Detectors: specific challenges for medical application

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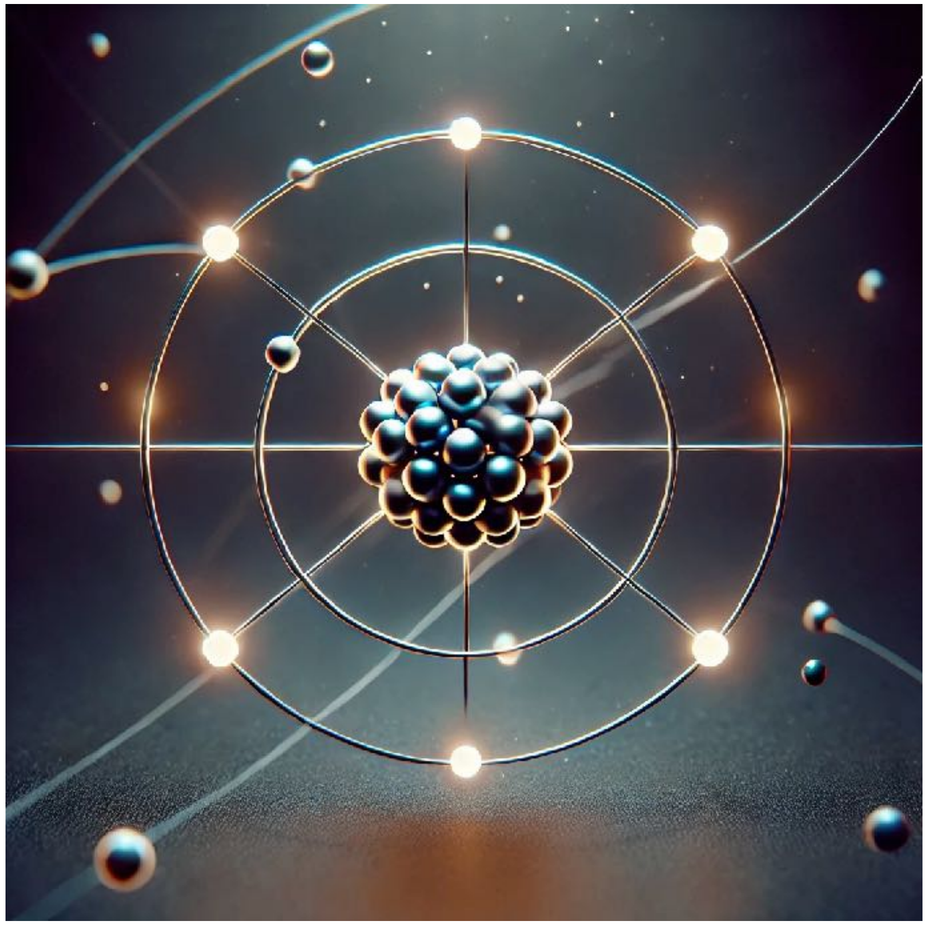
Christophe Theisen alias Tof

Dedication to Tof:

This lesson will be “tout pourri” (completely rotten)

Detectors: specific challenges for medical application



- Interaction particle-matter
- Gaseous Detectors
- Scintillators
- Semi-conductors
- Applications

➡ To detect a particle, an energy loss mut be observed in the sensor

➡ I will not present ALL kind of detectors and ALL kind of medical applications

➡ “Personal” choice

iPHC Institut Pluridisciplinaire Hubert Curien Strasbourg
cnrs Université de Strasbourg

Interaction particle - matter (i)

- Energy loss for charged particles:
  - Loss given by Bethe – Bloch formula:

$$-\frac{dE}{dx} = \frac{ZN}{4\pi\epsilon_0^2} \times \frac{z^2e^4}{\beta^2 m_e c^2}\left[ln\left(\frac{2m_ec^2\beta^2\gamma^2}{I_0}\right) - ln(1-\beta^2) - \beta^2 - \delta - \frac{C_k}{Z}\right]$$

$$\beta = v/c \qquad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

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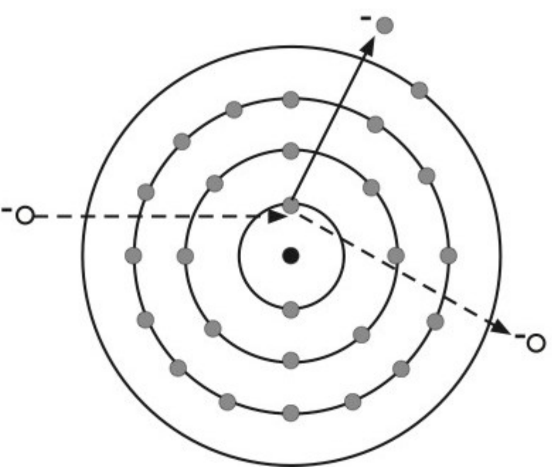
Depend on

- Velocity β and charge z^2 of the impinging particle
- Charge density of medium ZN
- Ionisation factor I_0 , shell C_k and charge δ corrections



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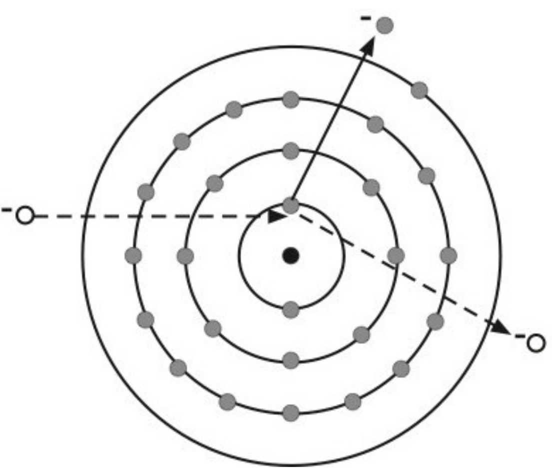

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Iso-butane	C_4H_{10}	10.6
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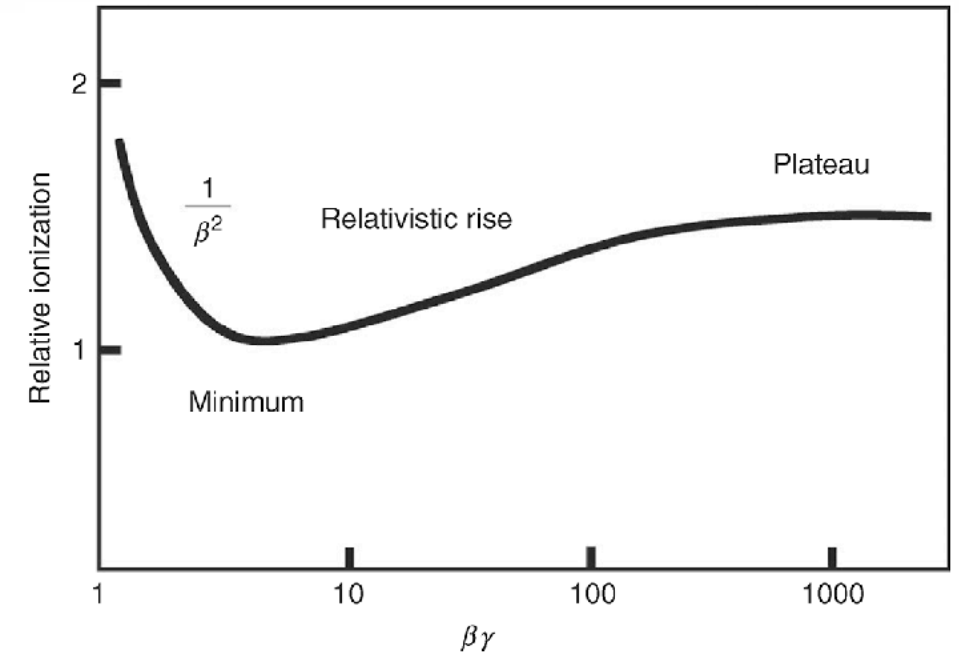

Electromagnetic interactions of charged particles with matter, F. Sauli

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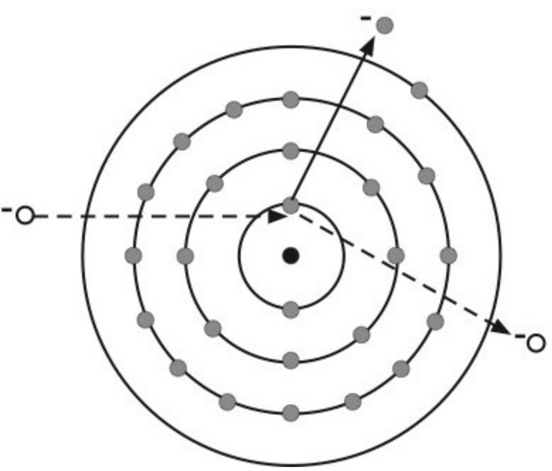

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- Minimum of ionisation: ~95% of mass
- Classical behaviour: $\beta \ll 1, \frac{dE}{dx} \propto 1/\beta^2$
- Relativistic rising: $\frac{dE}{dx} \propto \ln(\beta^2)$
- Fermi plateau: $\beta \gtrsim 0.95$

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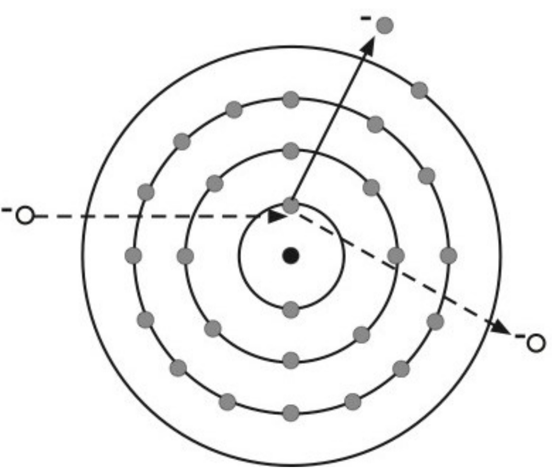

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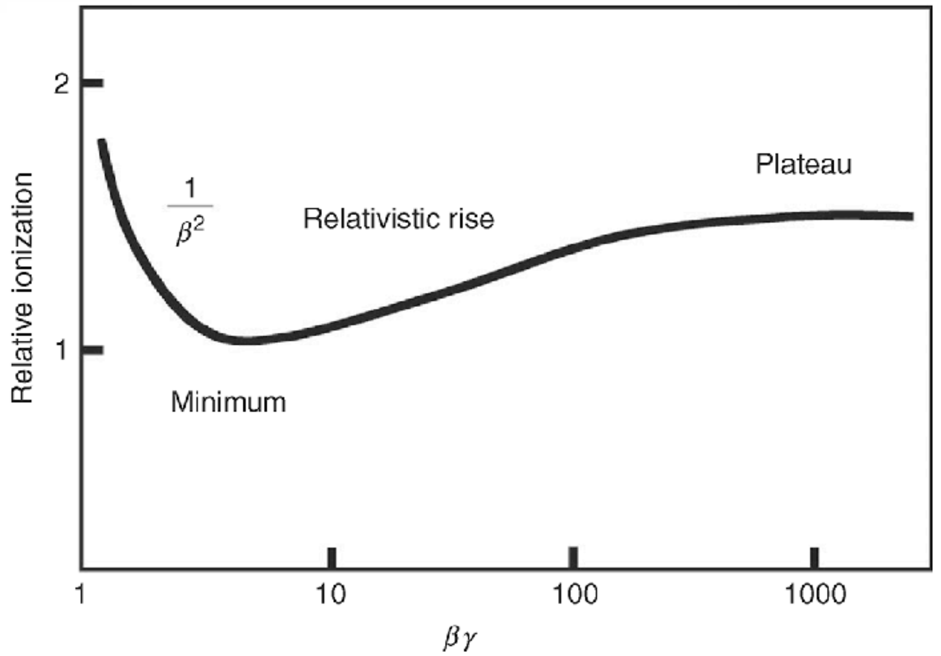

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➡ $\frac{dE}{dx} \nearrow$ when $\beta \searrow$

Interaction particle – matter (ii)

- Energy loss for neutral particles:
  - Loss by nuclear scattering:
    - Elastic scattering

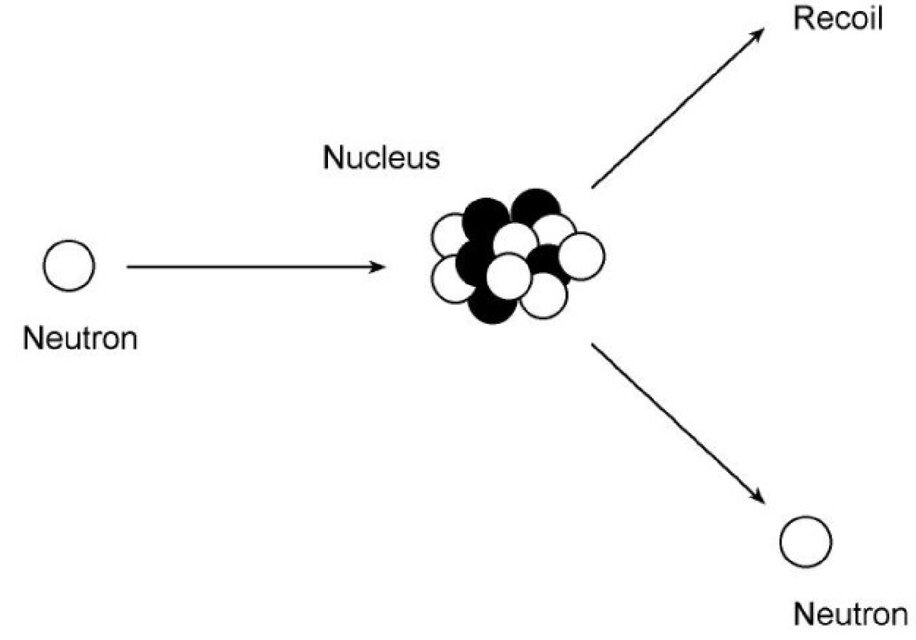
$$n +_Z^A X \rightarrow n +_Z^A X$$

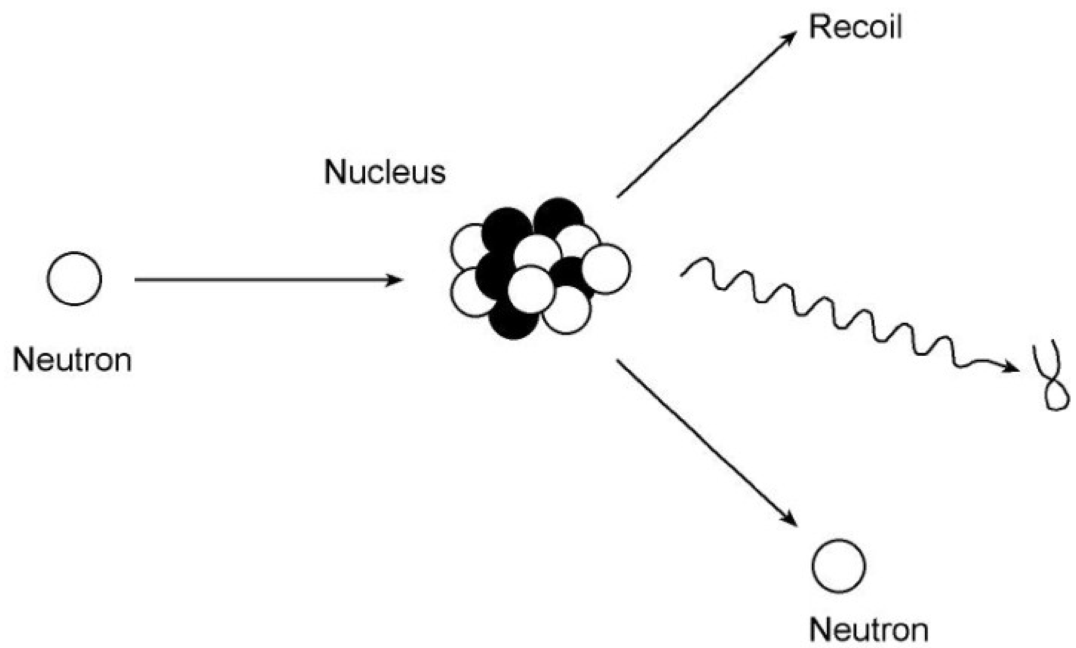
    - Inelastic scattering

$$n +_Z^A X \rightarrow n +_Z^A X^* \rightarrow n +_Z^A X + \gamma$$

➡ Losing energy by successive collisions

➡ Does not include capture or fission reaction





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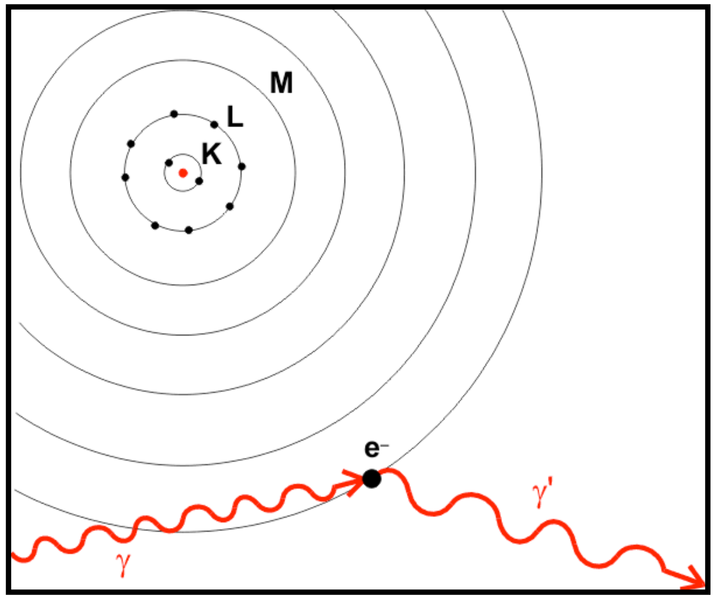

