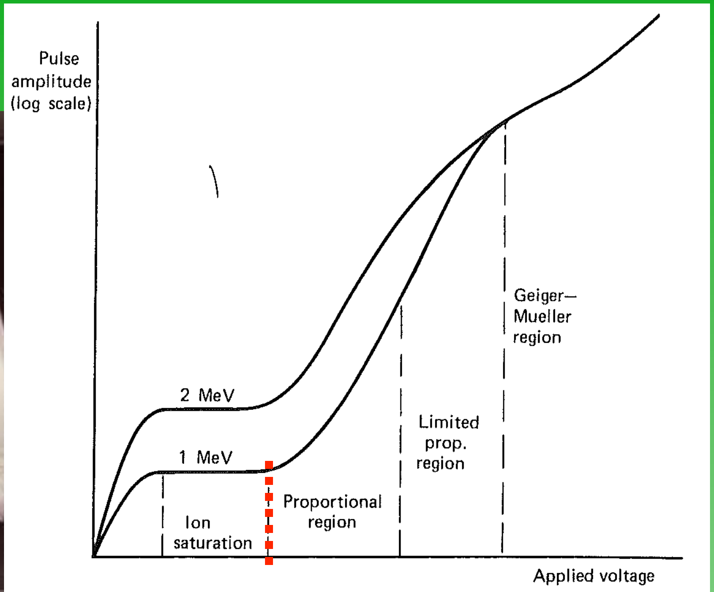
Wires used to limit the proportional region to a small volume (reduces position-dependence of gain)

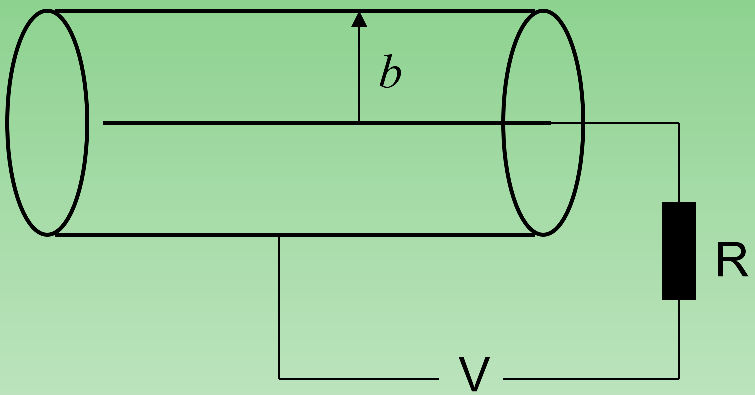
Basic cylindrical configuration

Multi-wire proportional counters can be made in various geometries to over large areas (tracking detectors)



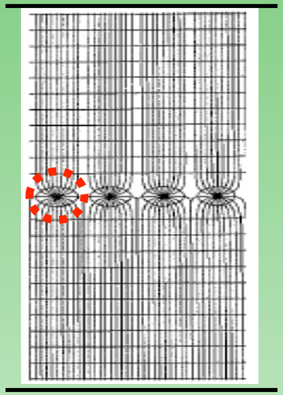
Georges Charpak (1924-2010)





$$E(r) = \frac{V}{r \ln(b/a)}$$

a = wire radius



Drift Chambers

Tracking detectors

Small channel count

High velocity beams (transmission detectors)

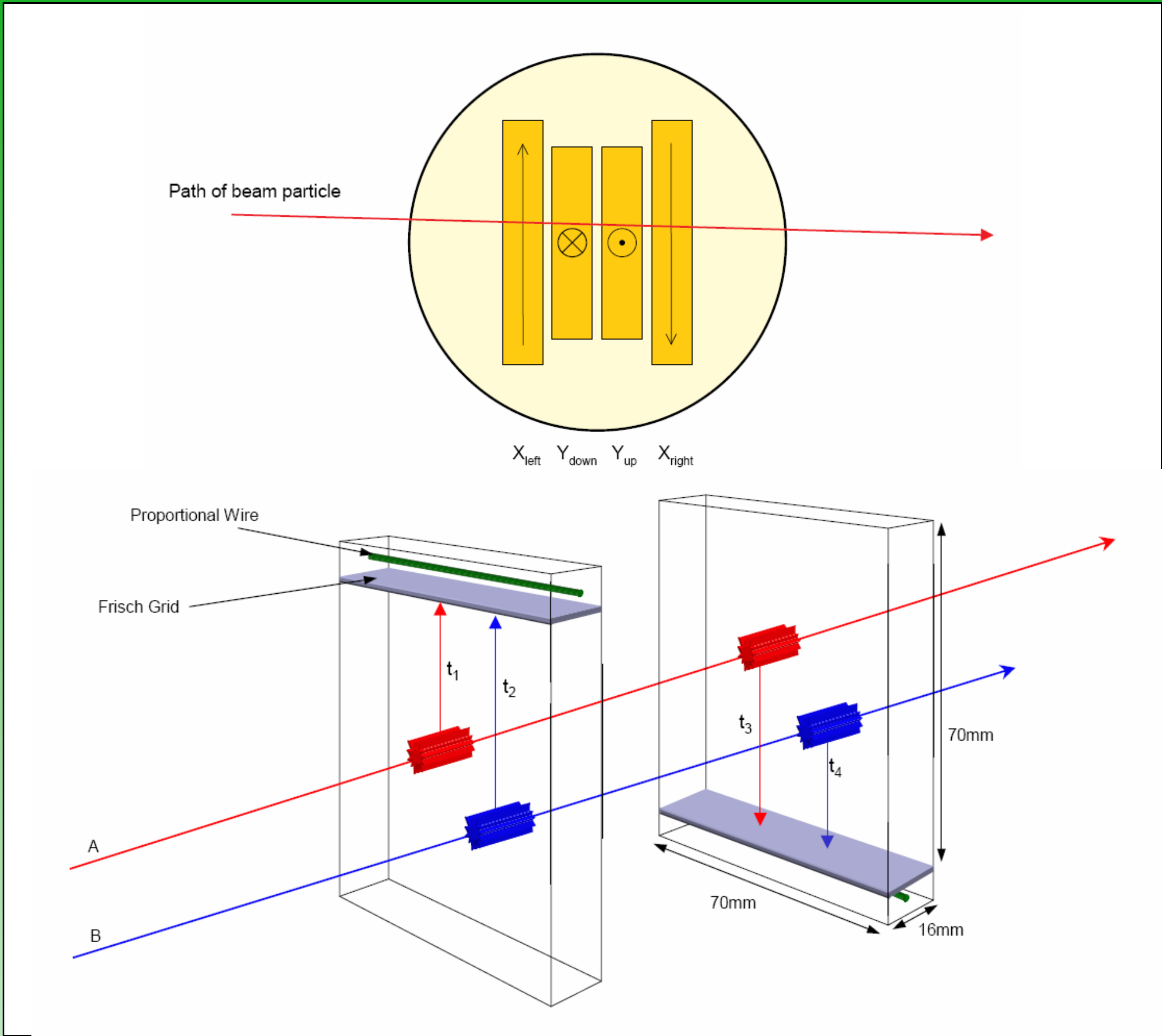
Linear signals

Drift velocity for ions

$$v = \frac{\mu \varepsilon}{p}$$

Isolate drift region from proportional region with Frisch grid

Measure time difference between *up*/*down* (*left*/*right*) signals



Drift Chambers

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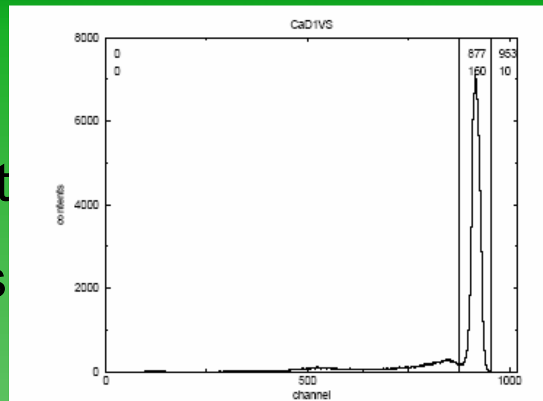
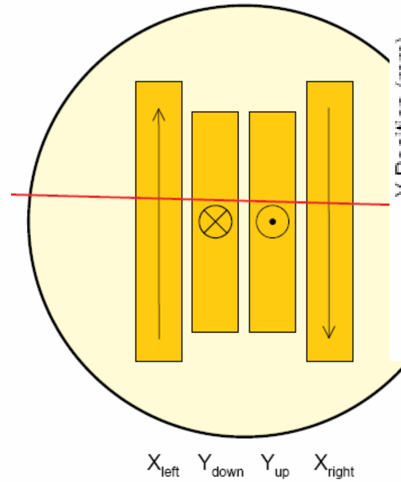
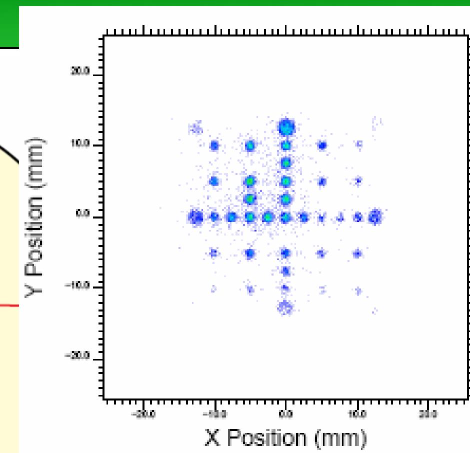
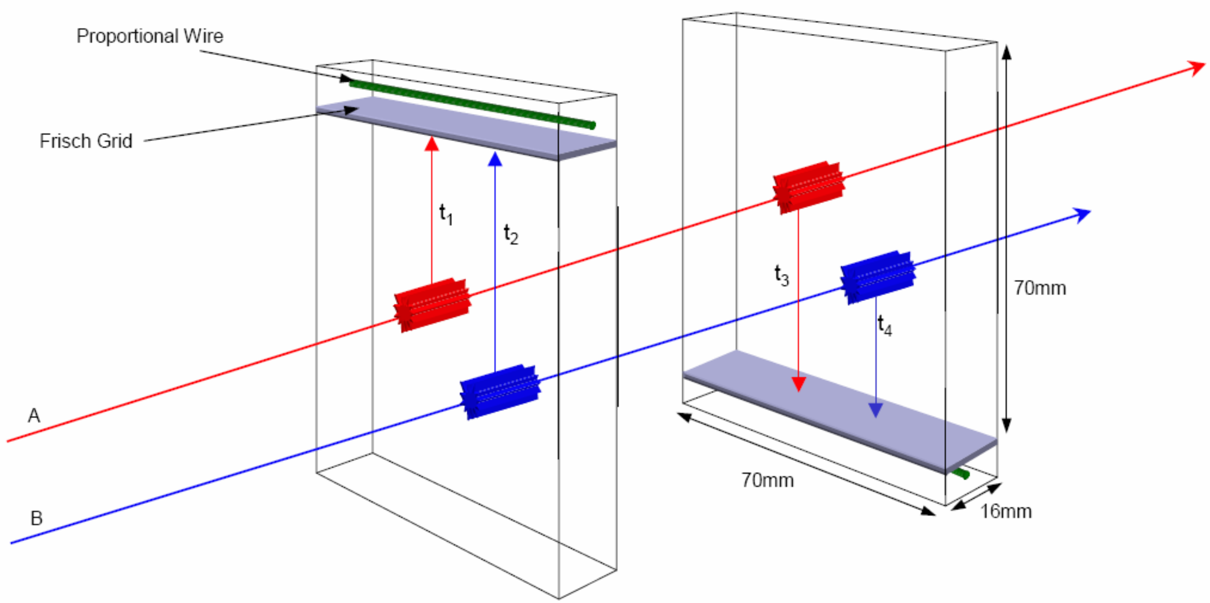