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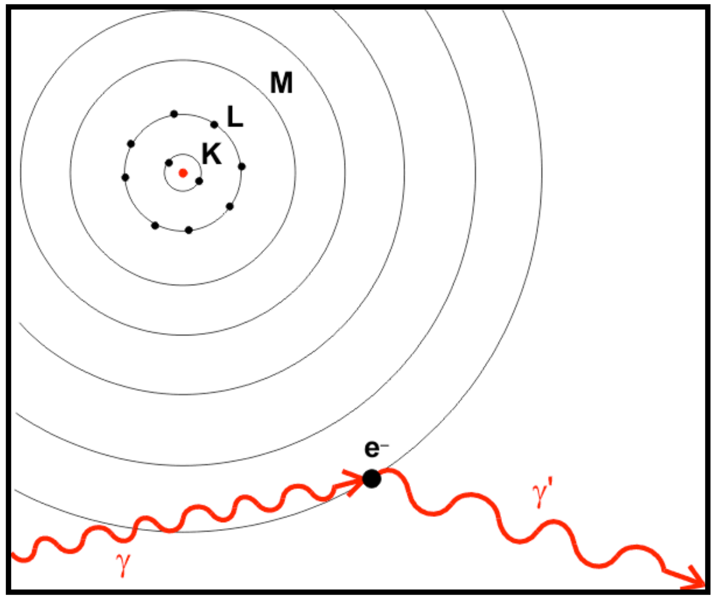

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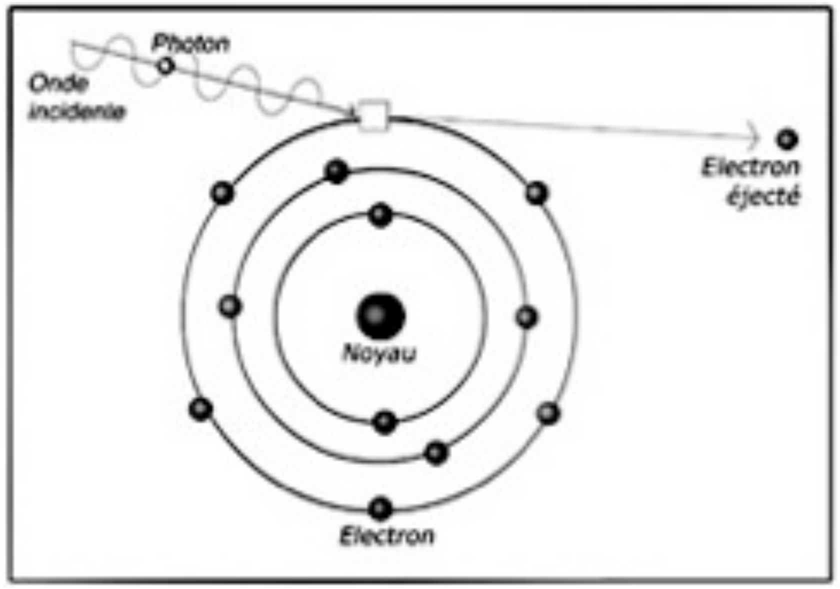

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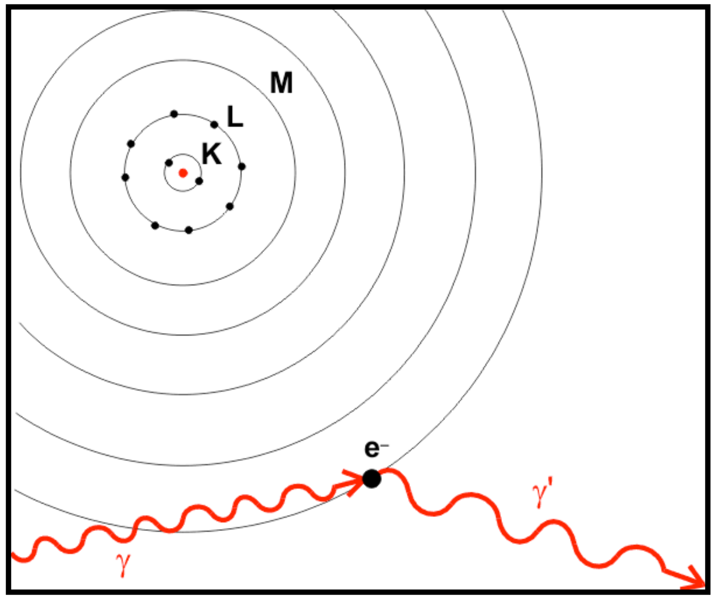
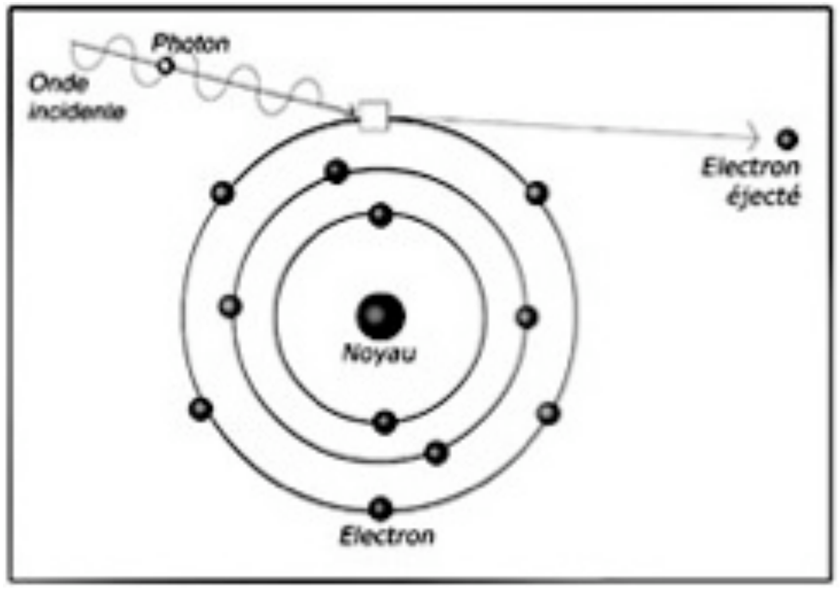
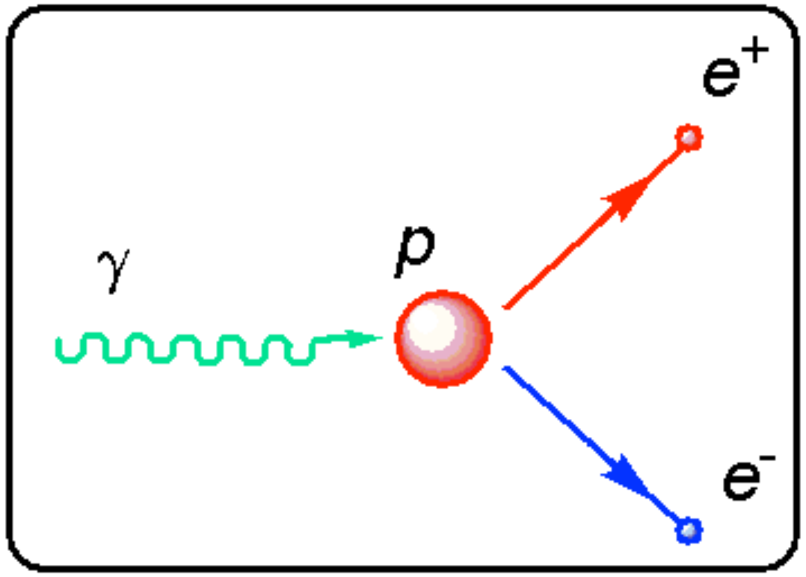
    - Photoelectric effect
    - Pair production







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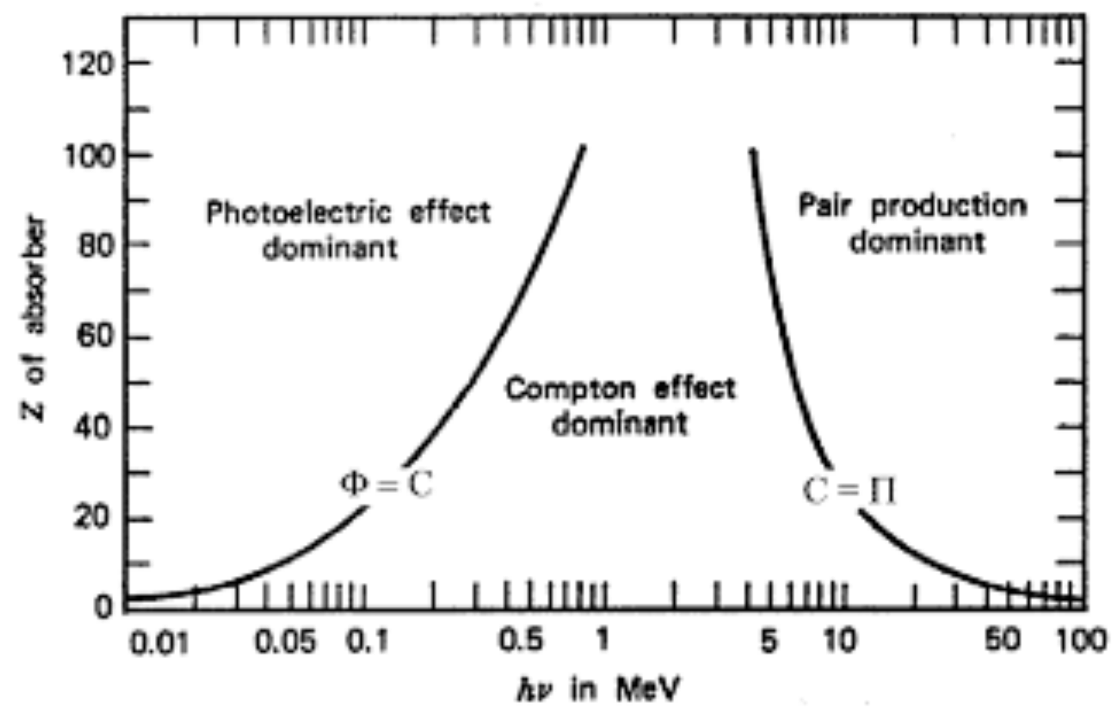