Semiconductor detectors

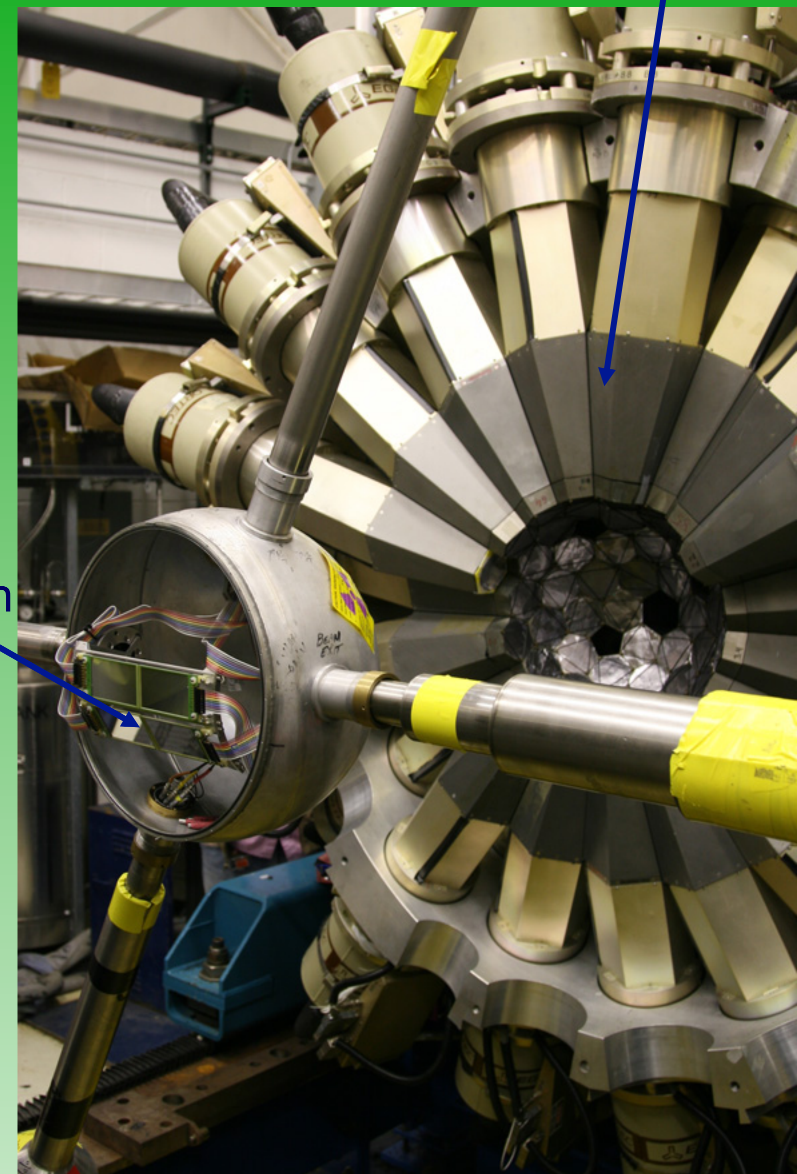
Charged particle and photons

Large arrays, in various geometries

High resolution

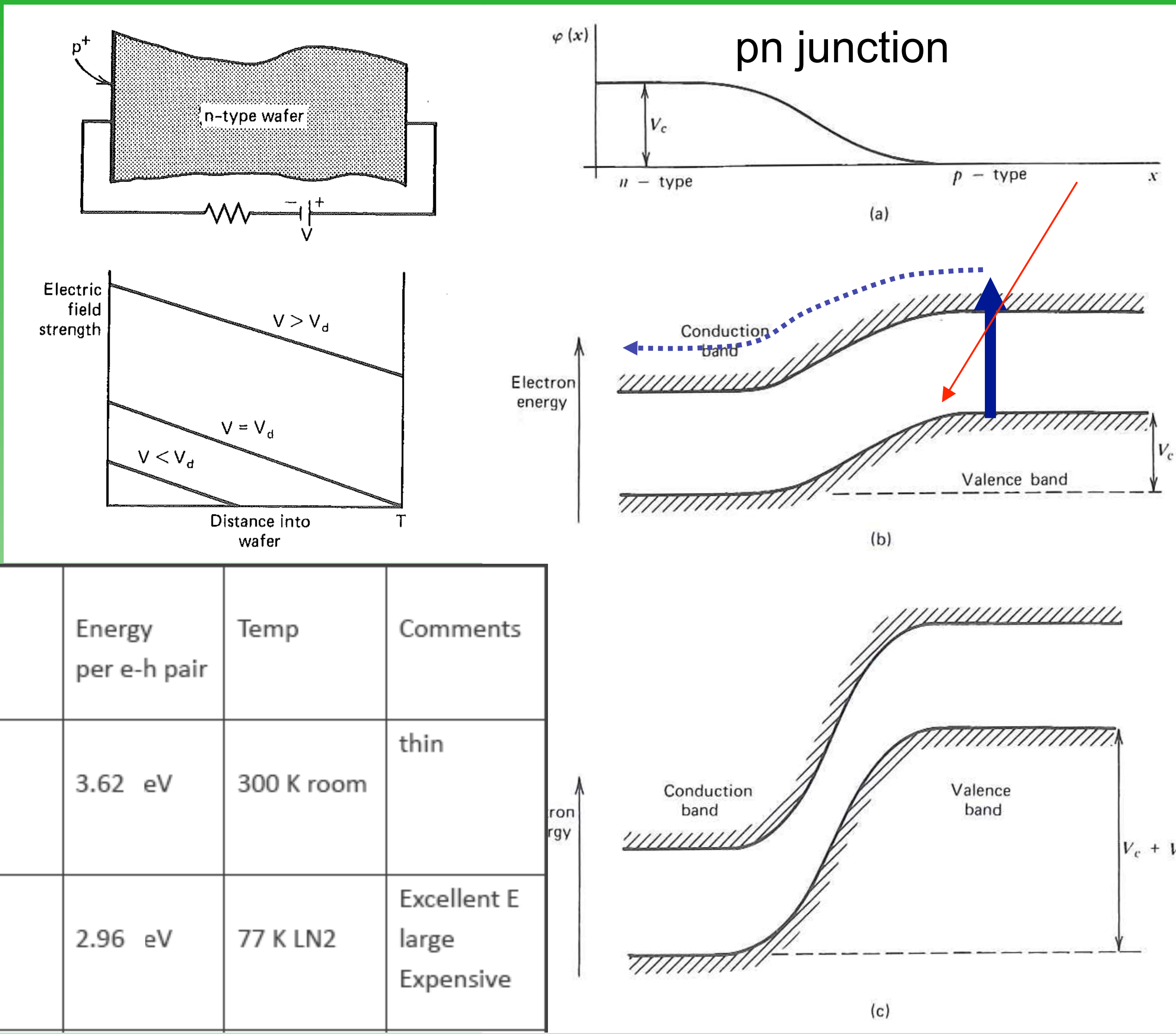
Compact (Si)

Delicate (esp radiation damage for stopping detectors)



Semiconductor detectors

- Active in depletion region around a pn junction
- Energy loss through electron excitation from valance to conduction bands
- For gammas, *Z* is important
- [Recall ~30 eV per e⁻ ion pair for gasses]



material	Atomic number	density	gap	Energy per e-h pair	Temp	Comments
Si	14	2.33 g/cm3	1.1 eV	3.62 eV	300 K room	thin
Ge	32	5.32 g/cm3	0.7 eV	2.96 eV	77 K LN2	Excellent E large Expensive

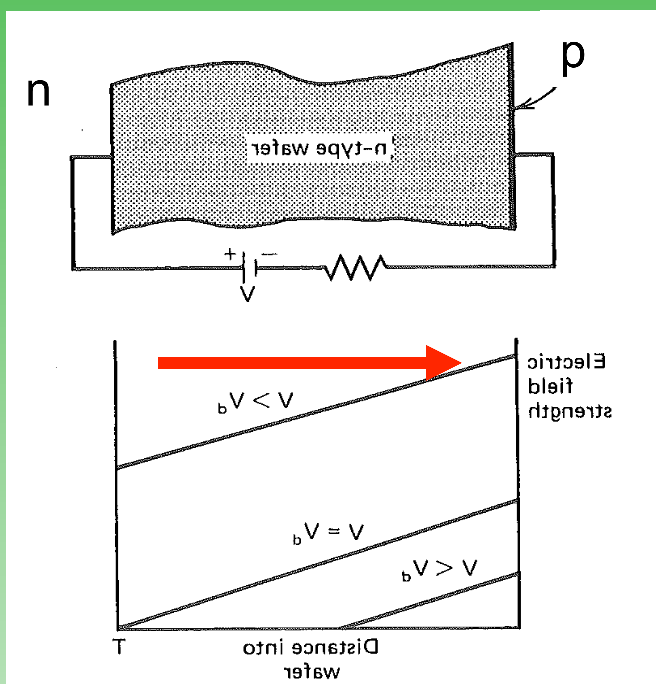
Semiconductor detectors

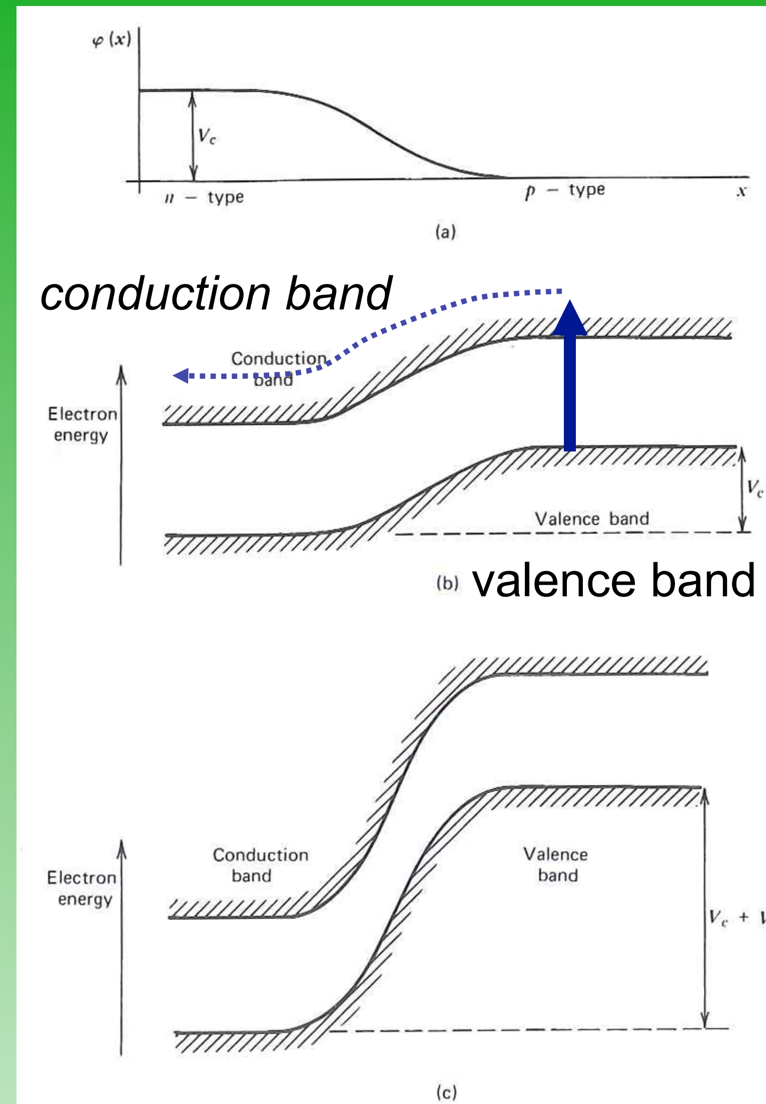
Leakage currents (thermal effects):

Diffusion current

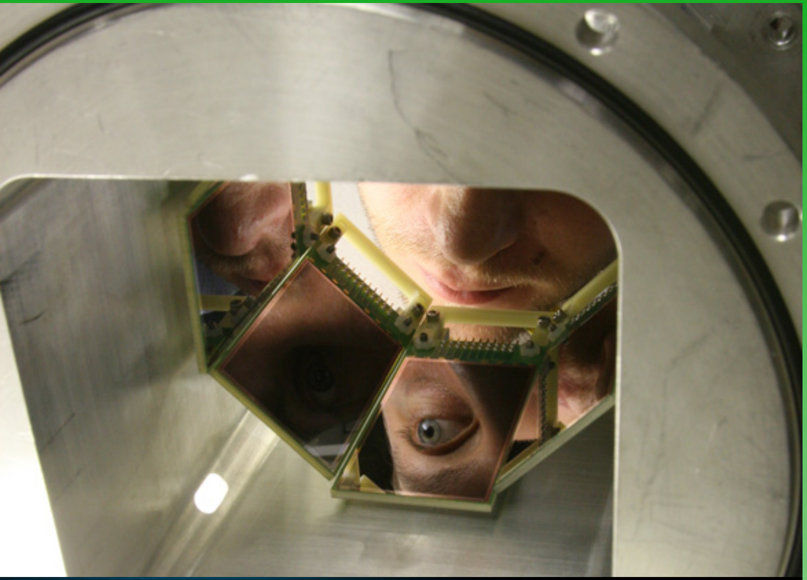
Drift current

Surface leakage





Silicon detectors



Thin particle detectors

Highly segmented

Range of thicknesses (~20 μm – ~2 mm)

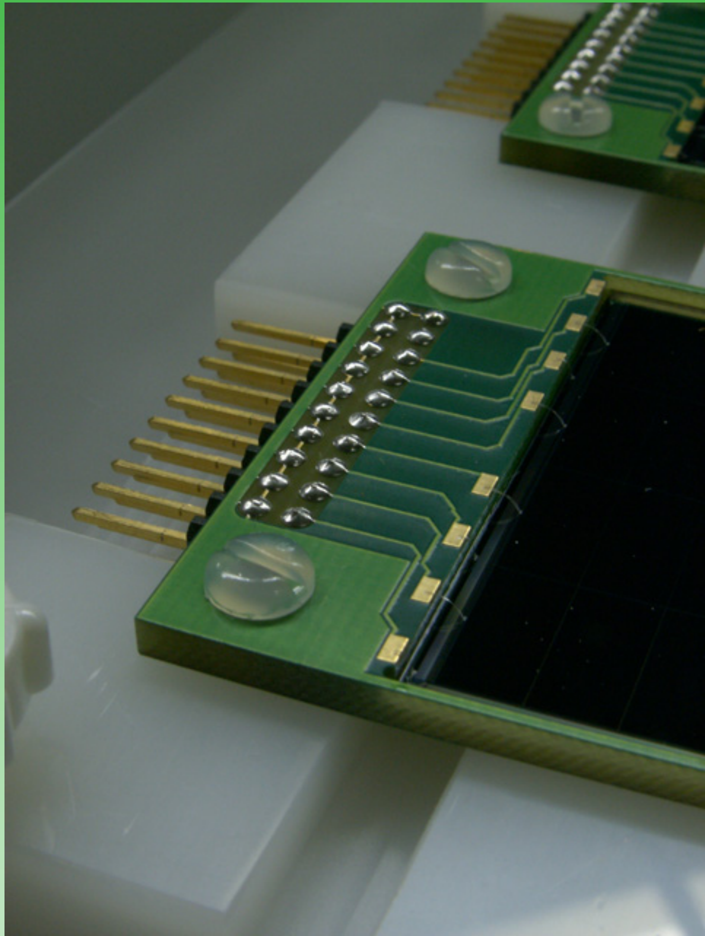
Large area

Room temp

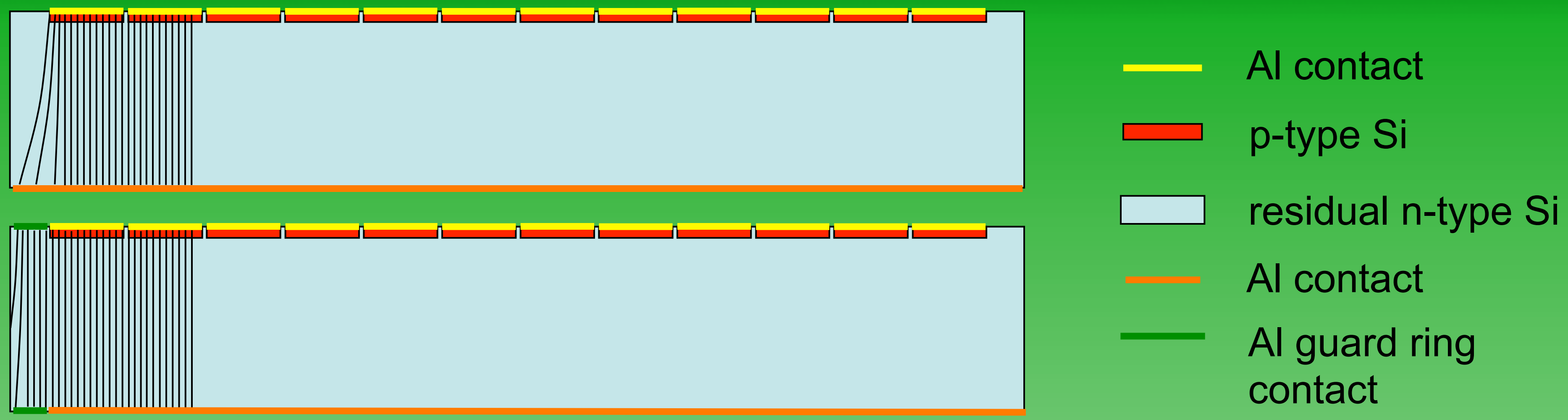
(performance

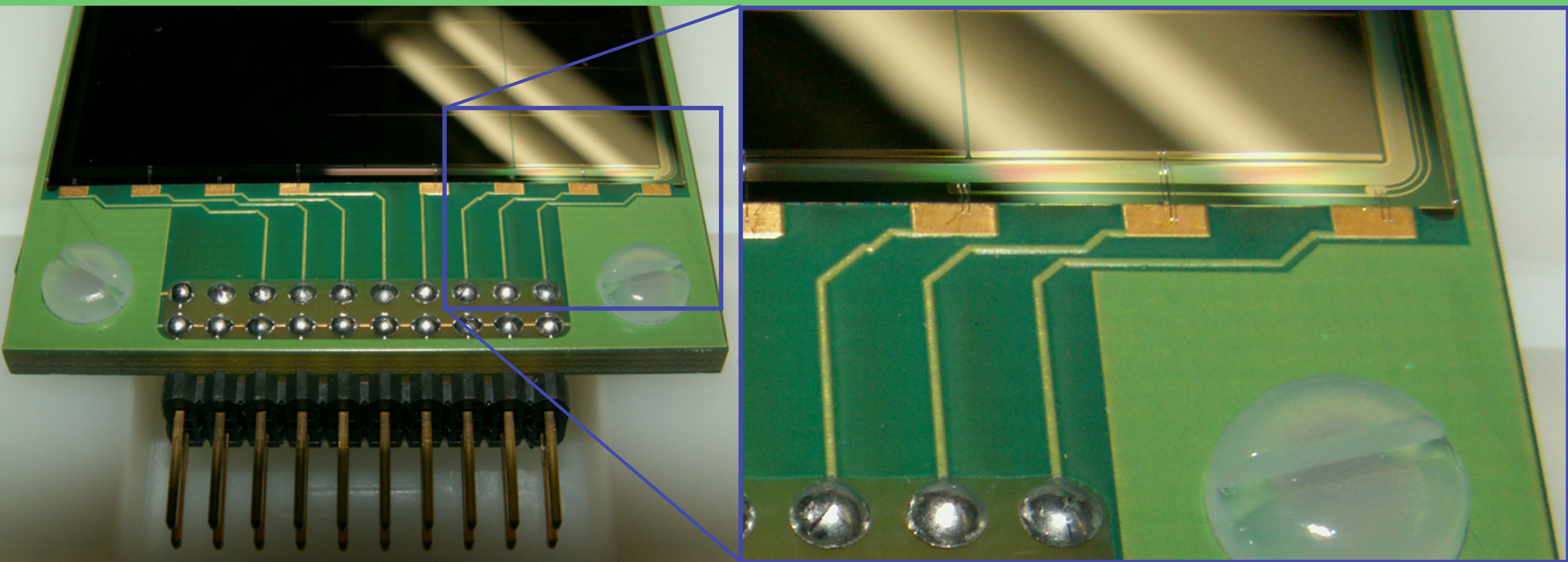
gains with

cooling)



Silicon detectors

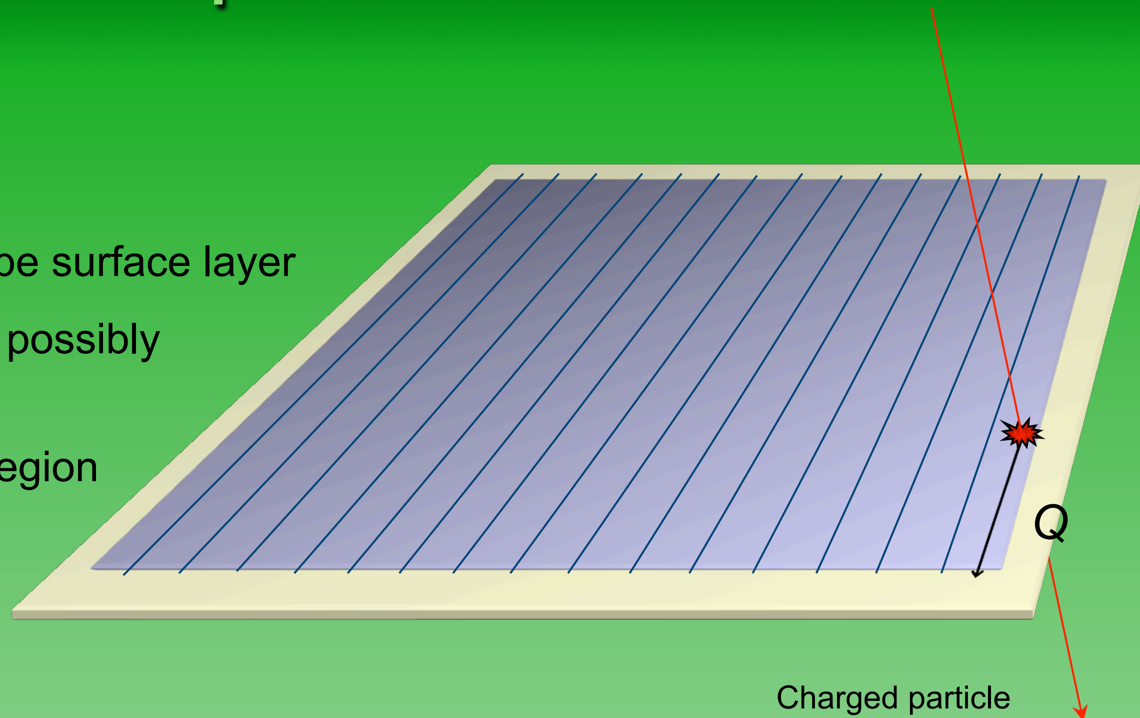


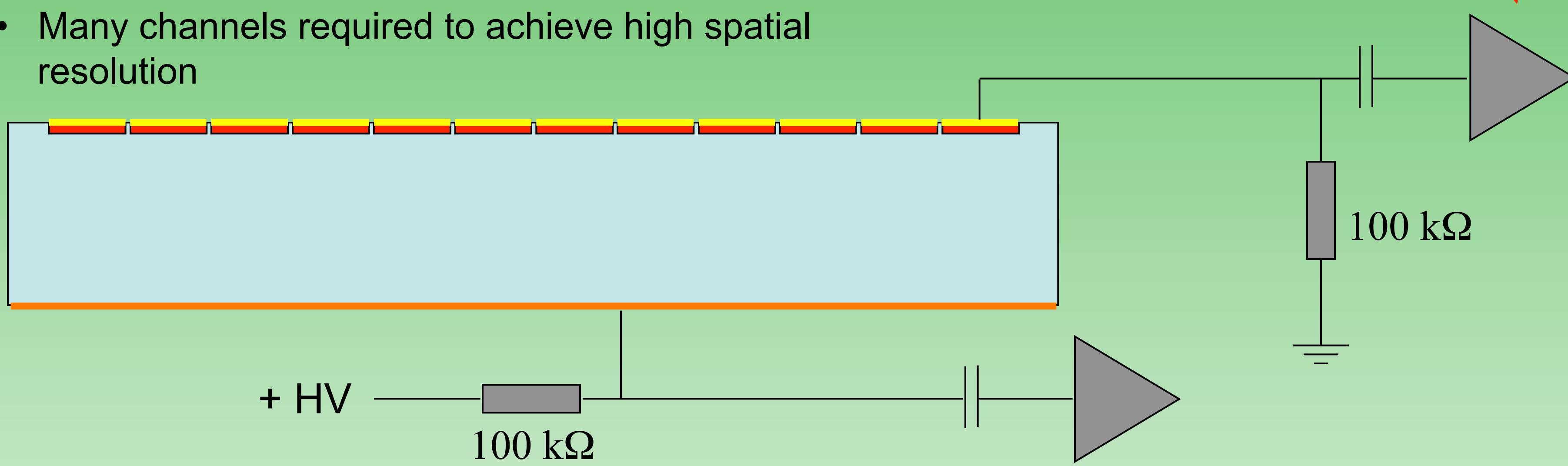


Silicon strip detectors

Si strip detectors

- p-n junction
- Residual n-type silicon, with p-type surface layer
- Front and rear faces aluminized, possibly divided into strips
- Biased, to extend the depletion region throughout entire volume
- Energy = Q
- Position = strip location
- Many channels required to achieve high spatial resolution