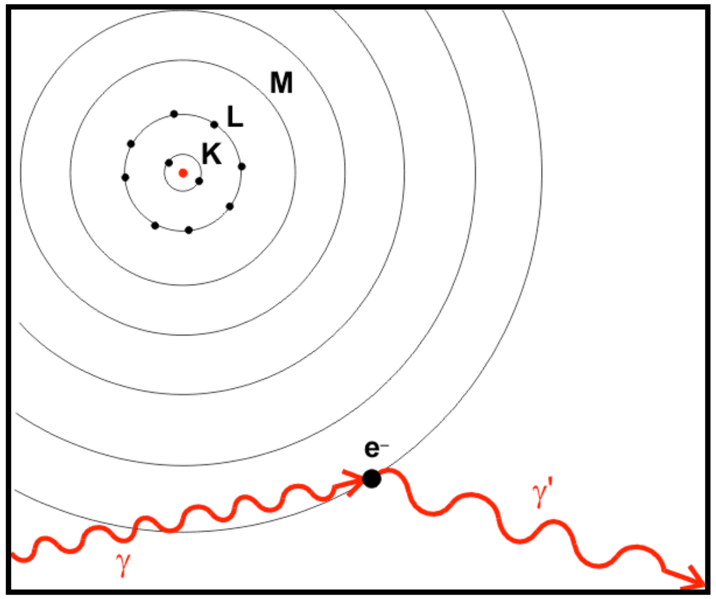

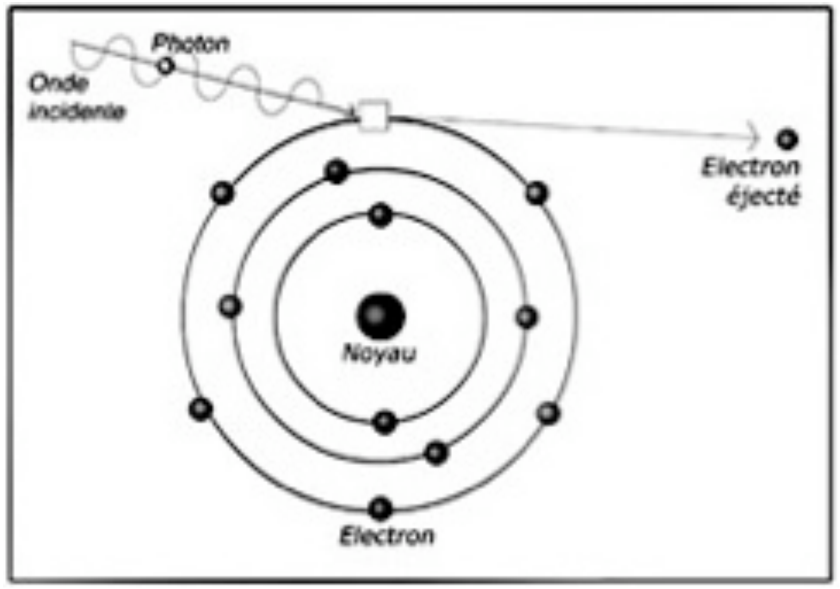

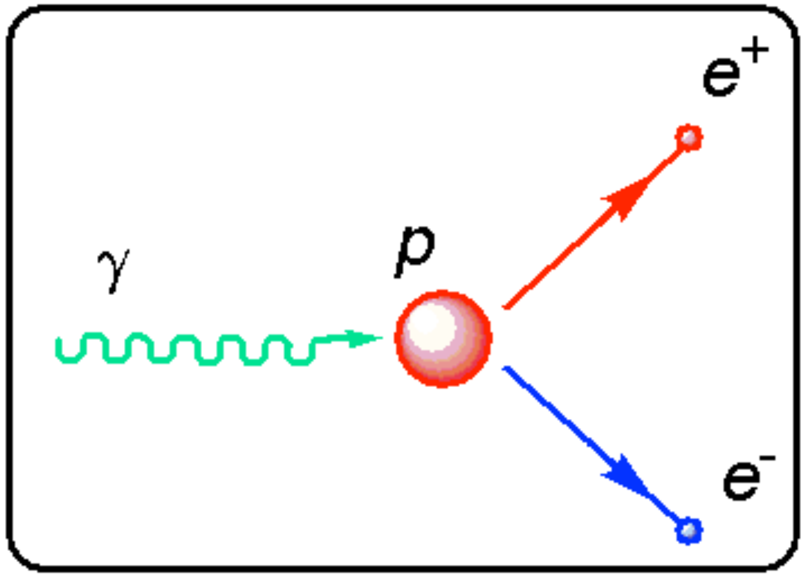

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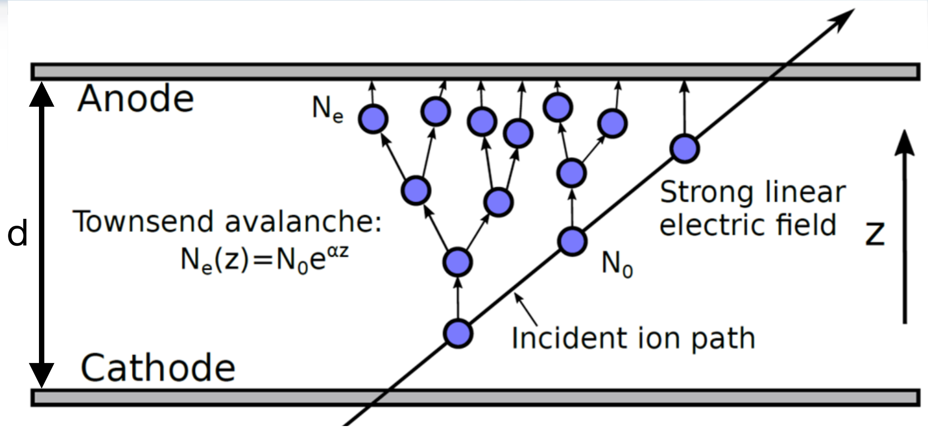
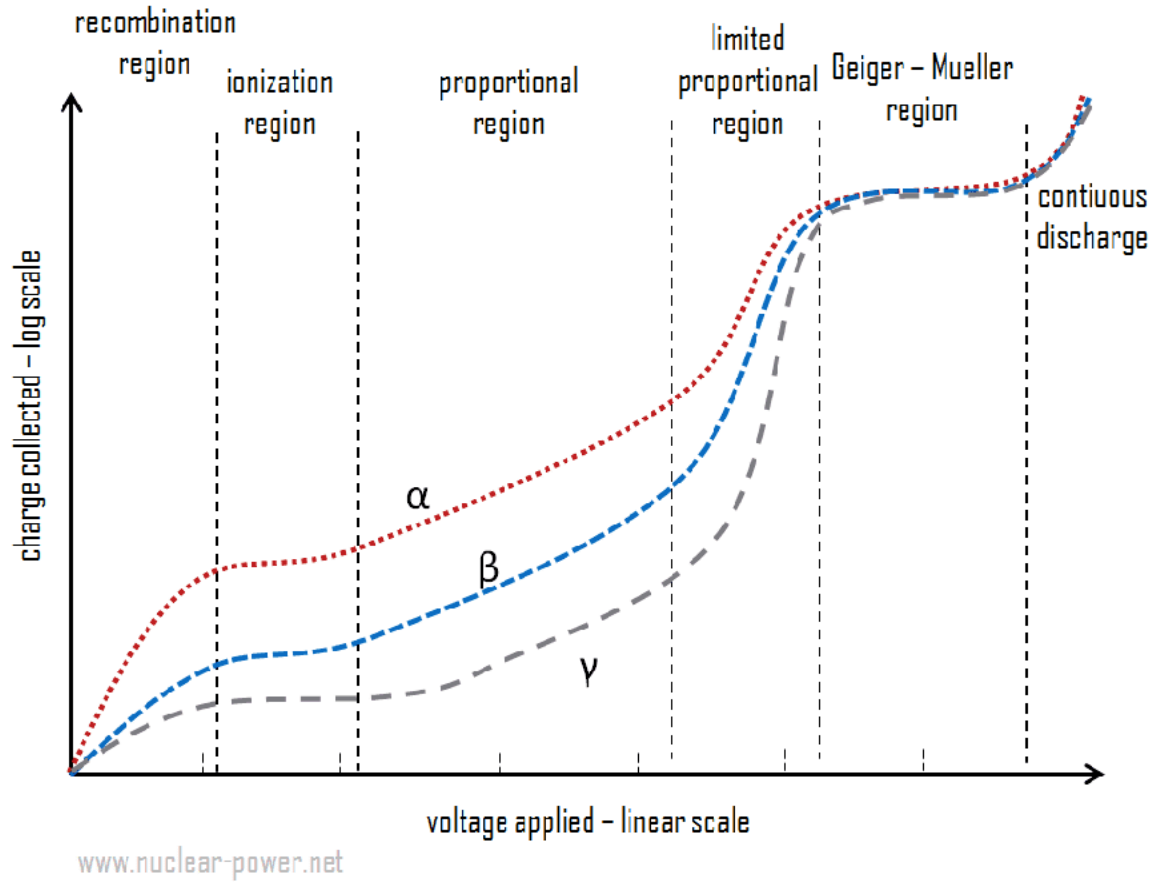
Gaseous detector (i)

- Response as function of HV:





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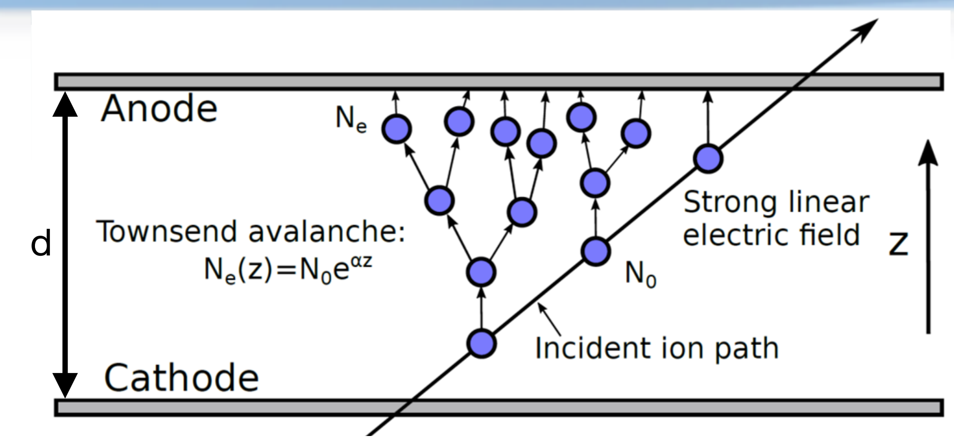

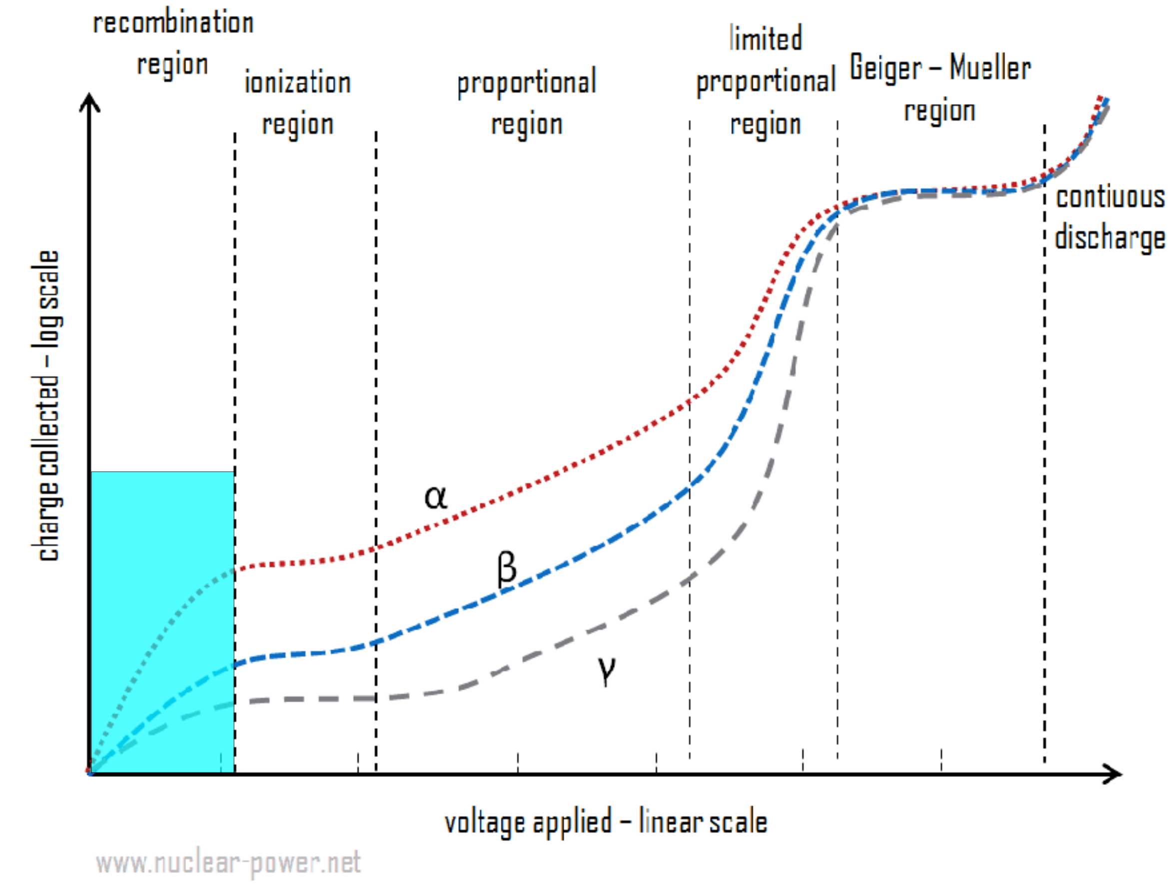

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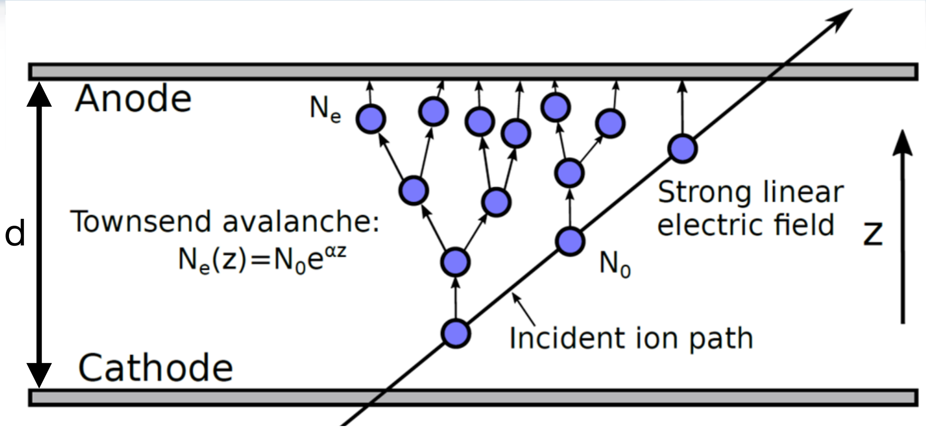

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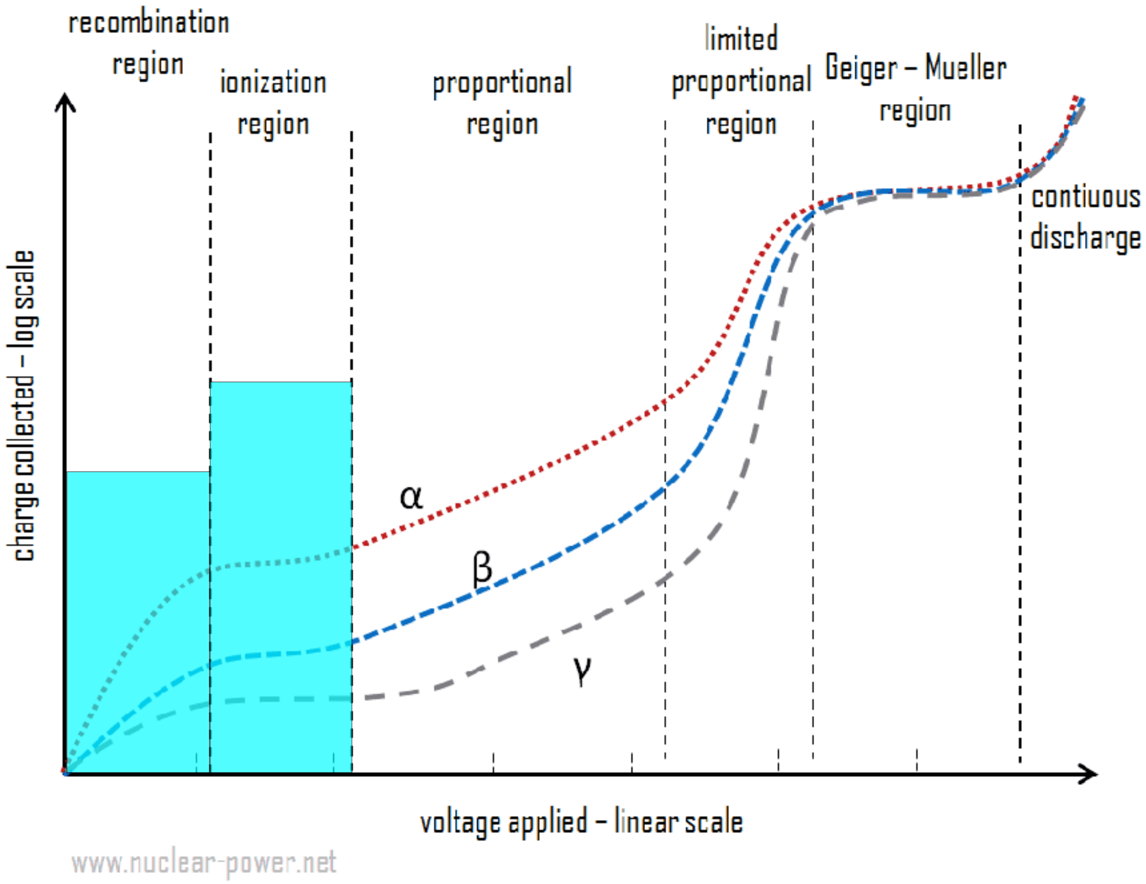

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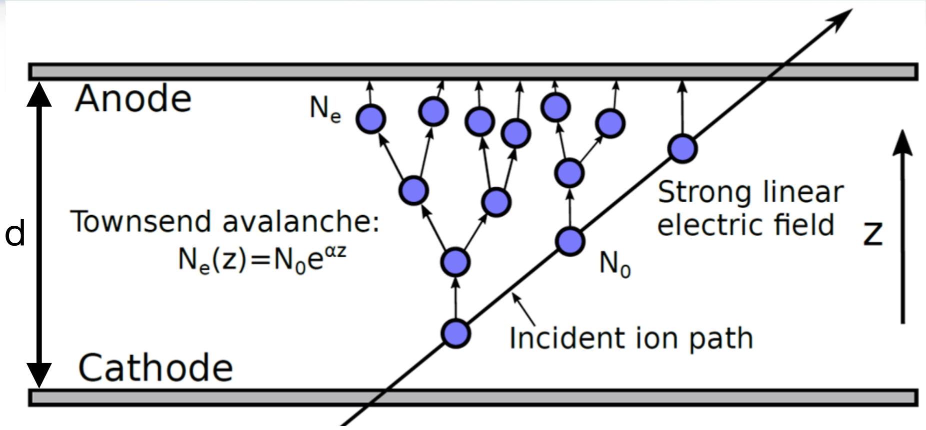