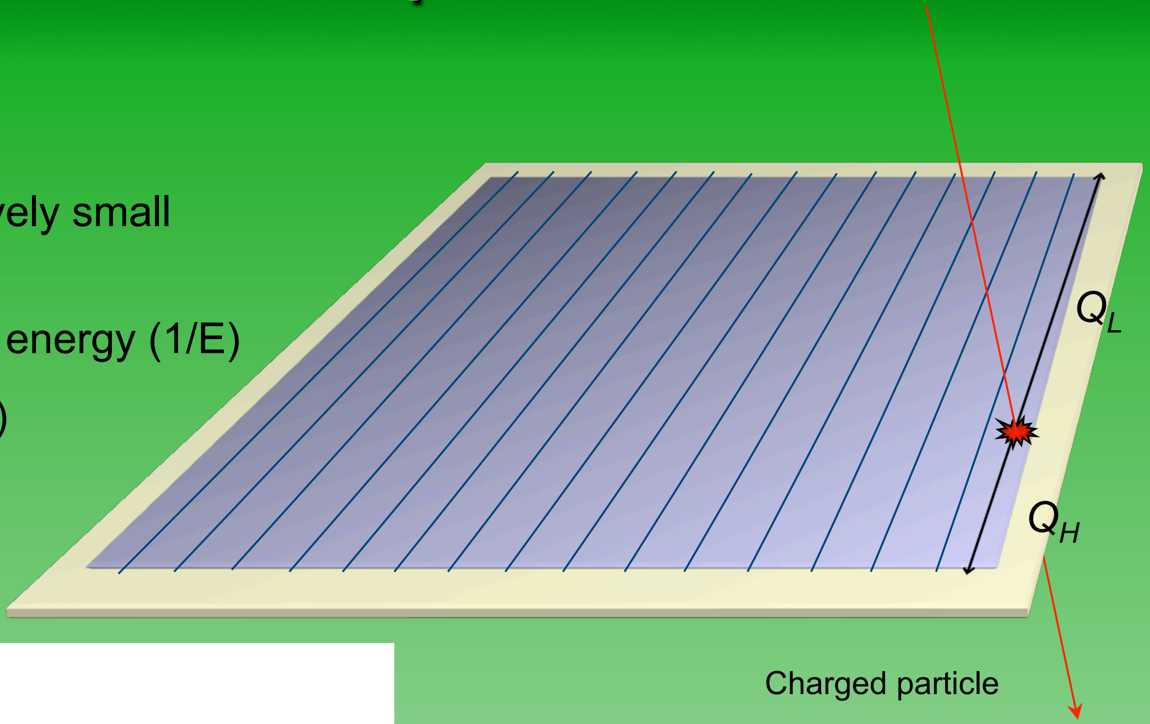


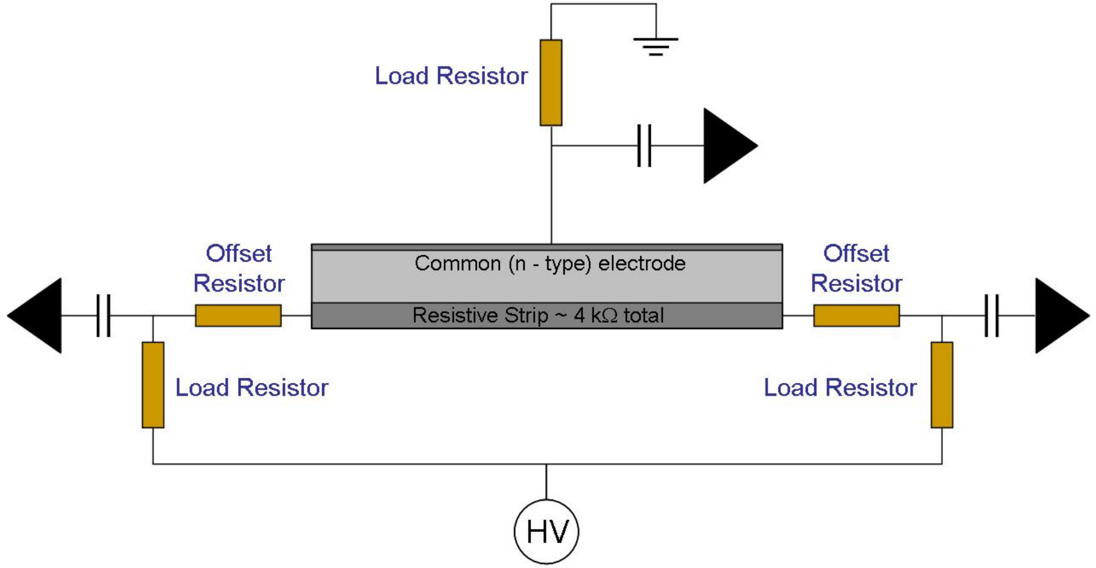


Resistive silicon strip detectors

Resistive strip Si detectors

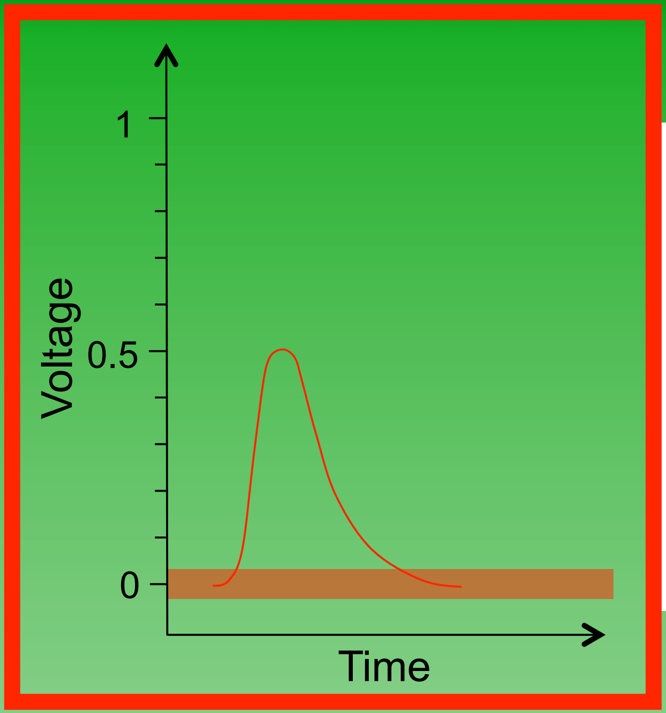
- Good position resolution with relatively small channel count
- Position resolution degrades at low energy (1/E)
- Threshold issues (esp at strip ends)

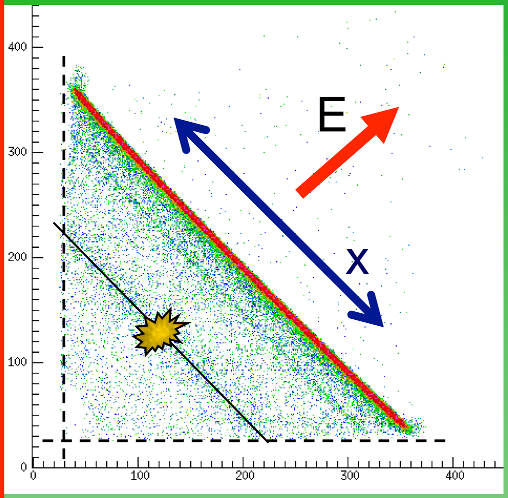


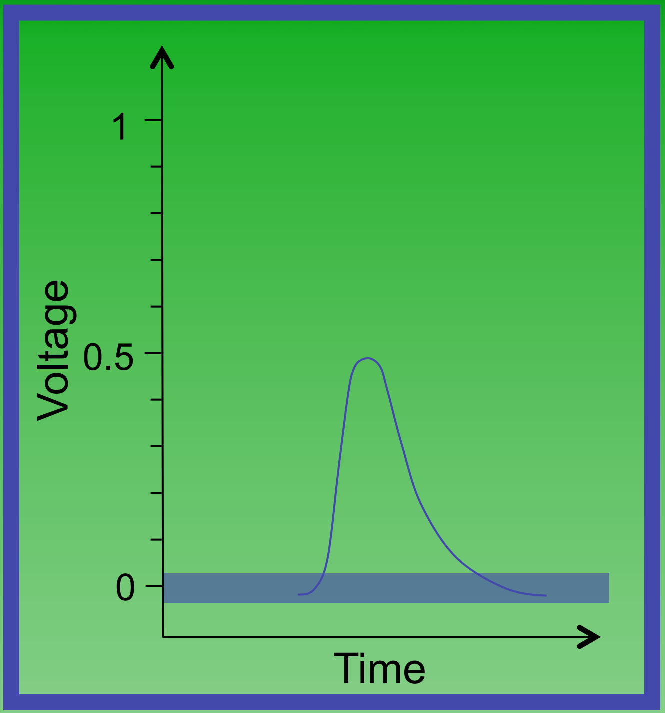


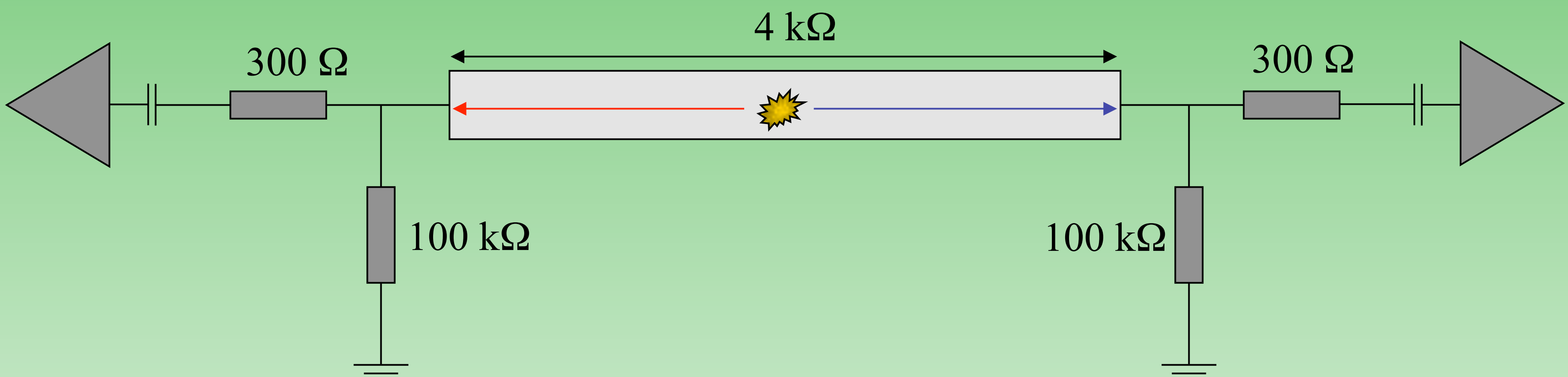
- Energy = $Q_H + Q_L$
- Position = $\dfrac{Q_H - Q_L}{Q_H + Q_L}$

Resistive silicon strip detectors

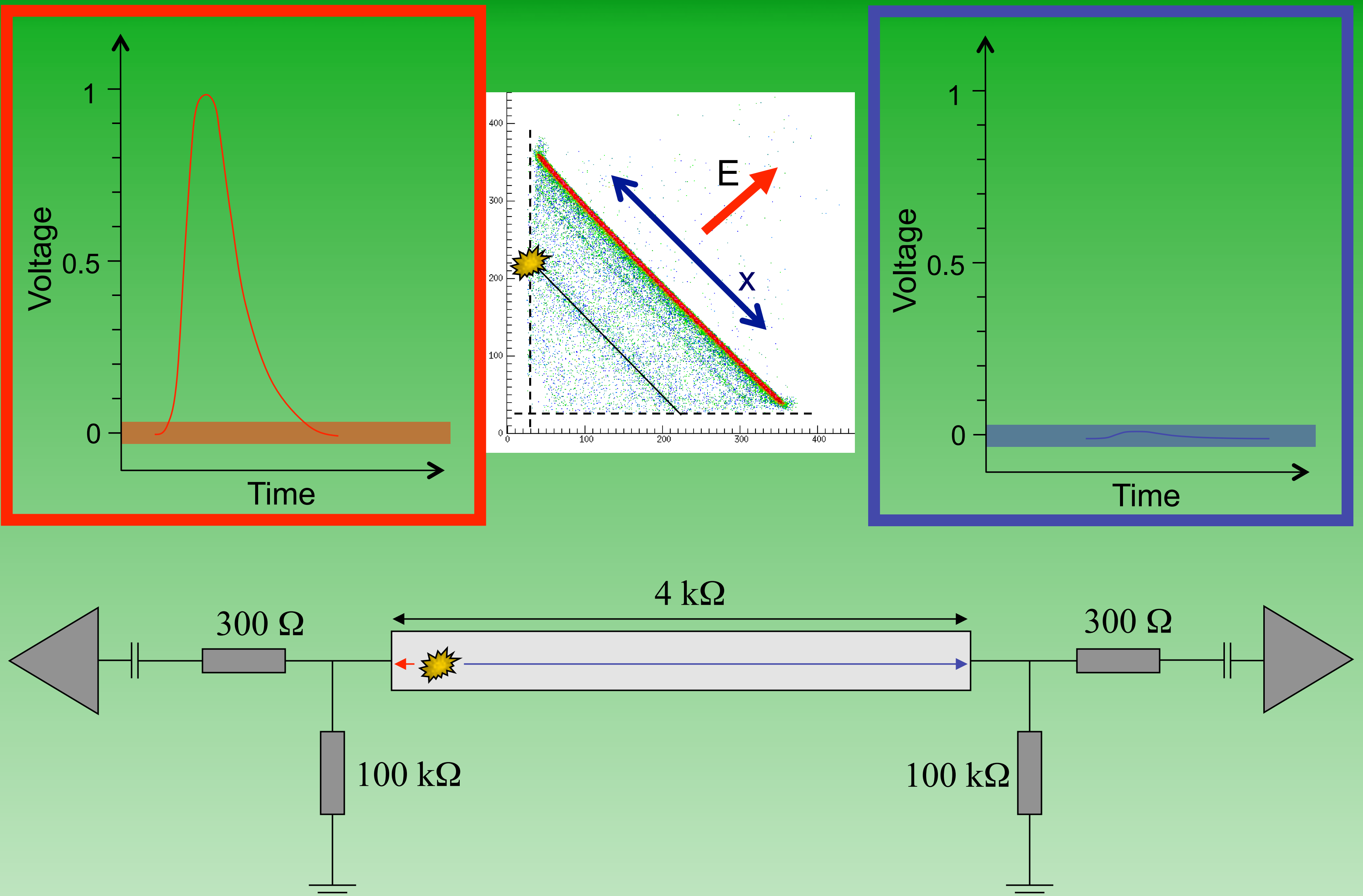




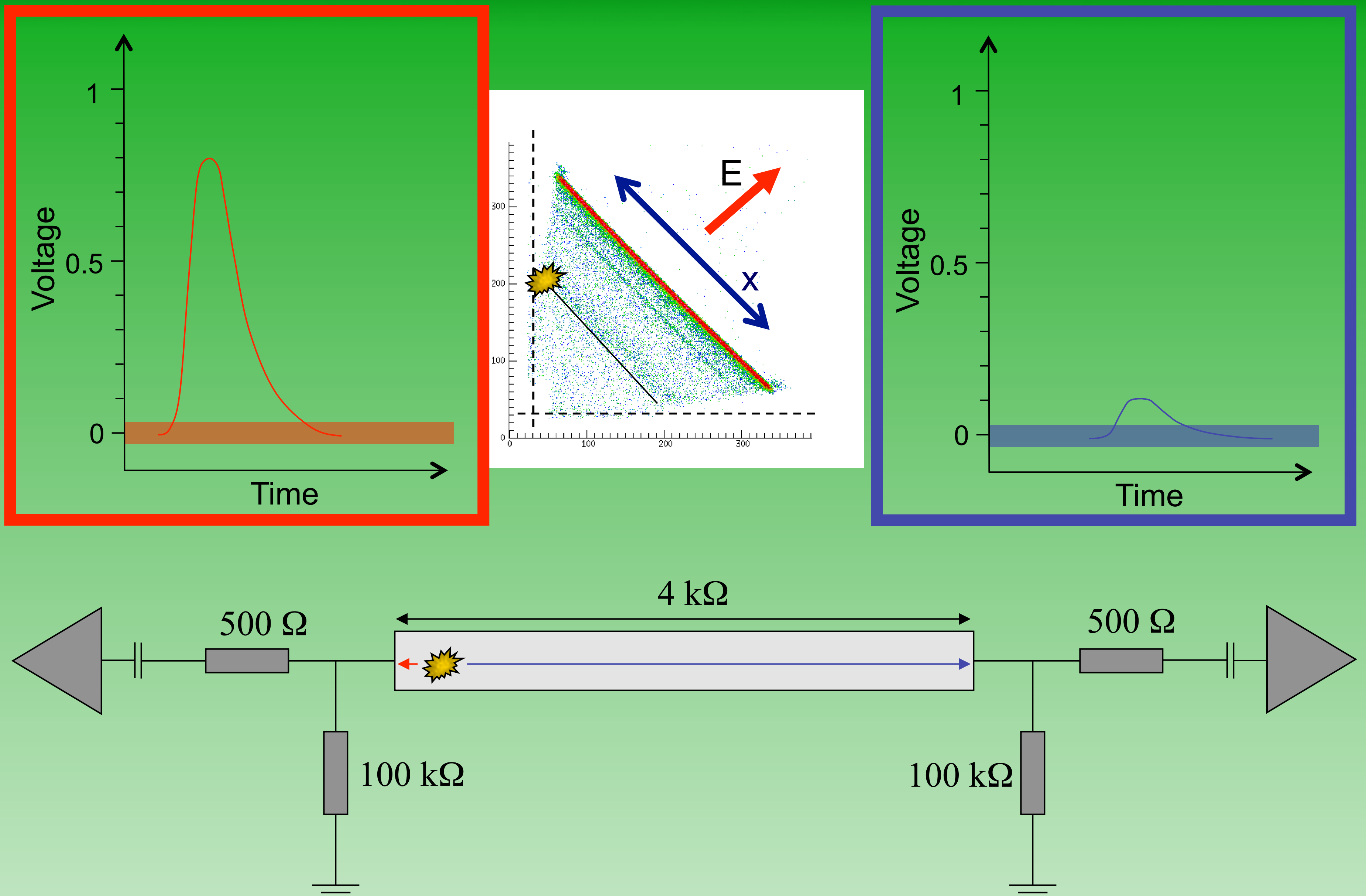




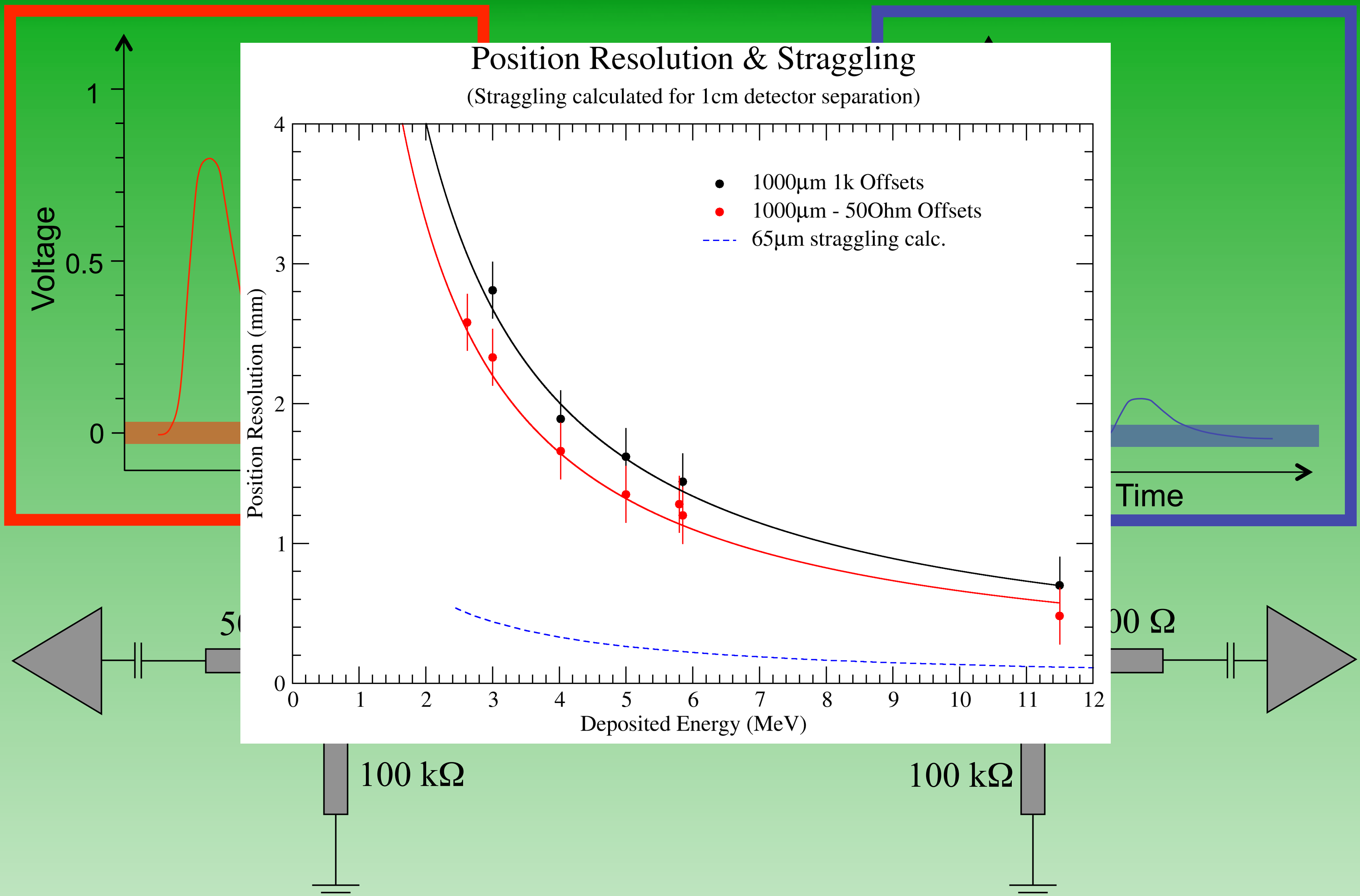
Resistive silicon strip detectors



Resistive silicon strip detectors



Resistive silicon strip detectors

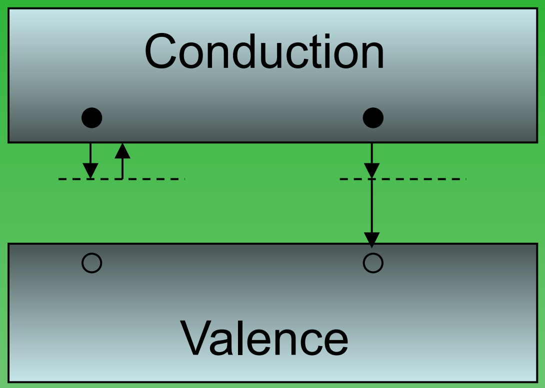


Charge collection in silicon detectors

Trapping and Recombination

Impurities in the crystal, and defects in the lattice structure, can cause energy levels within the energy gap (at certain spatial points)

This leads to worse charge collection



Trapping

At such sites, electrons can be trapped from the conduction band for a time. If their release time is significant compared to the charge collection time, can cause signal degradation

Recombination

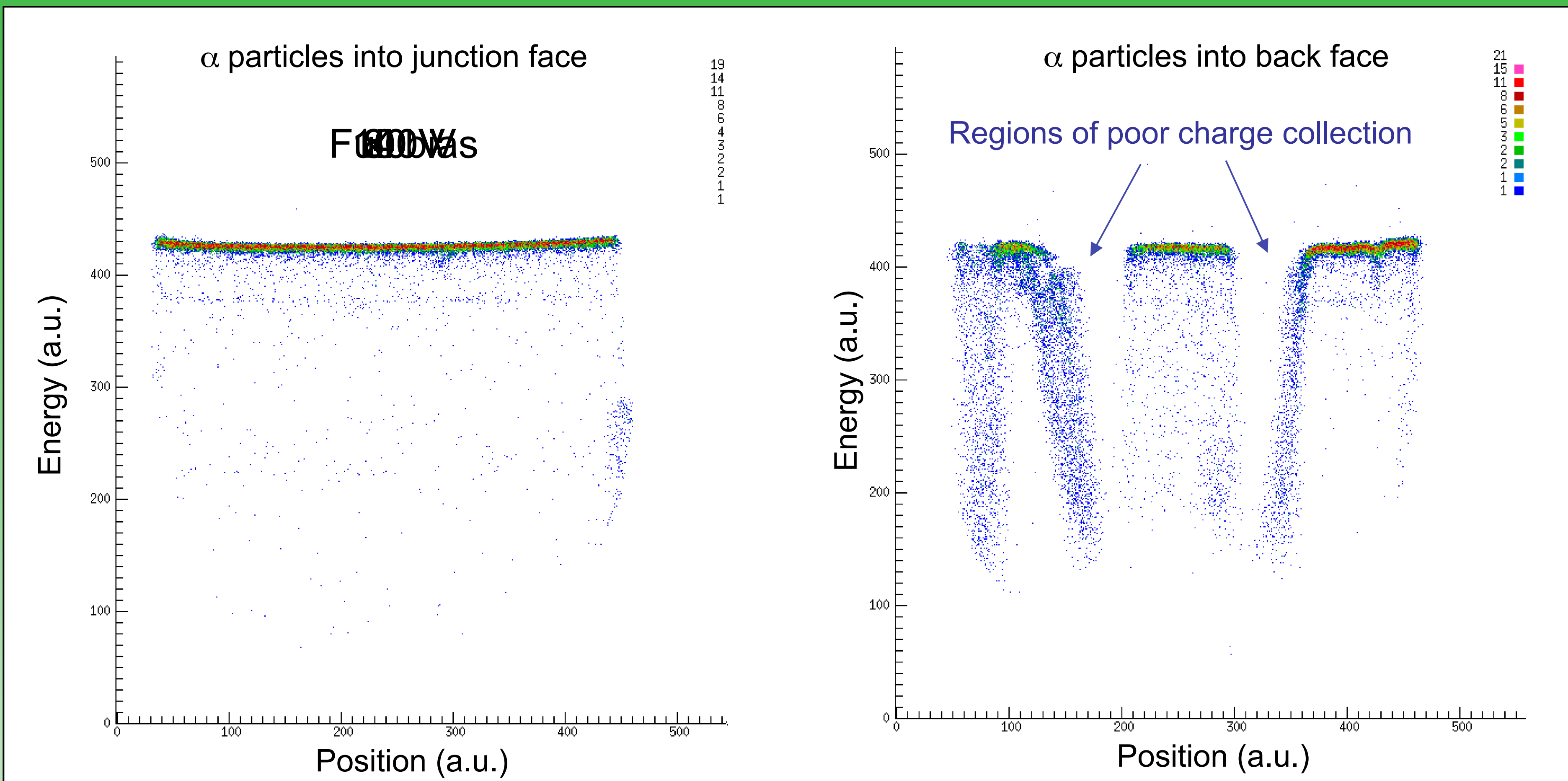
At recombination sites, electrons trapped from the conduction band for a time. A hole may be captured within this time, leading to recombination (loss of charge carriers)

Charge collection in silicon detectors

5.8 MeV α-particles only penetrate 30μm into detector

Non-uniformities in Si (eg leading to trapping)

Ballistic deficit (see later)



Charge collection in silicon detectors

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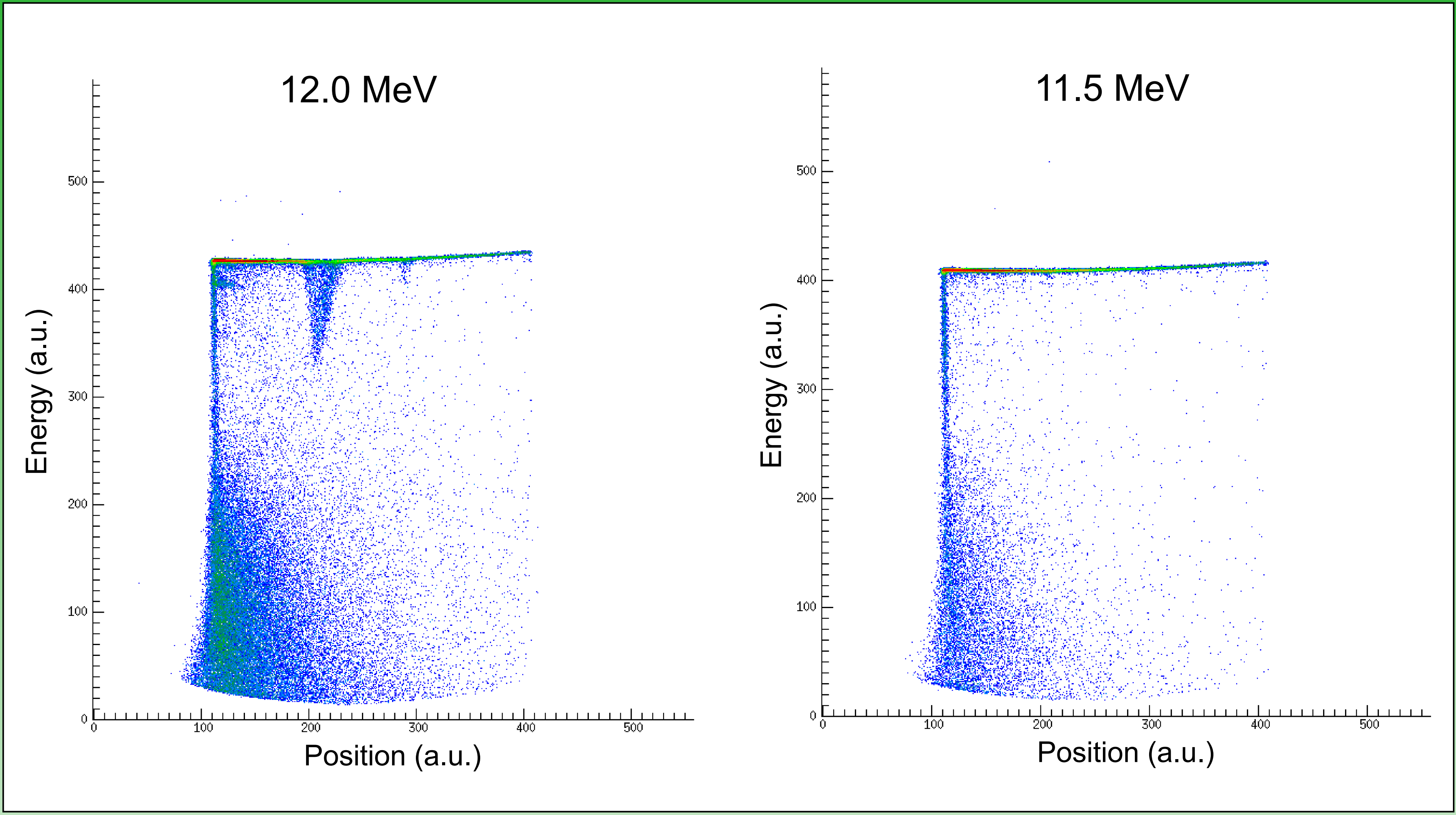