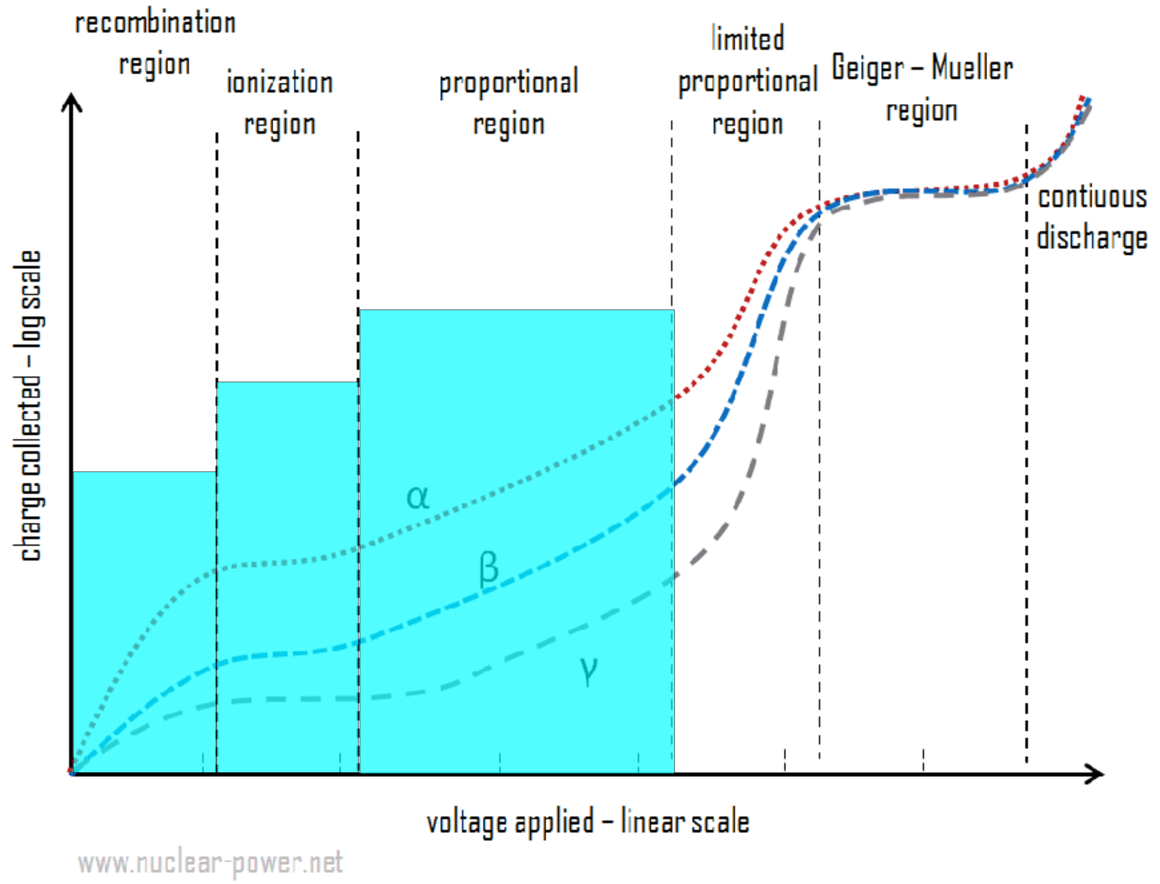

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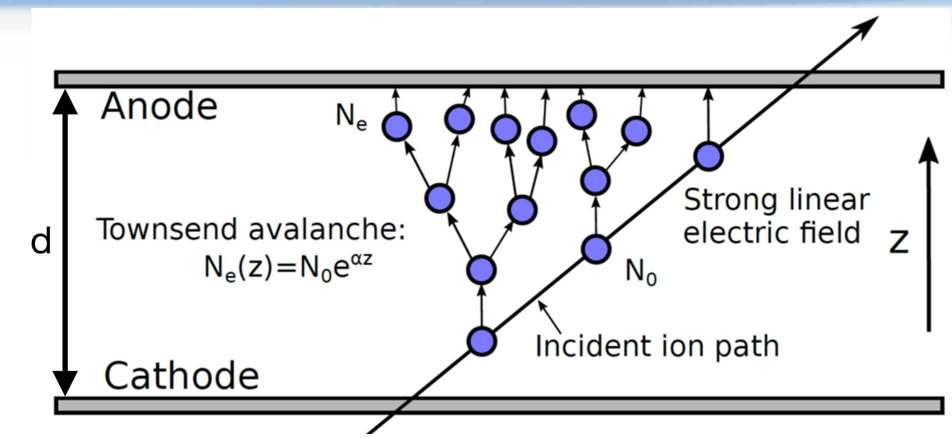

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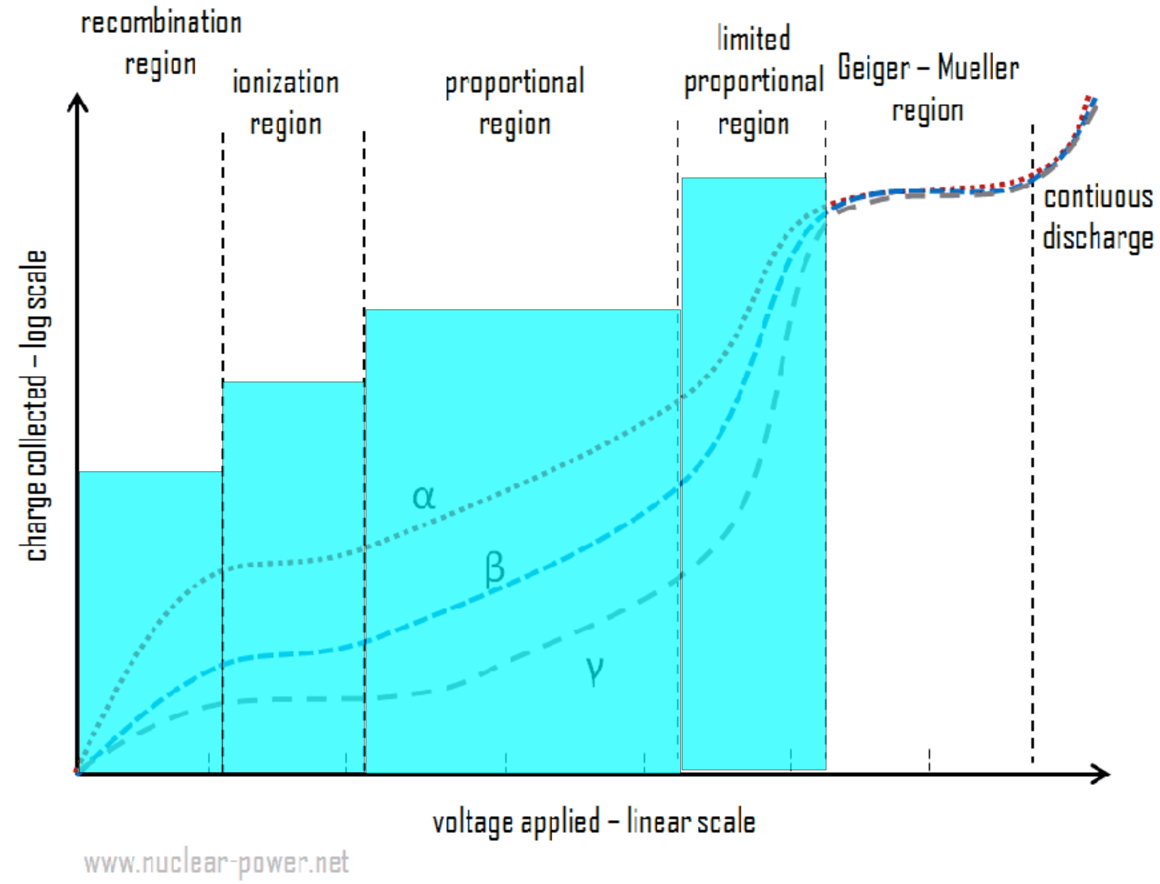

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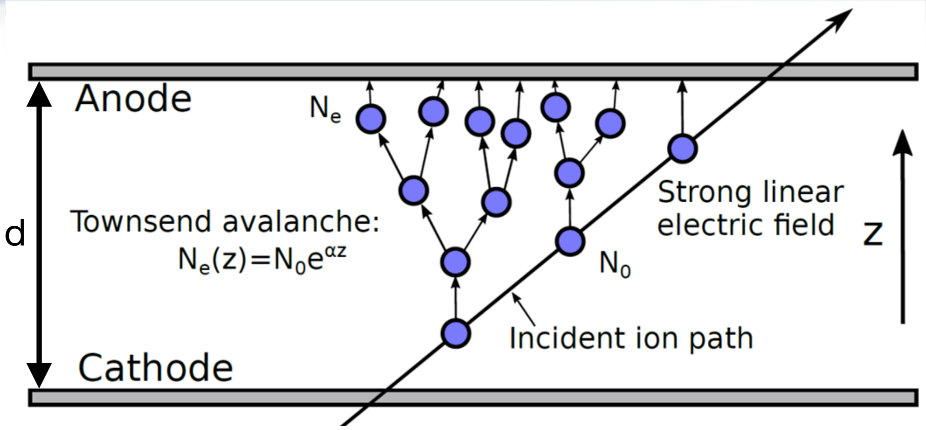

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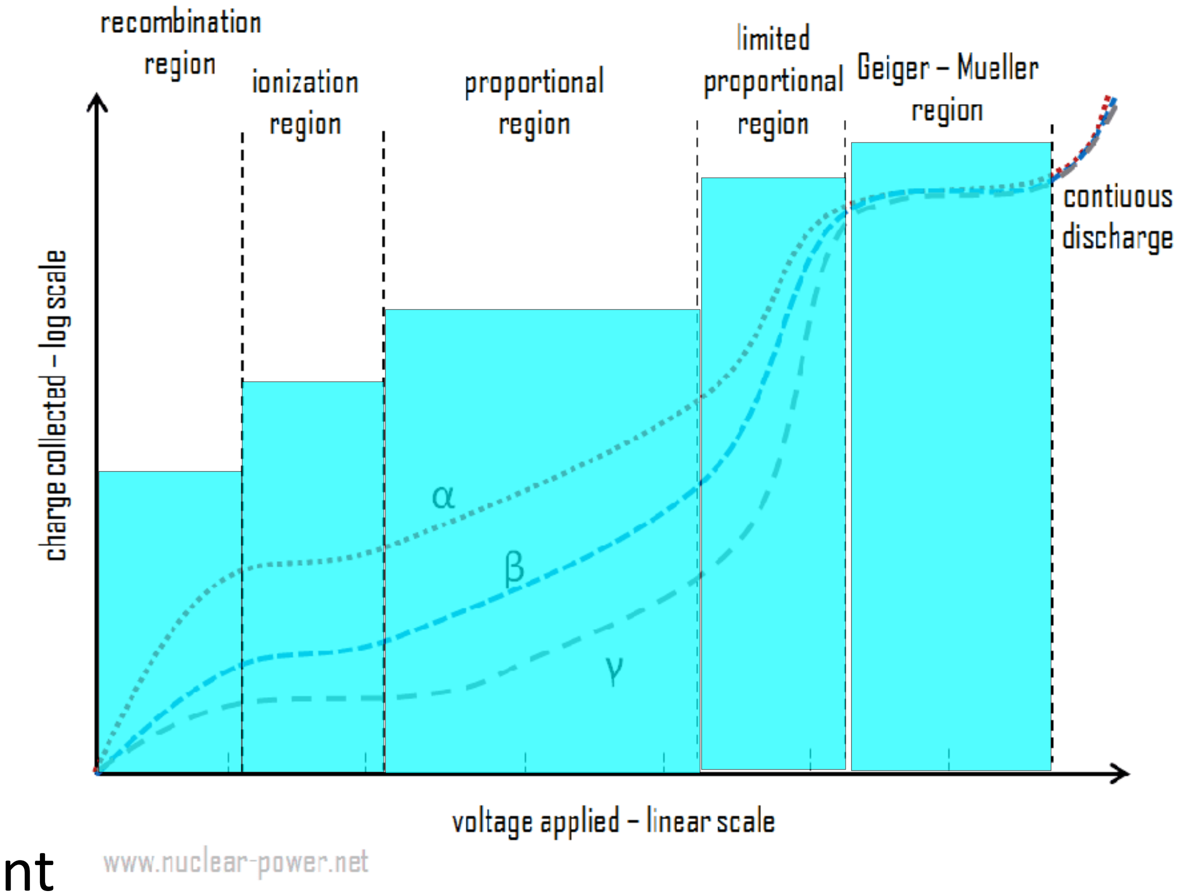
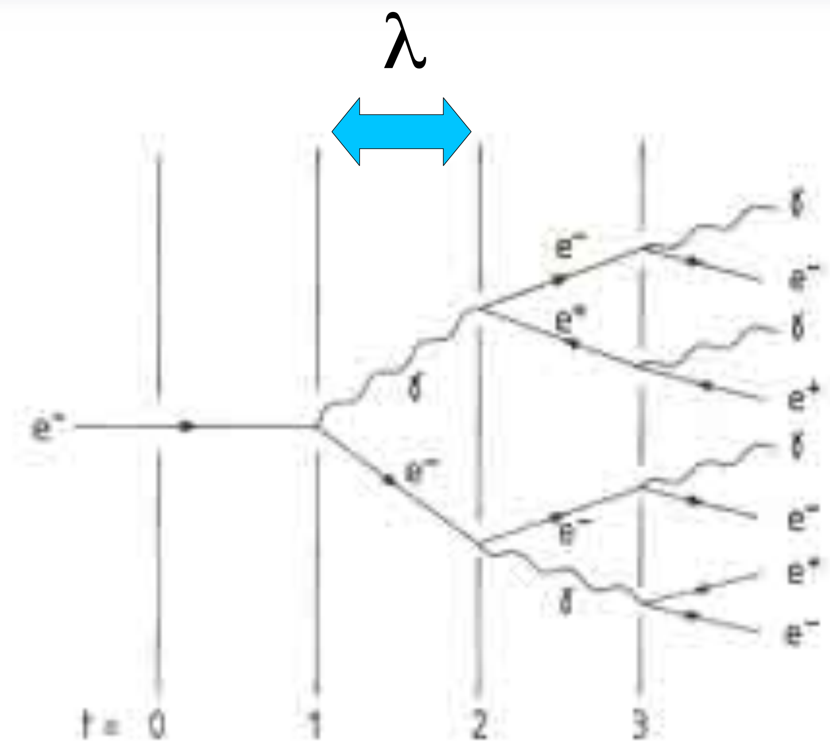
- HT >> 1, geiger-streamer mode, presence of important space-charge effects.



Gaseous detector (ii)

- Primary ionisation:
  - Probability to have n pairs of e^{-}-ion created for μ_0 ionisations created in gap d ($\mu_0 = d/\lambda$):

$$P(\mu_0, n) = \frac{\mu_0^n e^{-\mu_0}}{n!}$$



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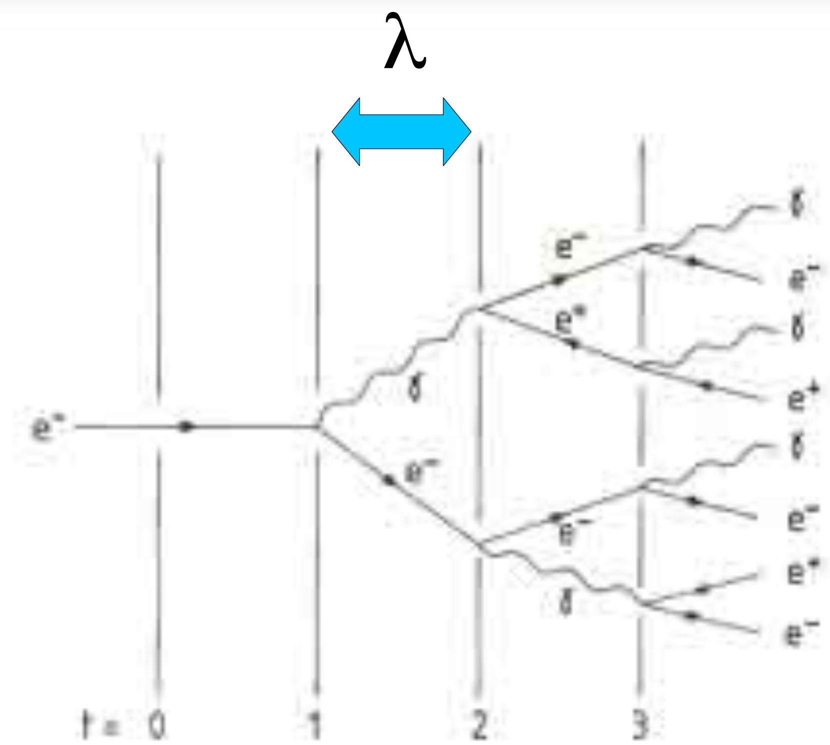