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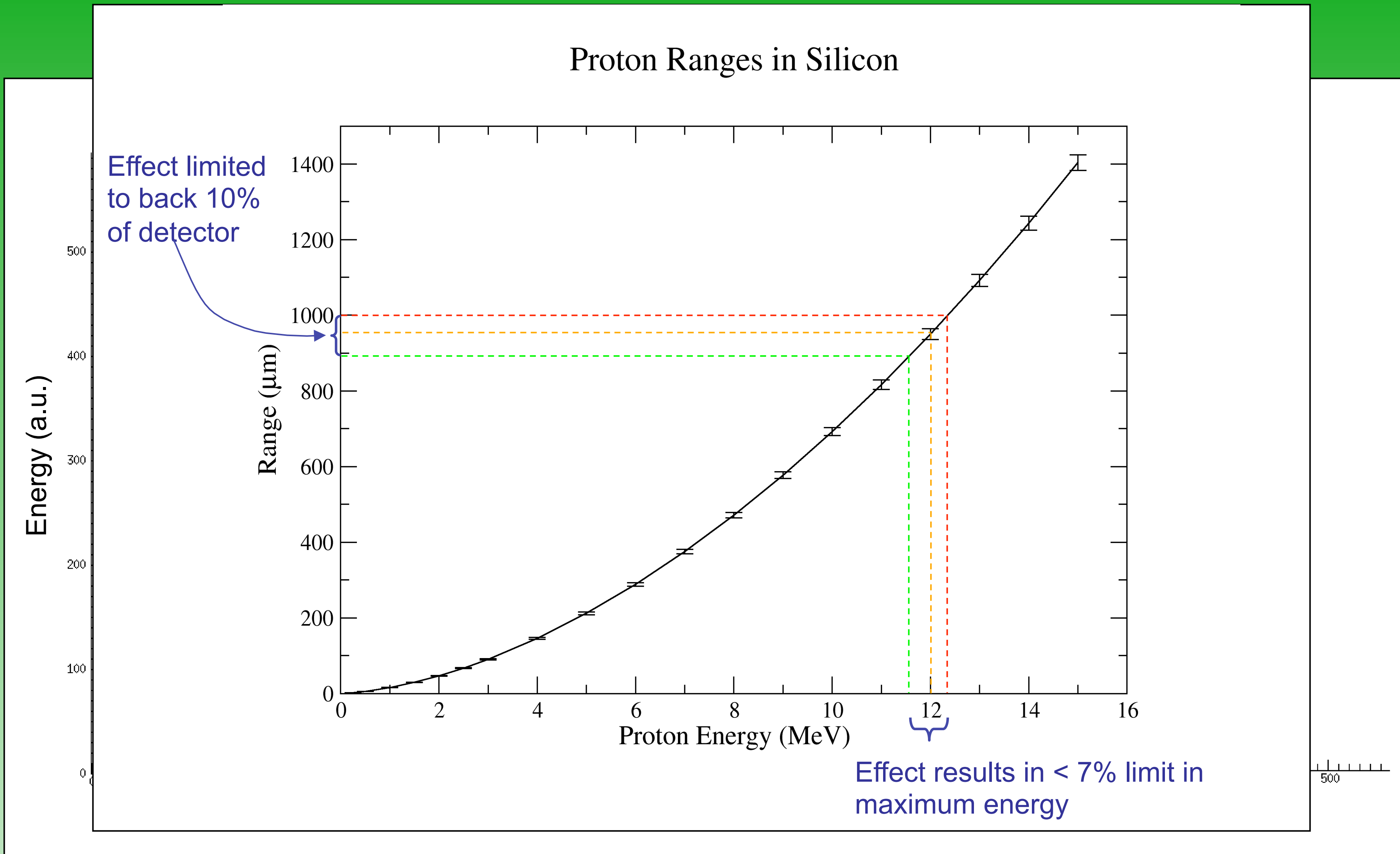
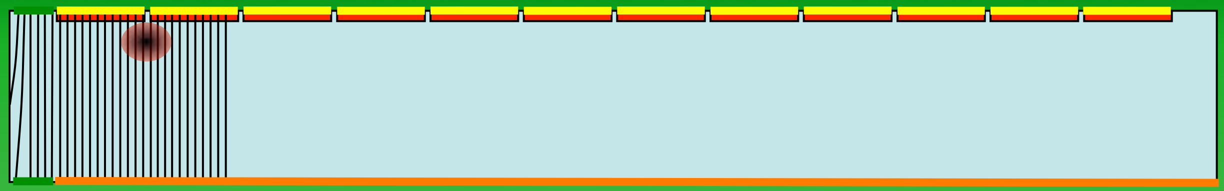
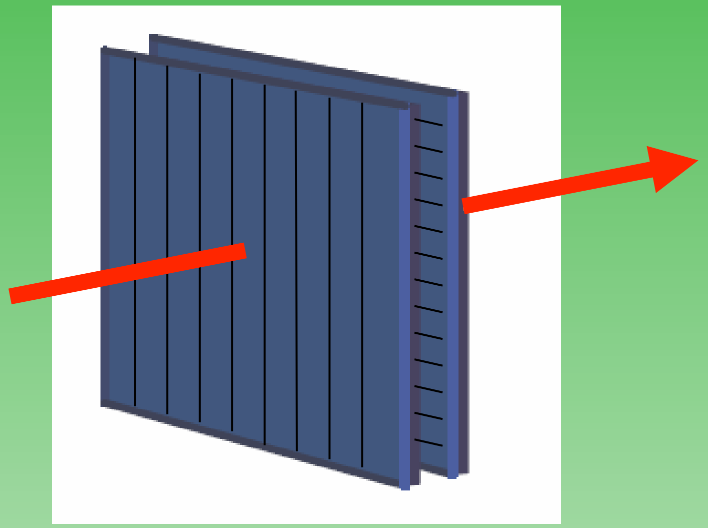


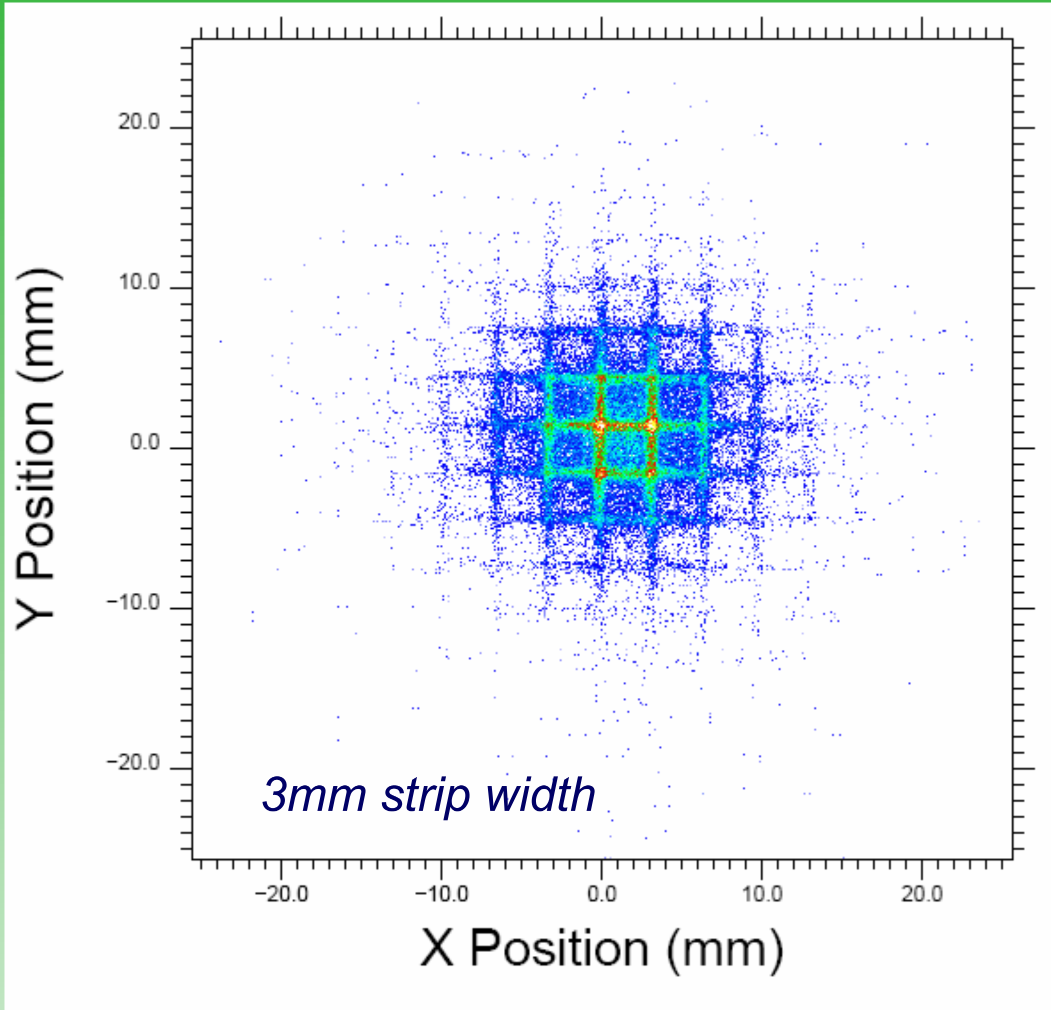
Charge collection in silicon detectors

Charge sharing



Two crossed resistive strip silicon detectors

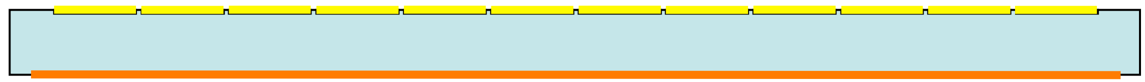




Requiring two hits on one detector, and plotting the position on the other, charge sharing events (along the strip edges) can be highlighted

Germanium detectors

Planar Ge detectors



Thin entrance window

Measuring low energy γ rays and x rays

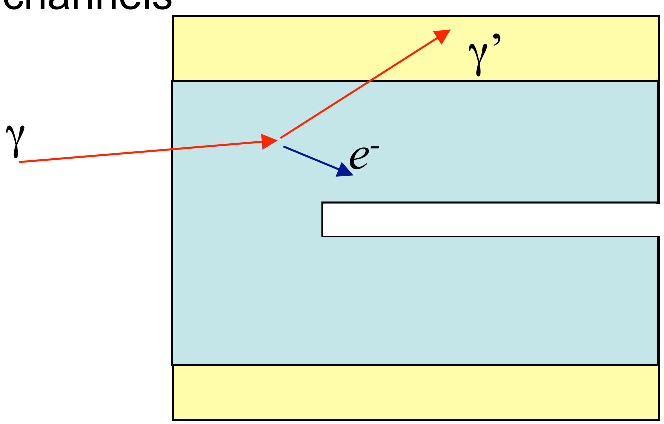
Coaxial Ge detectors

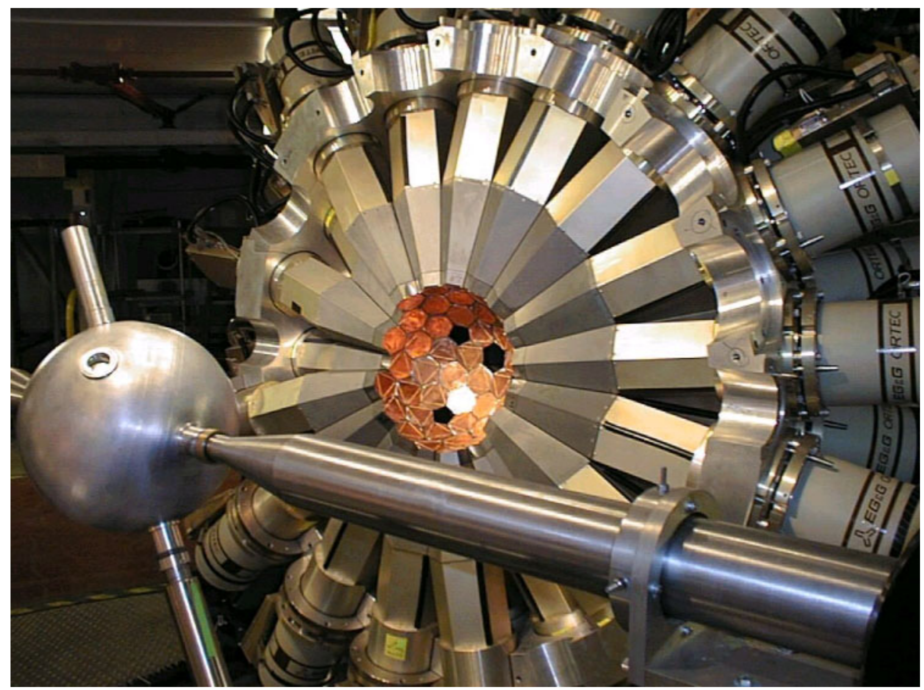
Large volume for measuring higher energy γ rays

Large arrays (eg Gammasphere)

Often Compton suppressed

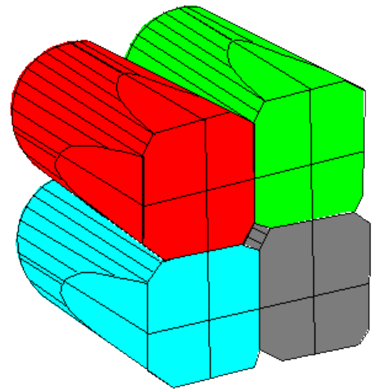
Some have coarse position from side-channels