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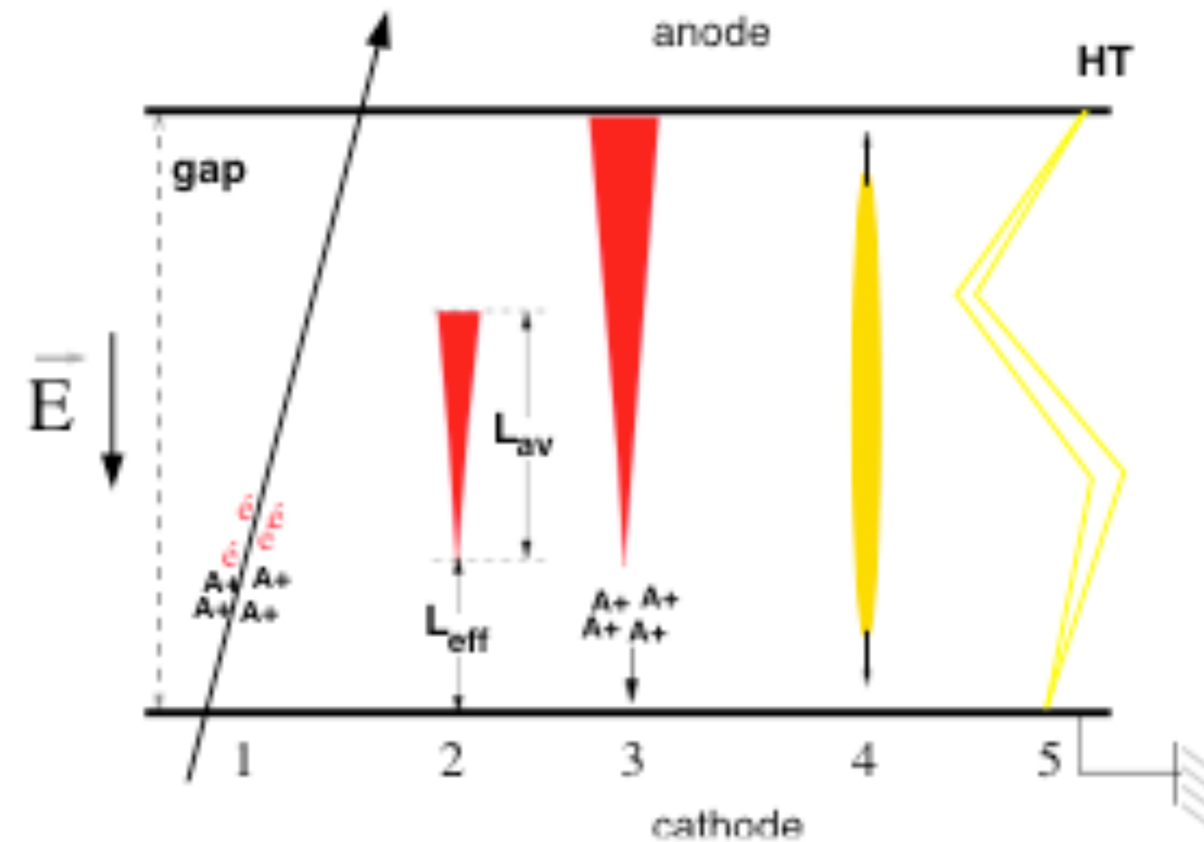
Carbone dioxyde	CO_2	22	34	33	3.01
Argon	Ar	18	30	26	2.44
Neon	Ne	10	12	36	1.41

F. Sauli. Principles of operation of multiwire proportional and drift chambers. CERN Internal Report, vol. 09, 1977.

- Charge amplification:
  - Gain: $G(E,p) = exp\left[\int_0^d \alpha(E,x)dx\right]$
  - Townsend coefficient: $\alpha = 1/\lambda$
  - Avalanche length:

$$L_{av} = \frac{N_\lambda}{\alpha}$$

  - Gap et E constants:
    - Gain: $G(E,p) = e^{(\alpha d)}$

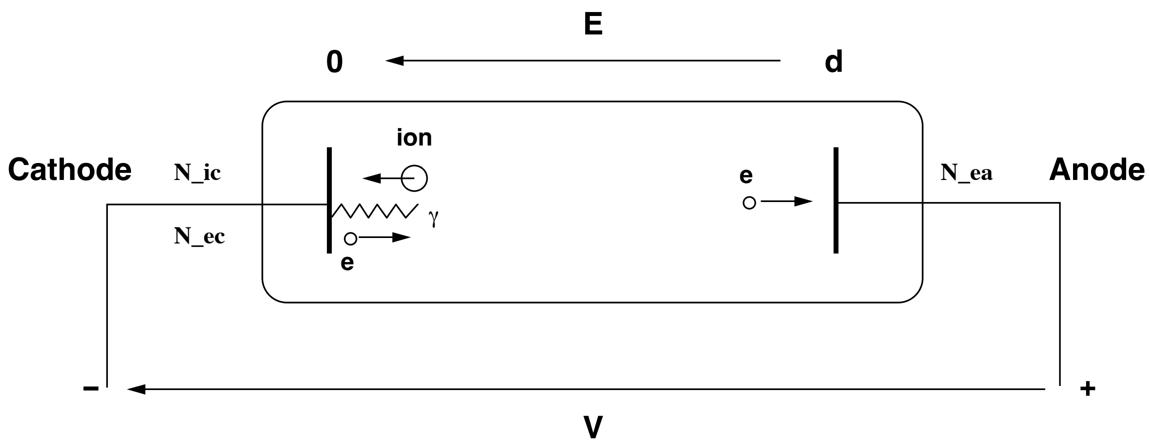


Gaseous detector (iv)

- Charge mobility:

  - Definition: $\vec{v} = \mu \vec{F}$ where $\vec{F} = e\vec{E}$ (electric field)
    - Electrons:

$$\mu_e = \frac{e}{2m_e} E \times \tau \text{ (where } \tau = \lambda/v)$$



    - Ions:

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Neon	Ne^+	4.14
Argon	Ar^+	1.53
Carbone dioxyde	$[CO_2]^+$	1.09

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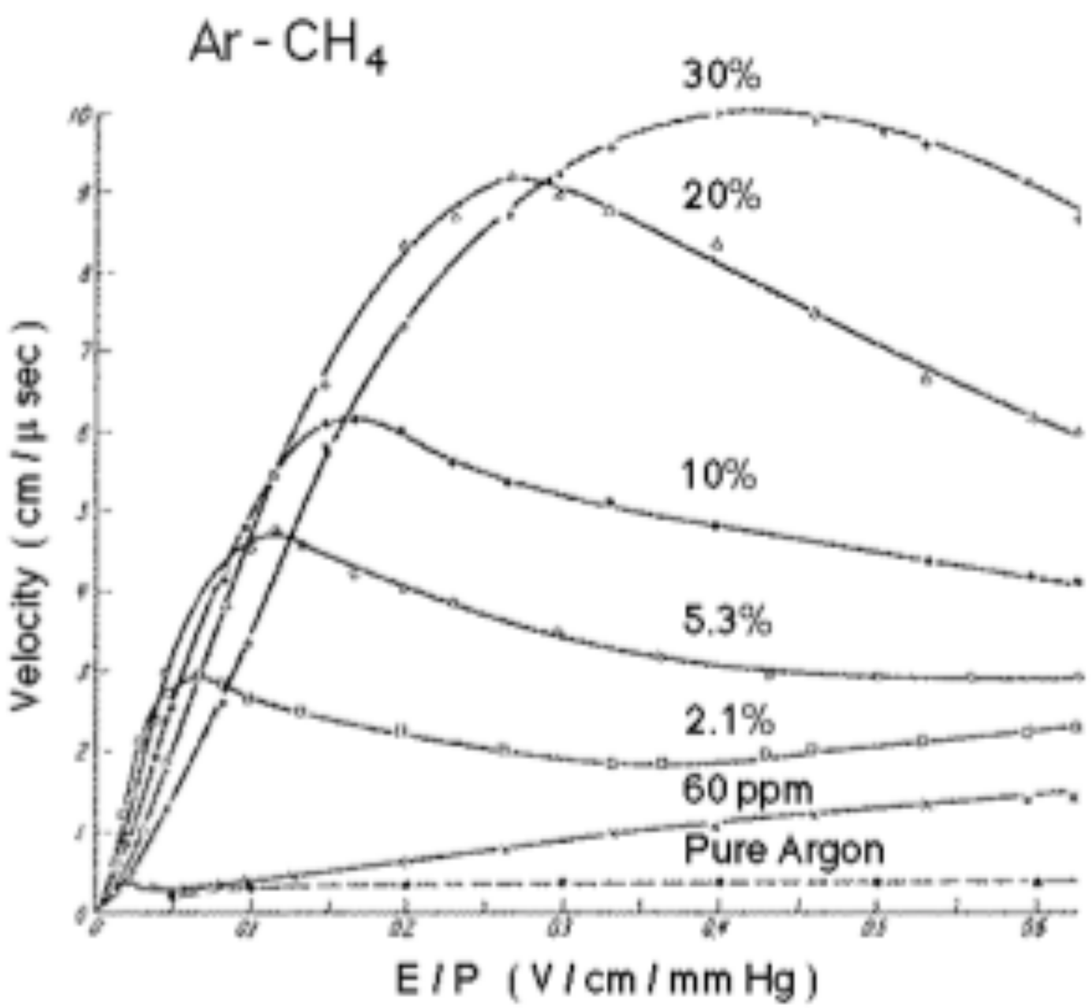

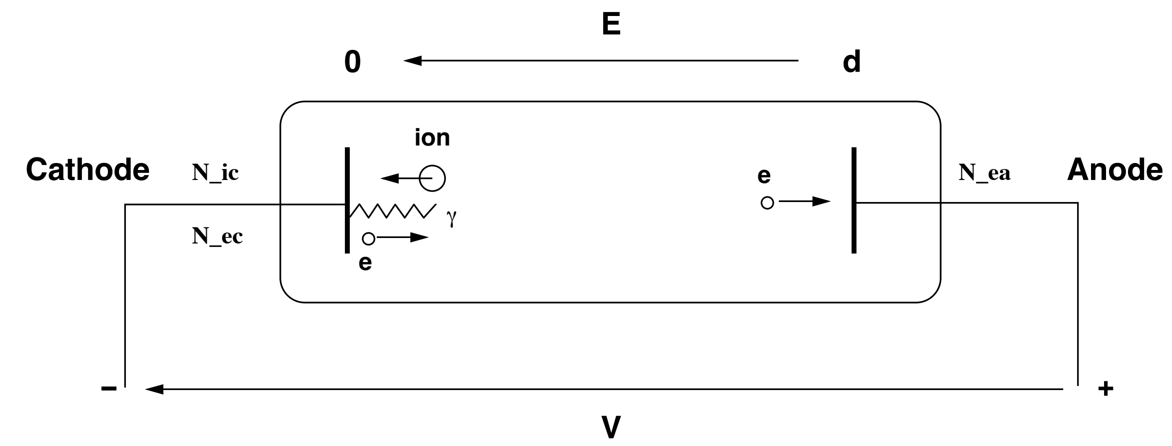

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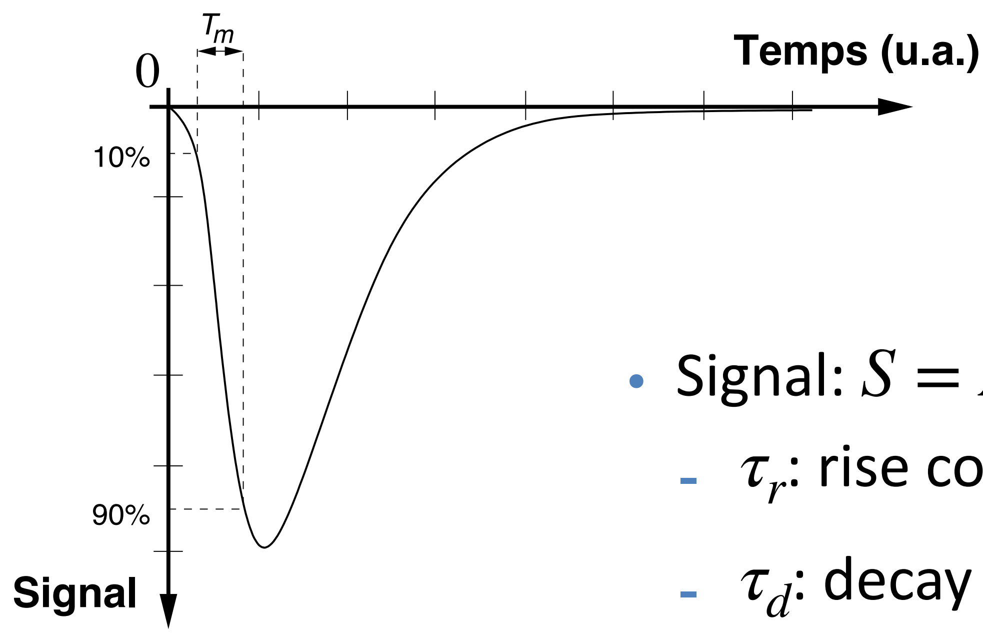
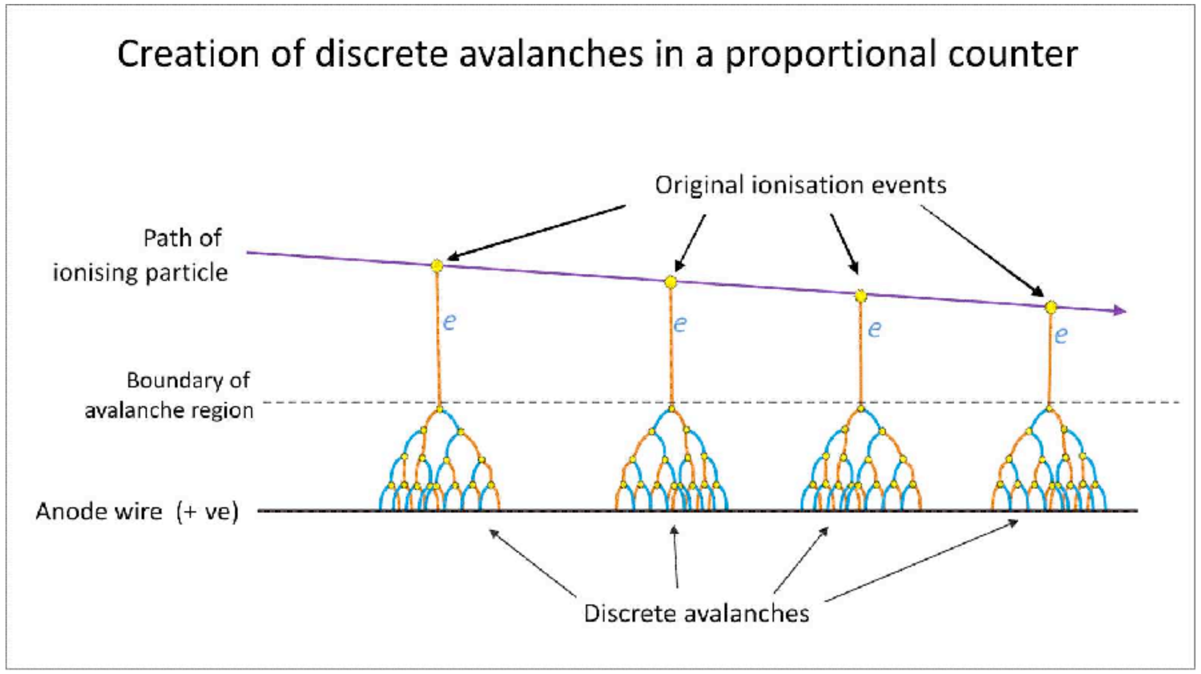
Gaseous detector (v)

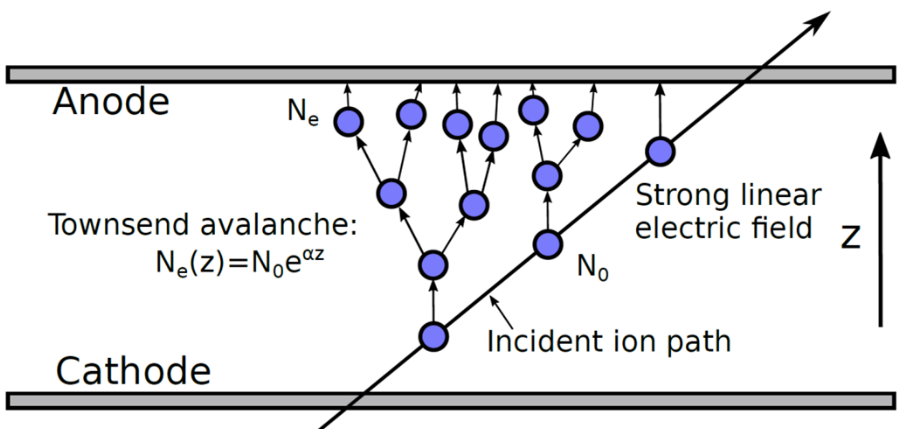
❑ Collected charge

- Shape:
  - Rise time mostly induced by electron movement
  - Fall time mostly due to ion movement



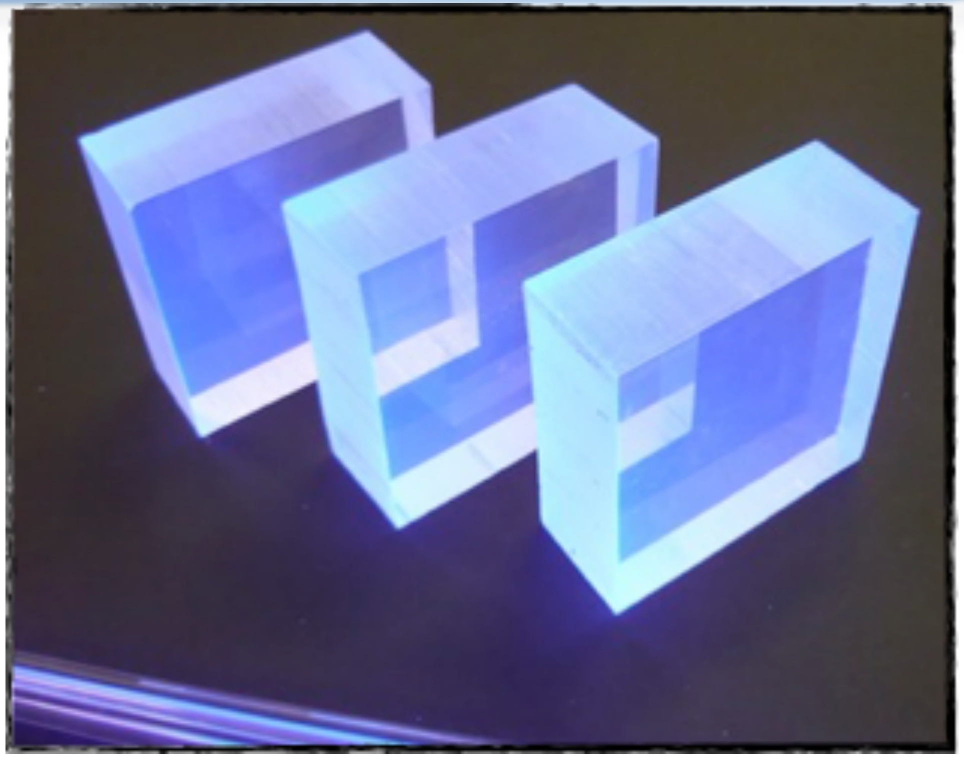
- Signal: $S = Ae^{-\tau_r} \times Be^{\tau_d}$
  - τ_r: rise constant
  - τ_d: decay constant





- Total charge: $Q_{tot} = -e\mu_0 e^{(\alpha d)}$

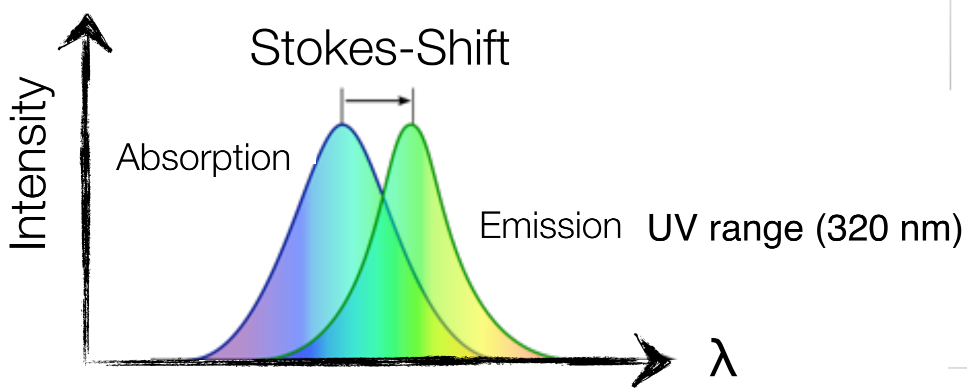
Scintillator (i)



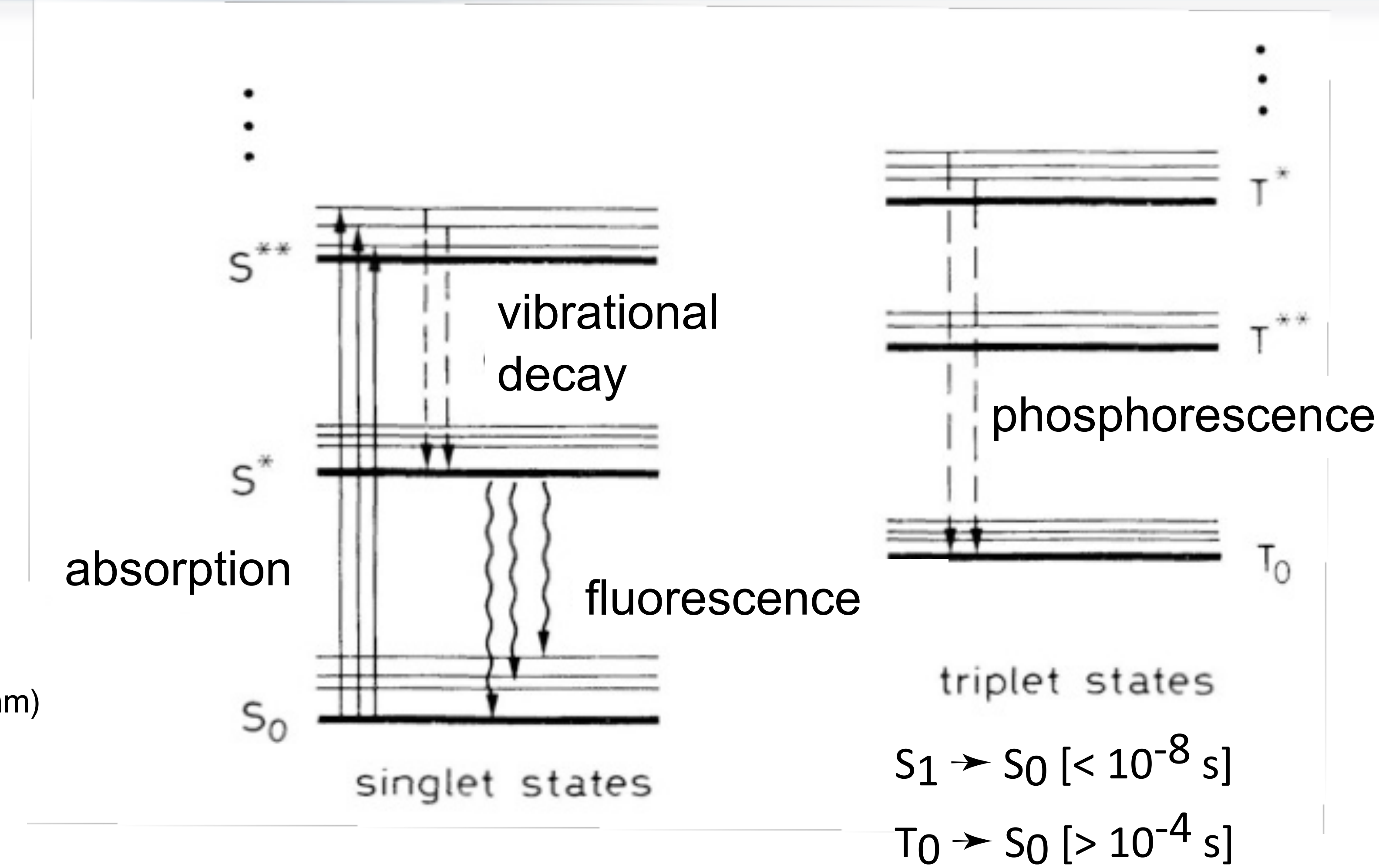
- Properties:
  - Principle:
    - dE/dx converted into light
    - Detection via photosensor (e.g. photomultiplier, …)
  - Main Features:
    - Sensitivity to energy
    - Fast time response (rise time < 10 ns decay time < few 100 ns)
    - Pulse shape discrimination
  - Requirements:
    - **High efficiency** for conversion of exciting energy to fluorescent radiation
    - **Transparency** to its fluorescent radiation to allow transmission of light
    - **Emission of light** in a spectral range detectable for photosensors

Scintillator (ii)

- Organic scintillator (contains C):
  - Mechanism:
    - Singlet molecular states
    - Triplet molecular states
  - Emission/absorption spectrum :



➡ Transparent to its own light



Scintillator (ii)

- Organic scintillator (contains C):
  - Mechanism:
    - Singlet molecular states
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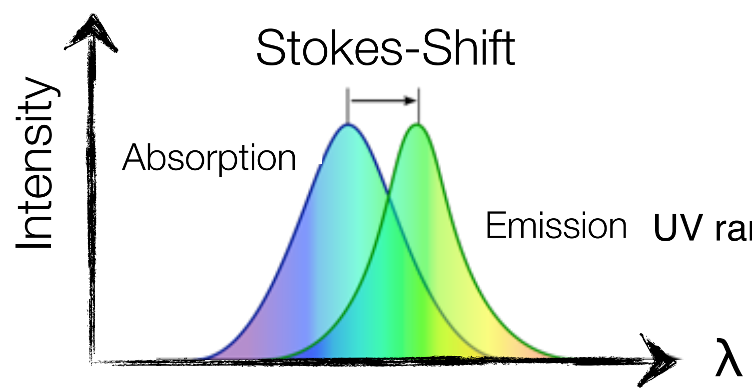
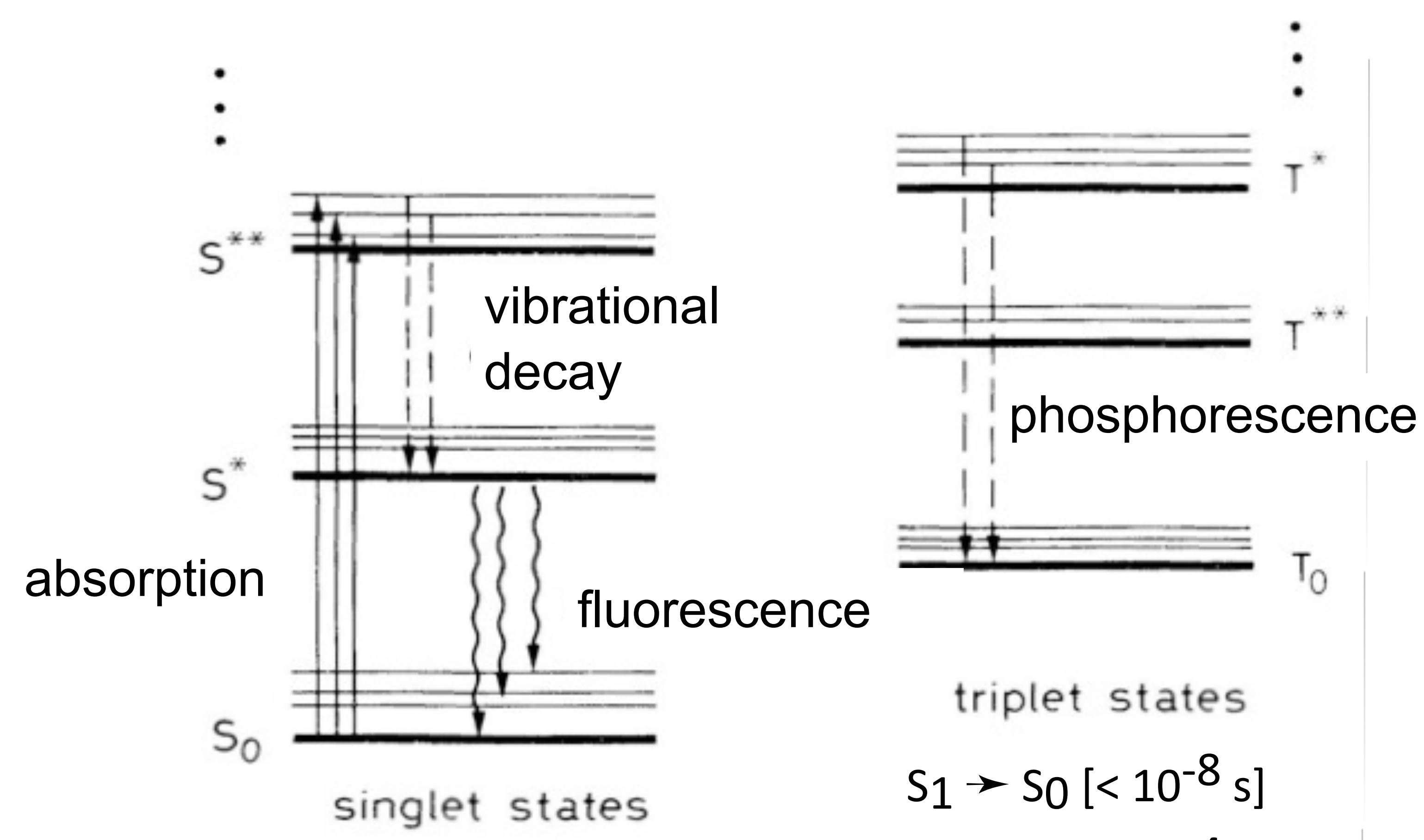
  - Emission/absorption spectrum :





$S_1 \rightarrow S_0$ [< 10^{-8} s]

$T_0 \rightarrow S_0$ [> 10^{-4} s]

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  - EJXXX (C_9H_{10})
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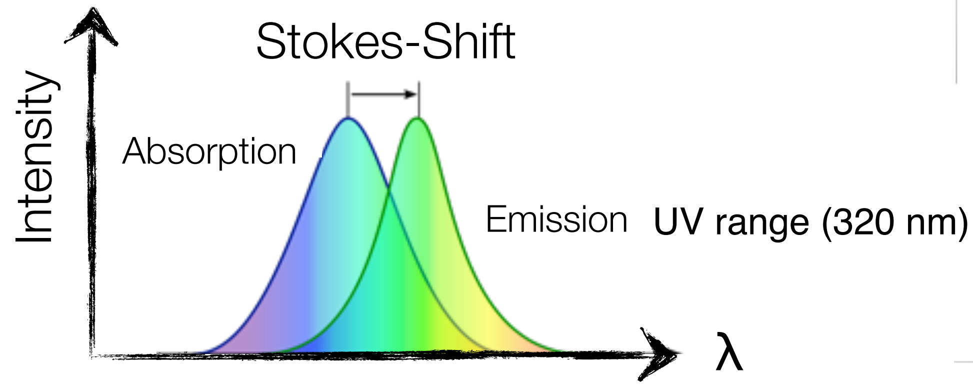