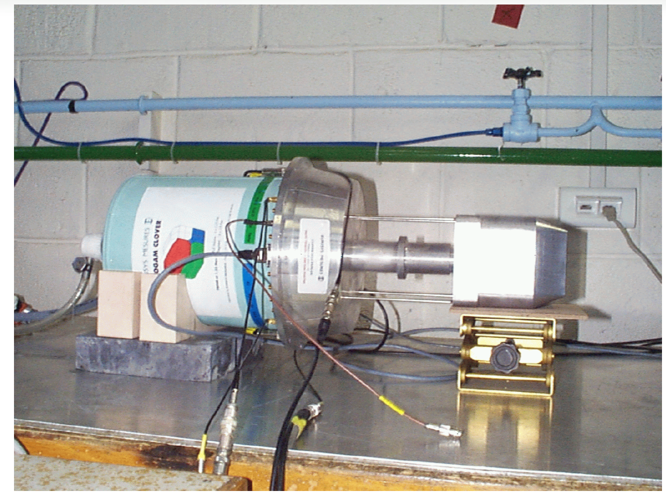




Charge collection in silicon detectors

Clover detectors

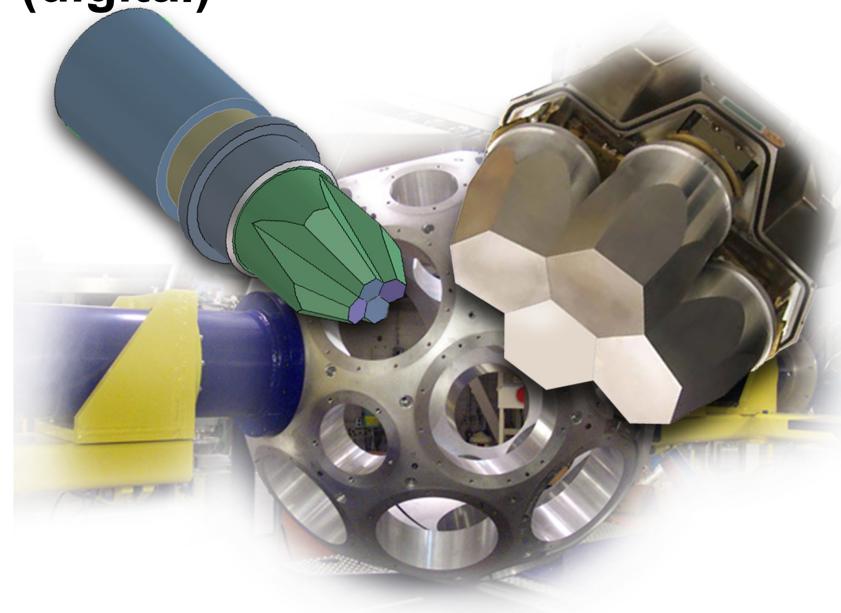




Four close-packed crystals in one cryostat

Segmented readout for better position (Doppler) correction

Highly segmented tracking detectors (digital)



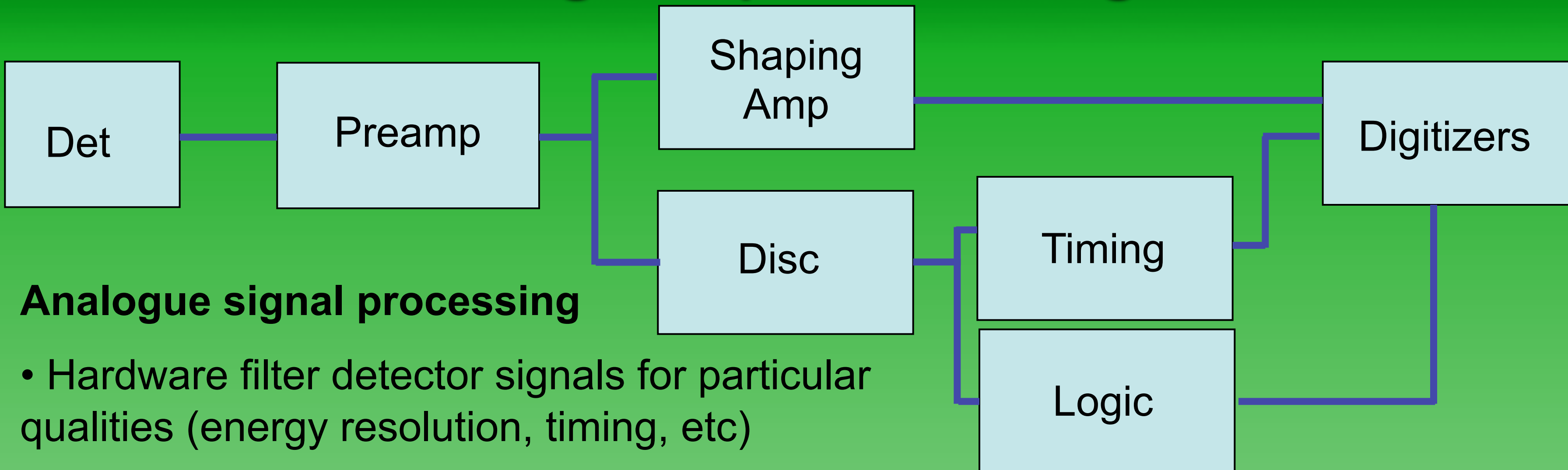
High segmentation

Digital readout allows event reconstruction (tracking) using pulse shapes

First point of interaction (Compton reconstruction) for Doppler correction

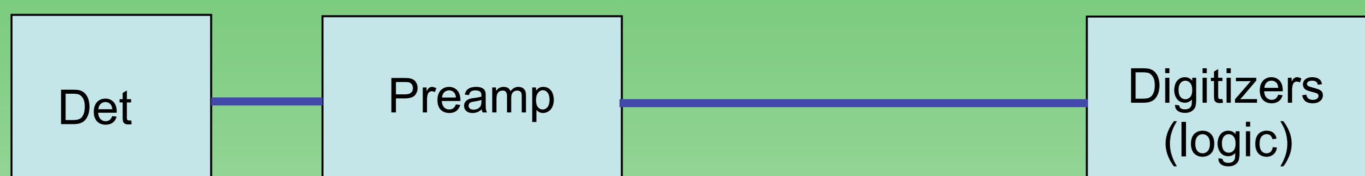
Can dispense with Compton suppression – higher efficiency possible

Signal processing



Analogue signal processing

- Hardware filter detector signals for particular qualities (energy resolution, timing, etc)
- Excellent resolution, but some information is discarded

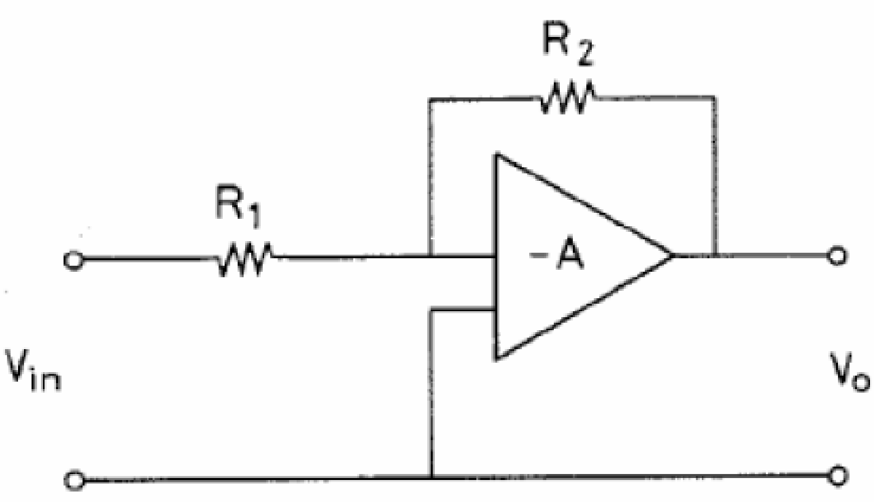


Digital signal processing

- Process (and sometimes store) a digital approximation of the trace from a detector/preamp
- All information encoded in the preamp trace can be processed (software)
- Single data stream can be multiplied and each stream processed independently

Analogue signal processing

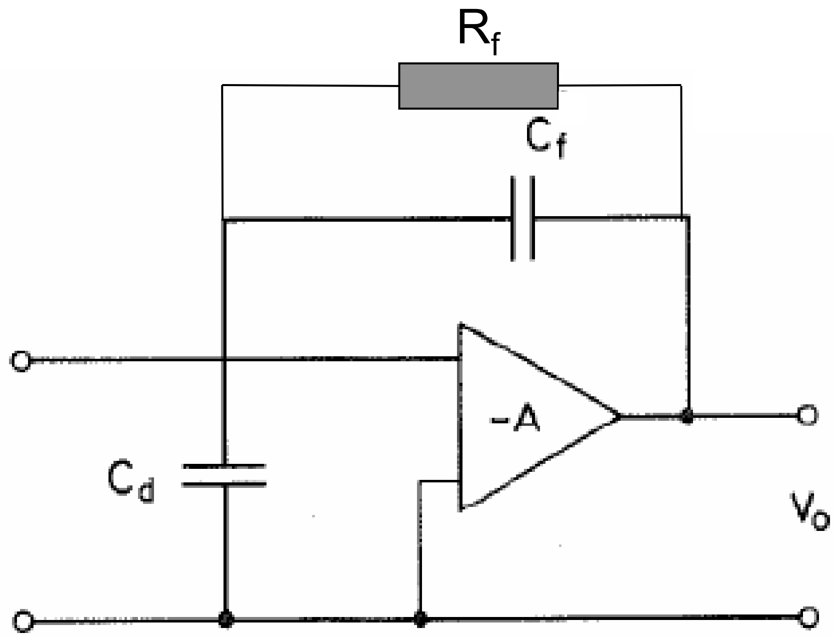
Voltage sensitive preamplifier



$$V_0 = \frac{Q}{C_{tot}}$$

Gain dependent on the detector capacitance (can vary)

Charge sensitive preamplifier

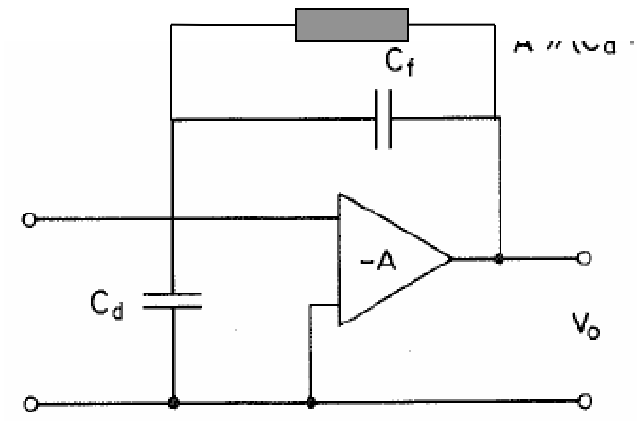


$$V_0 = -\frac{Q}{C_f}$$

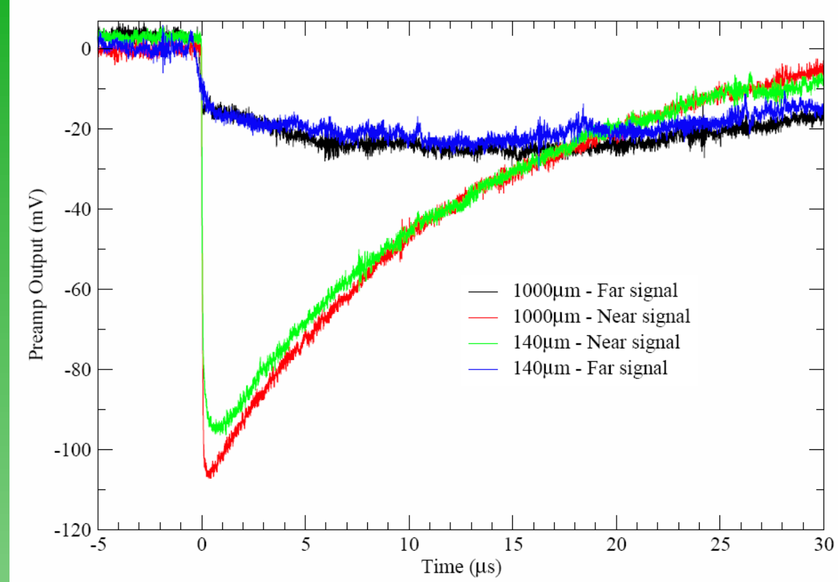
Output is proportional to charge integrated on C_f, if signal is fast compared to $R_f C_f$