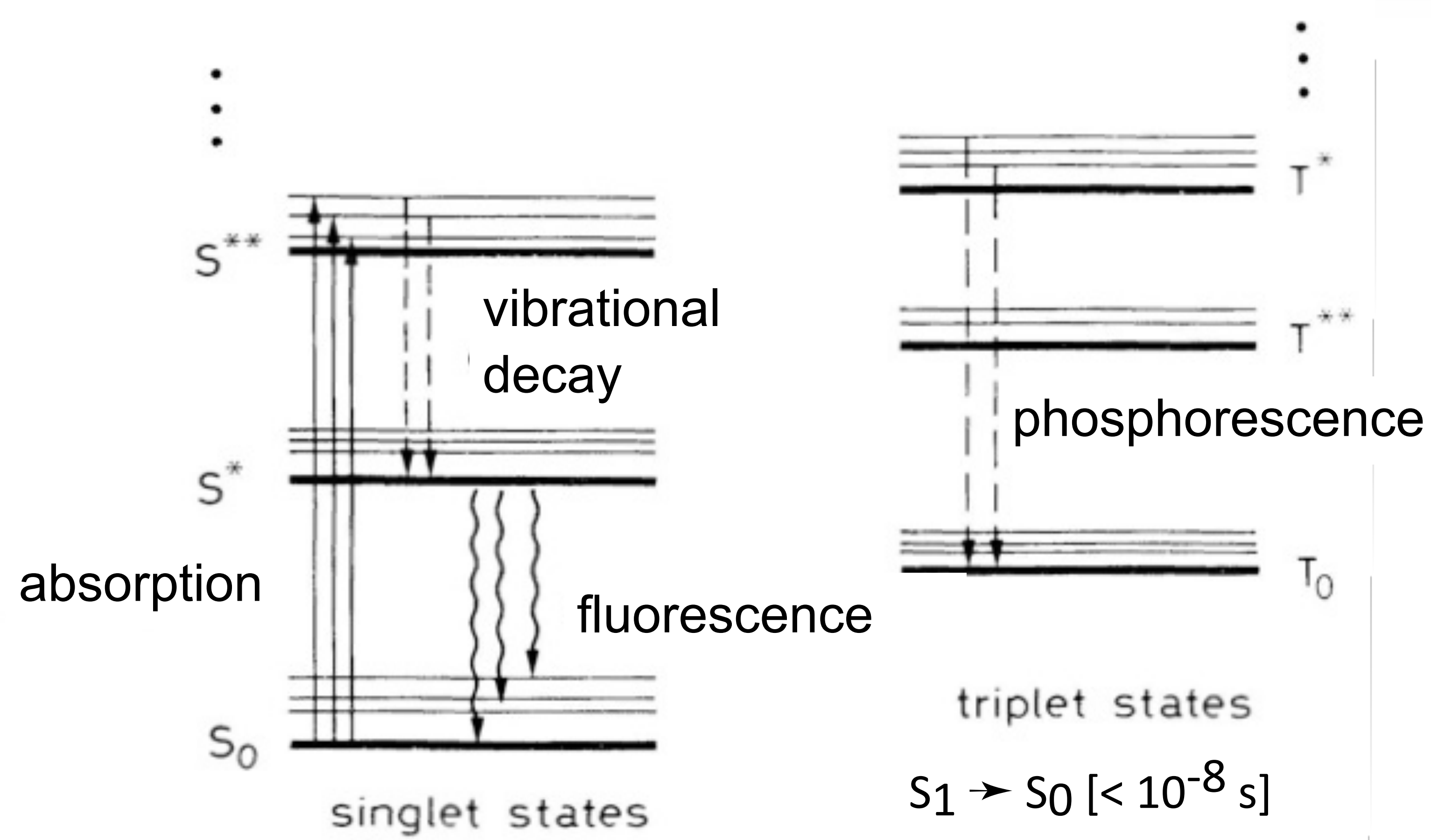

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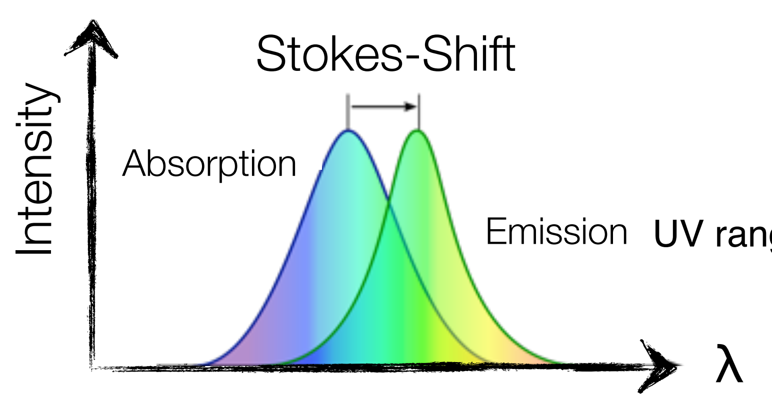

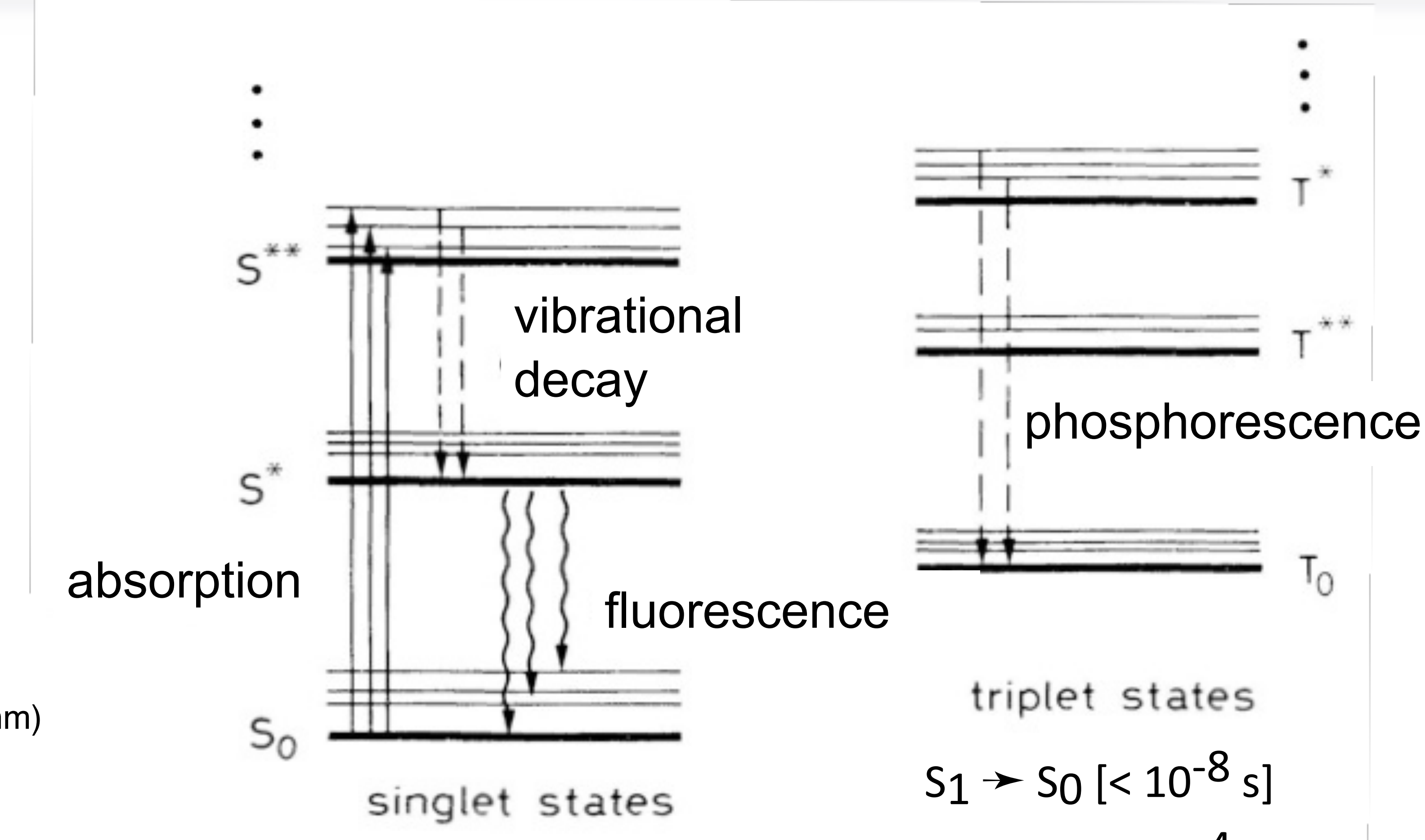

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- Low light yield
  - < 20 photons/keV

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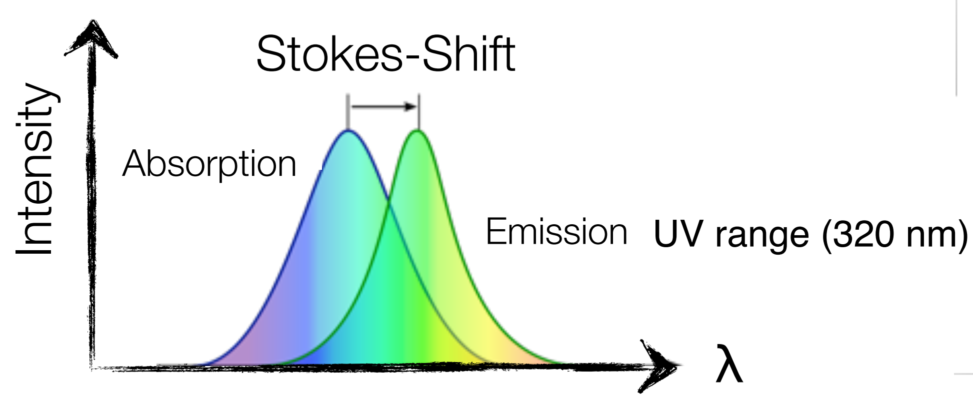

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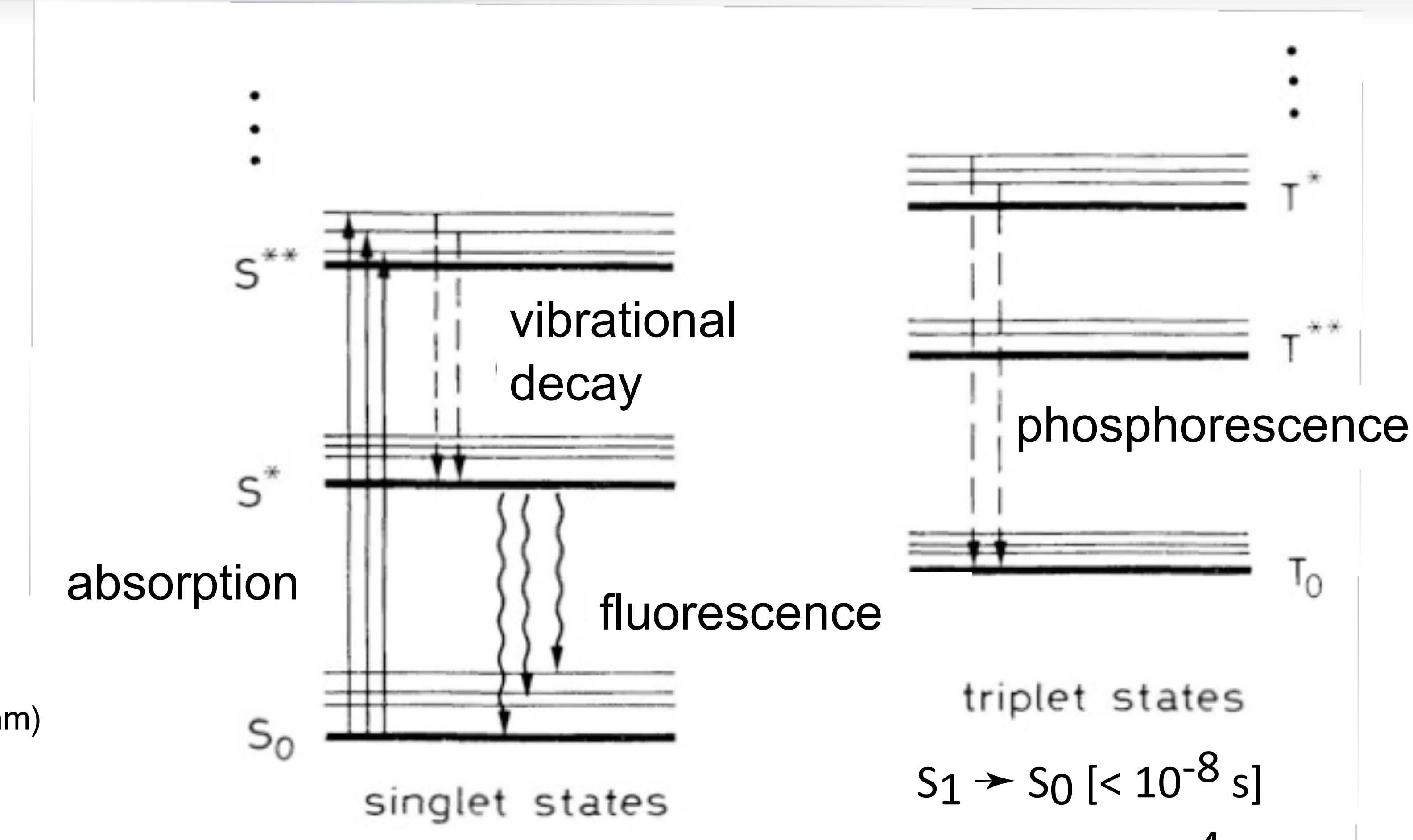

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➡ Use for time measurements

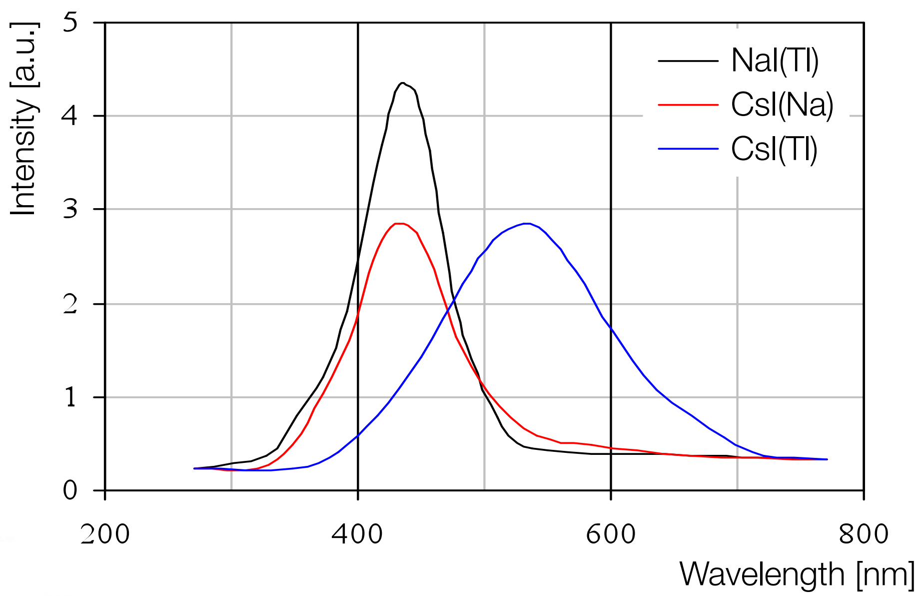
- Low light yield
  - < 20 photons/keV

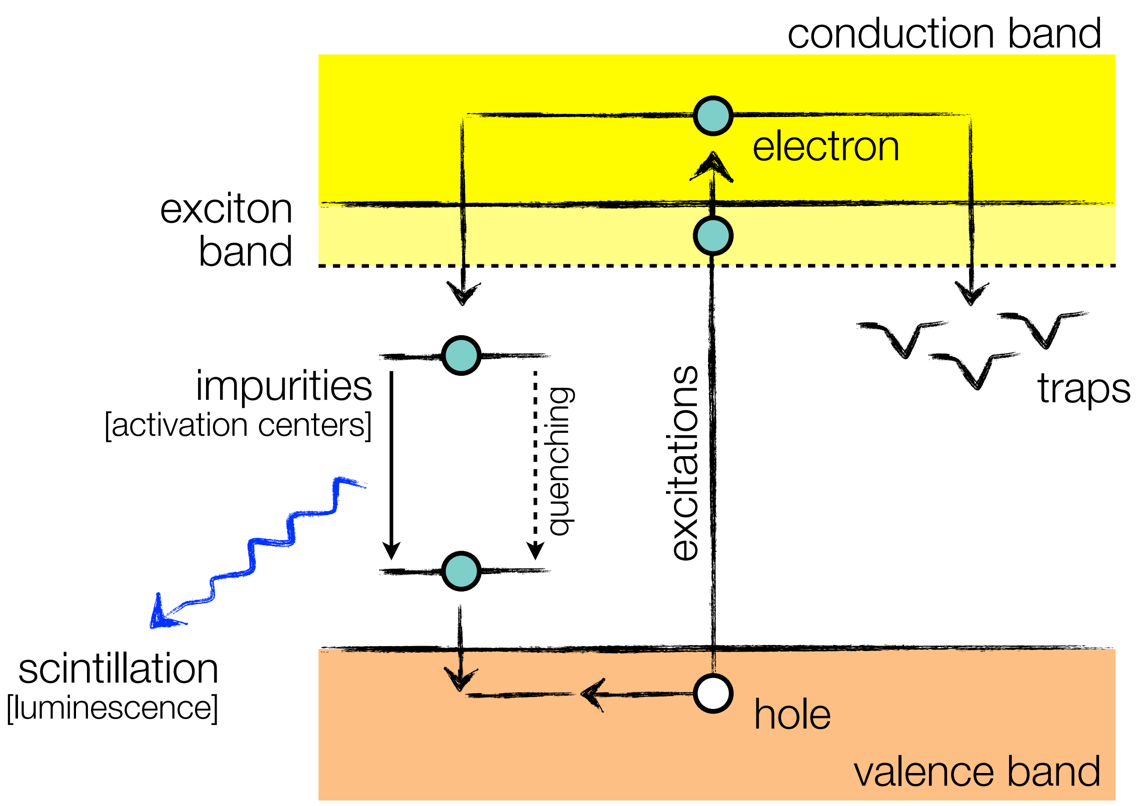
➡ Not suited for E measurements

➡ Cheap and easy to produce

Scintillator (iii)

- Inorganic scintillator (i):
  - Mechanism:
    - Energy deposition by ionisation
    - Energy transfer to impurities
    - Radiation of scintillation photons
  - Emission/absorption spectrum (visible):