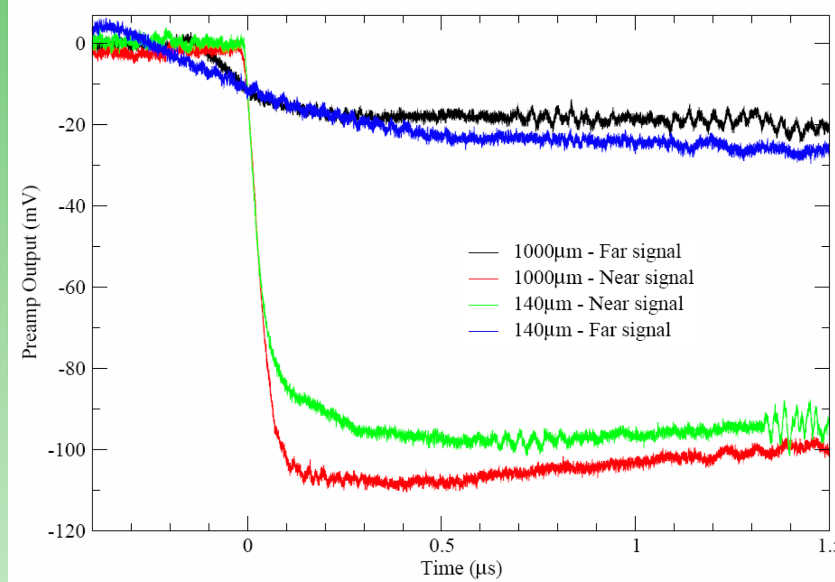
Noise is proportional to C_d

Analogue signal processing



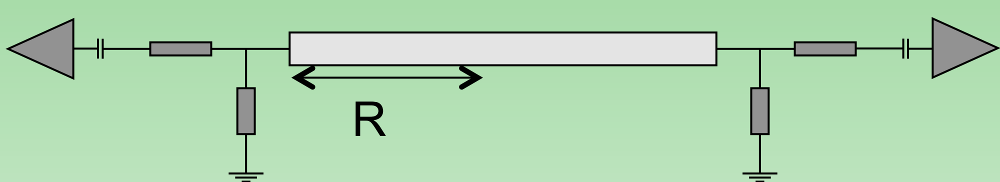
Charge sensitive preamplifier



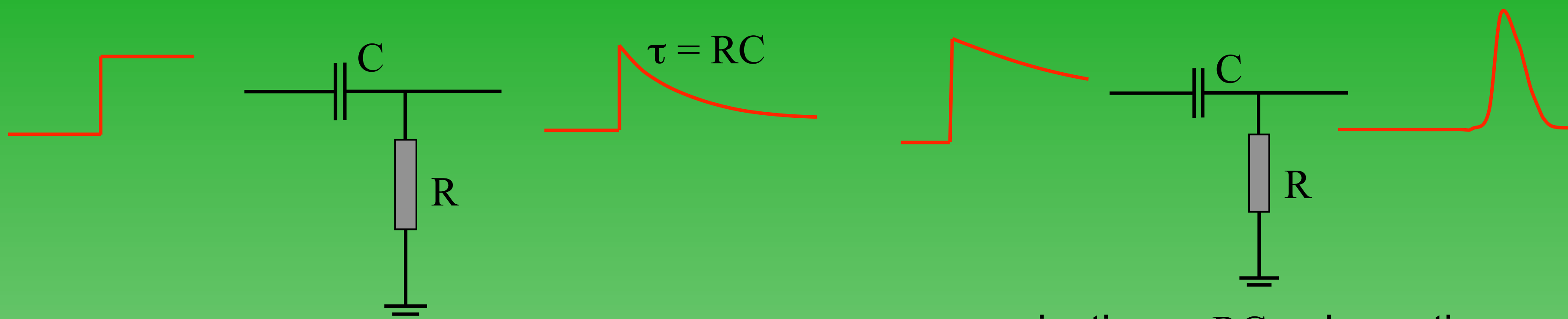


Fast rise-time – pulse height proportional to input signal

Slow rise-time – rise and decay convolved (non-linear signals, worse resolution) – *ballistic deficit*

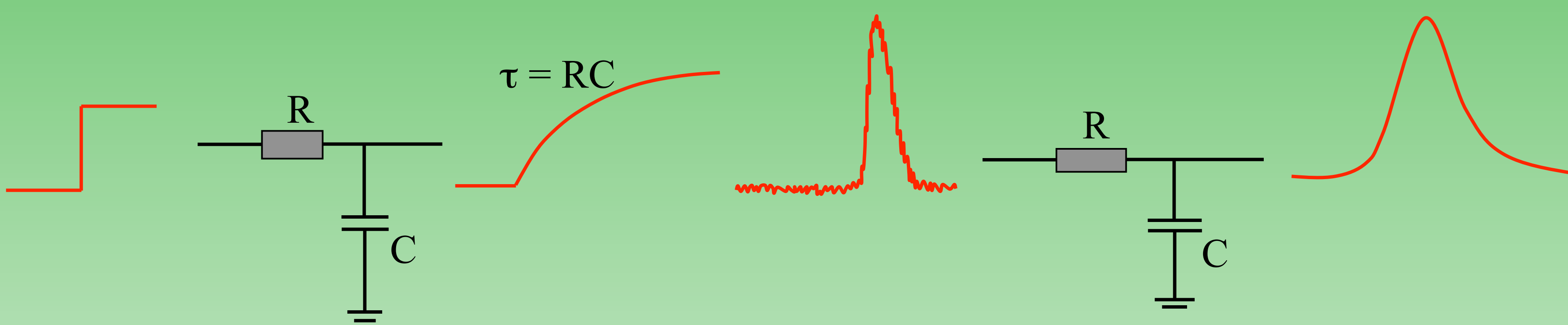


Analogue signal processing



risetime < RC < decay time

High pass filter



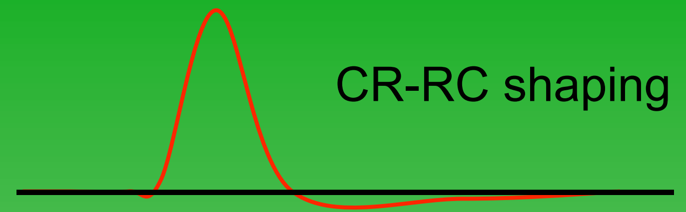
signal length < RC

Low pass filter

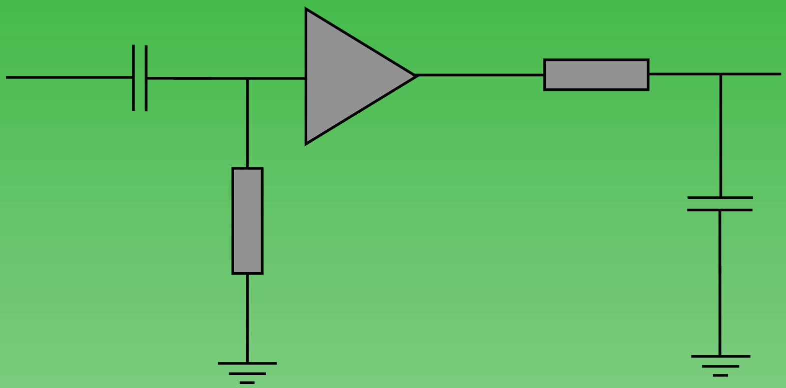
Shaping amplifiers

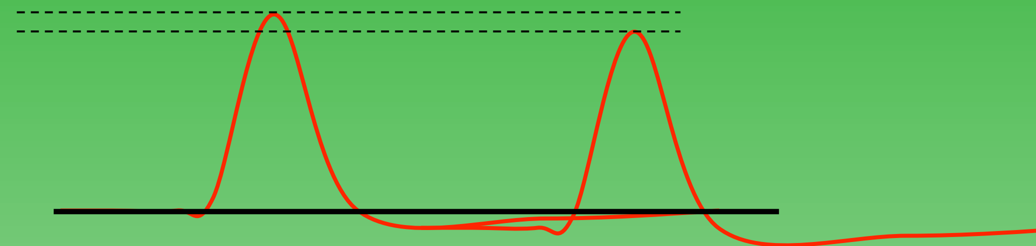
Shape pulses to:

- *Improve signal to noise*
- *Reduce pileup effects*

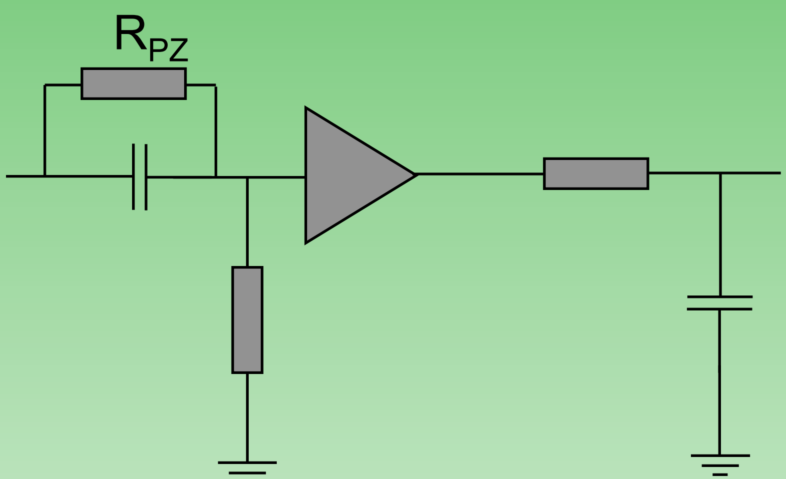


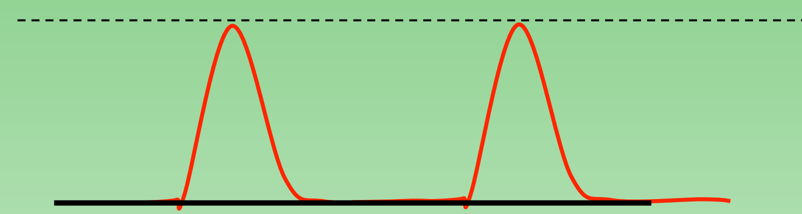
CR-RC shaping





Undershoot leading to degraded energy resolution



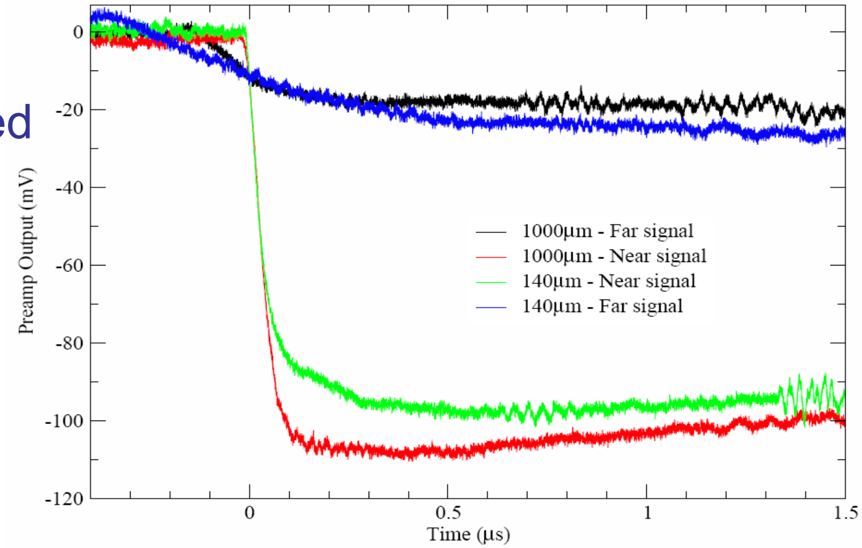


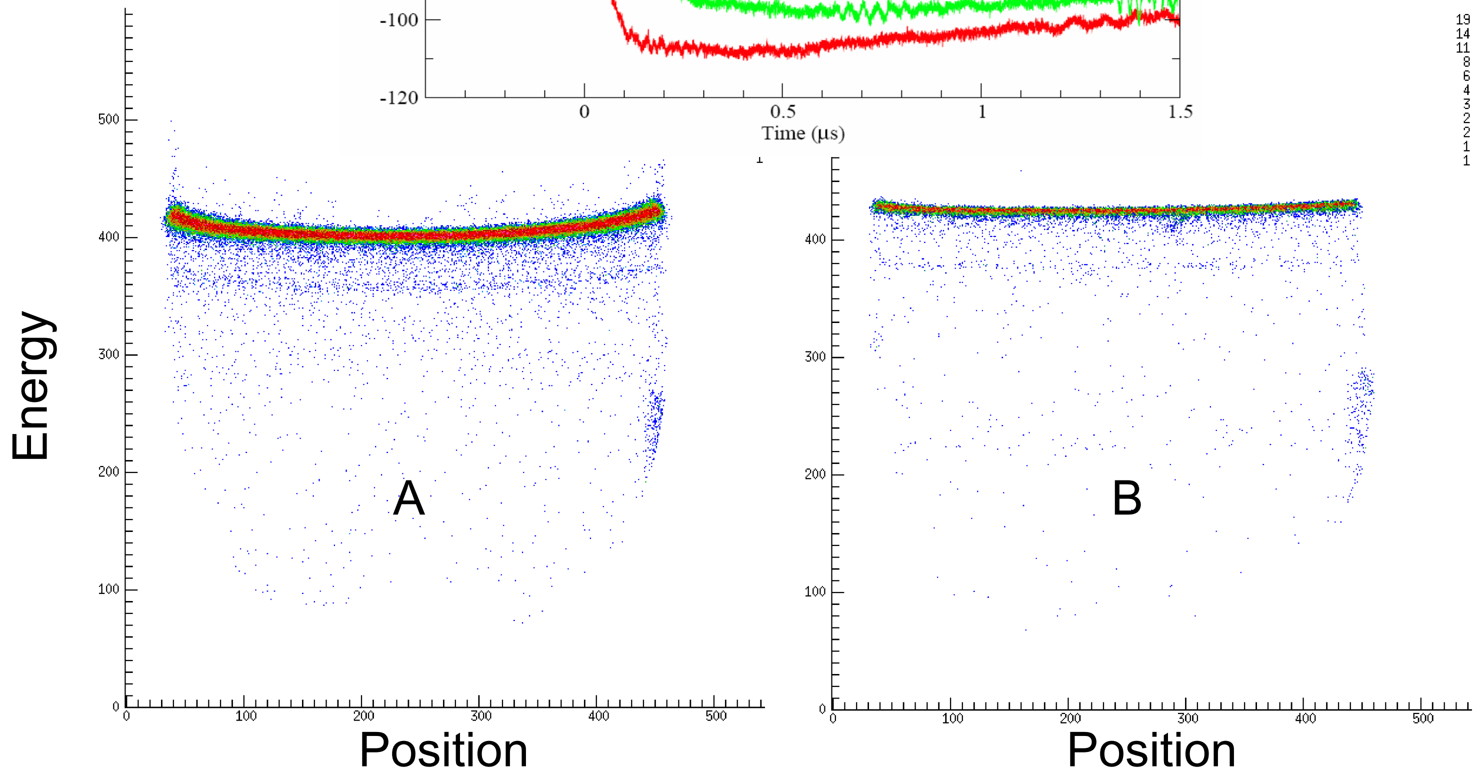
Pole zero variable resistor used to tune undershoot

Shaping amplifiers – ballistic deficit

A = Shaping time too short

B = Shaping time better matched





Shaping amplifiers

Shape pulses to:

- *Improve signal to noise*
- *Reduce pileup effects*

Keep signal height information

Lose shape information

→ *Digital!*