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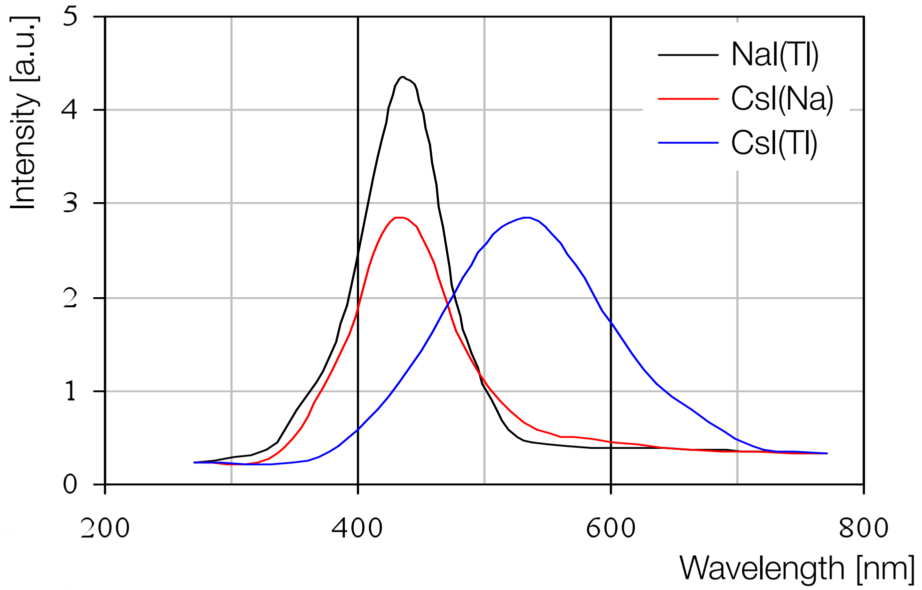

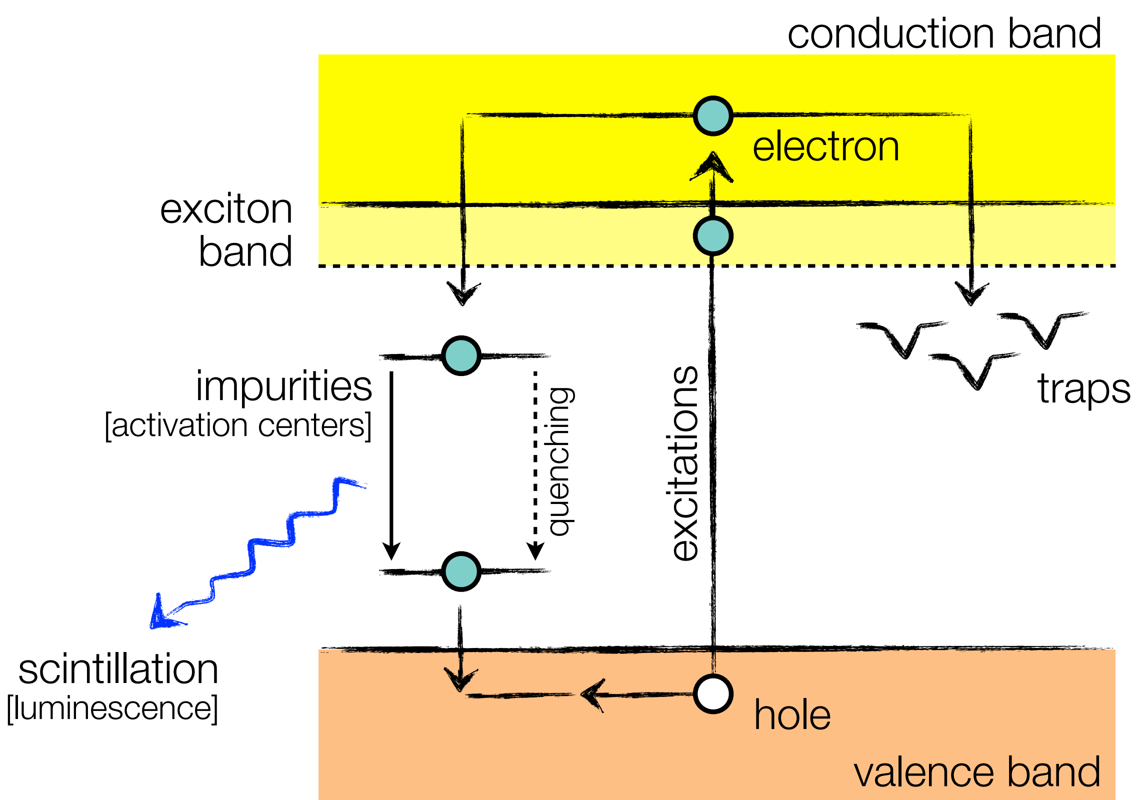

➡ Transparent to its own light

- High light yield
  - > 30-80 photons/keV

➡Use for E measurements

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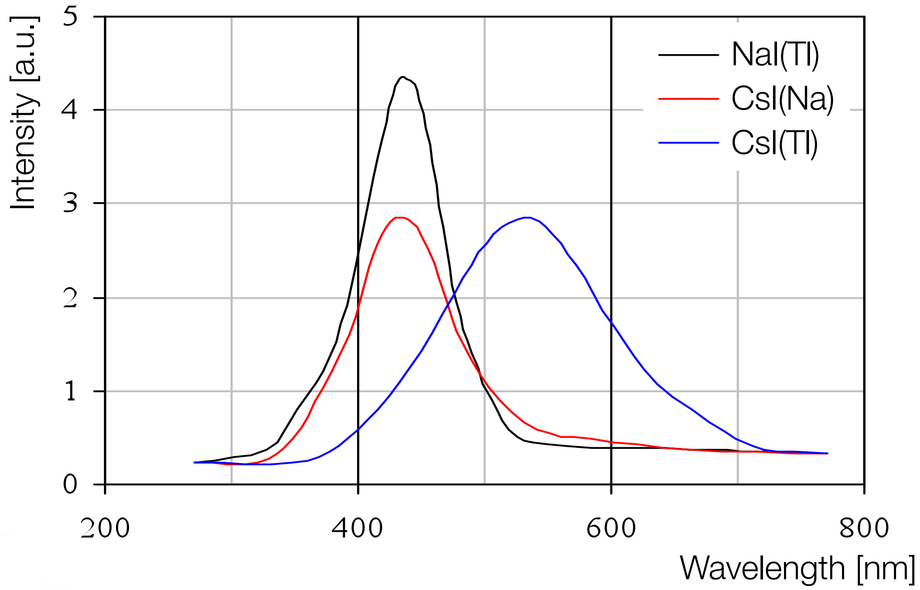
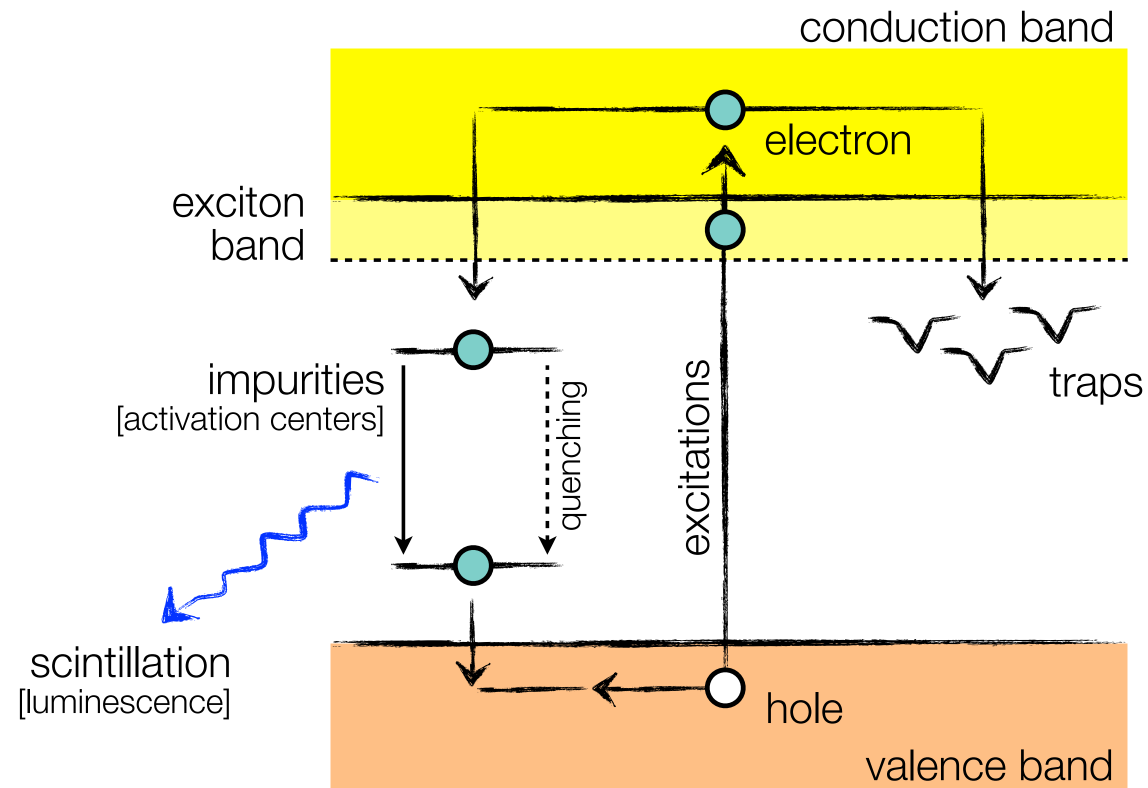




➡ Transparent to its own light

- High light yield
  - > 30-80 photons/keV

➡ Use for E measurements

- Slow timing:
  - Rise time > 10 ns
  - Signal length > few 100 ns

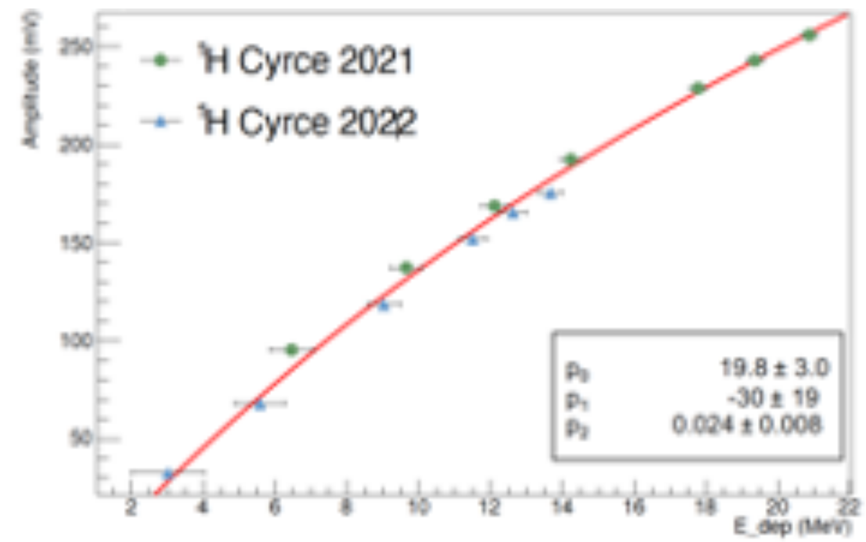
➡ Not suited for time measurements

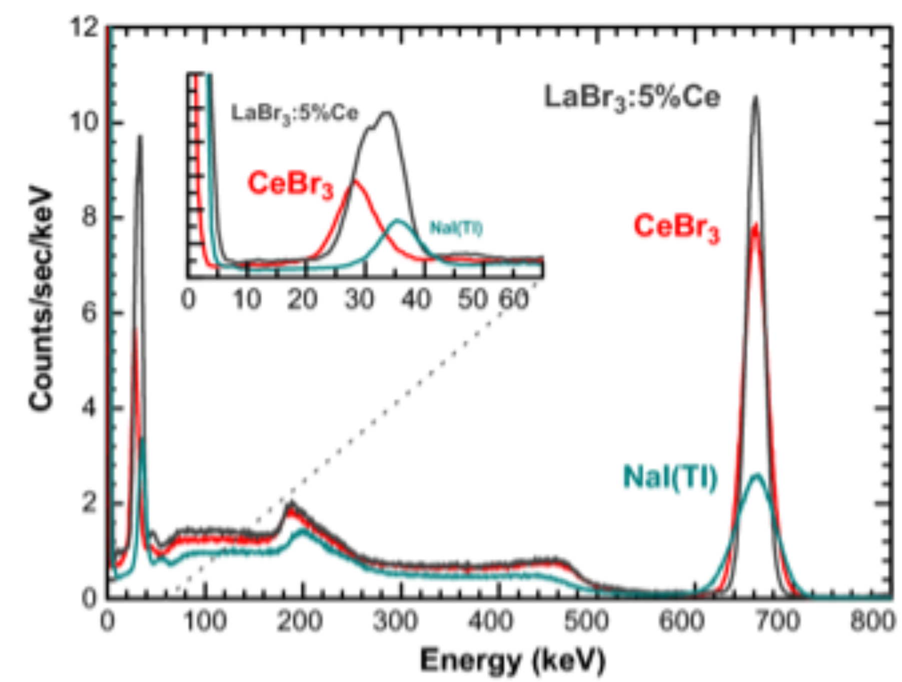
Scintillator (iv)

- Inorganic scintillator (ii):
  - Light production, Birk's Law:

$$\frac{dL}{dE} = L_0 \frac{\frac{dE}{dx}}{1 + k_B \frac{dE}{dx}}$$ with k_B Birk coefficient

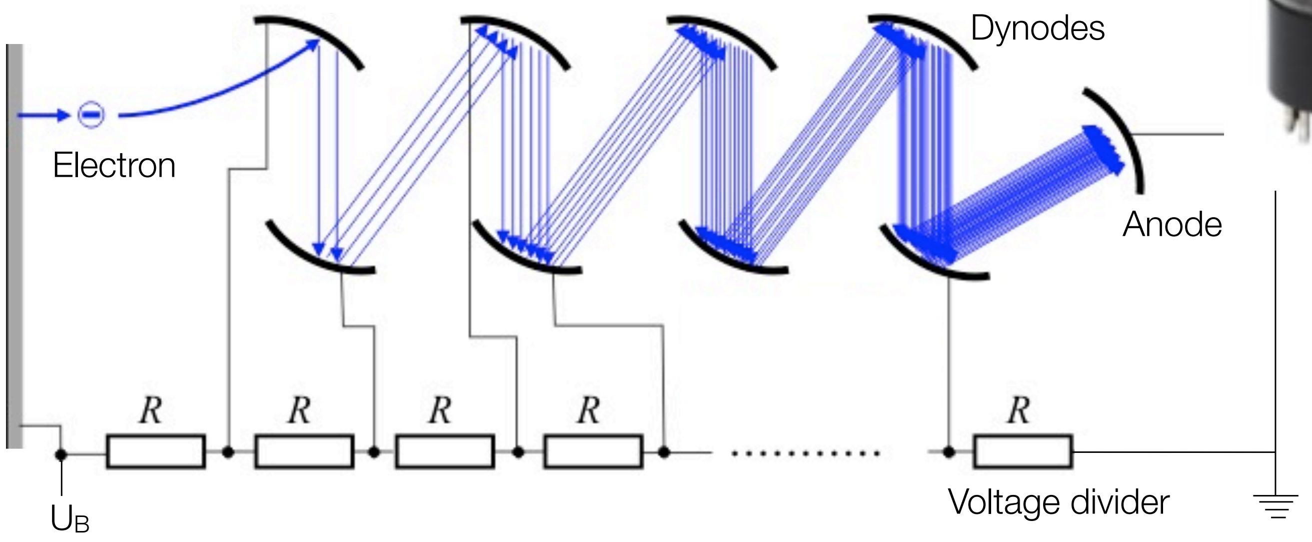
  - Examples:
    - **Sodium Iodide** (NaI): good photon yield, available in big volumes, cheep but hygroscopic.
    - **Cesium Iodide** (CsI): better photon yield than NaI, but slow.
    - **Baryum Fluoride** (BaF2): fast timing (rise time << 1 ns), poor photon yield.
    - **Bismuth Germanate** (BGO): highly efficient, but very slow (decay time : 300 ns), poor photon yield.
    - **Lanthanum Bromide** (LaBr3)/**Cerium Bromide** (CeBr3): excellent photon yield, very fast (rise time ≲ 10 ns), but hygroscopic and expensive (+ lanthanum is radioactive).





Scintillator (v)

- Scintillator coupling (need to convert photon to signal):
  - Photomultiplier: (most used)
    - Photon converted in e- by photocathode (photoelectric effect)
    - Amplification of signal by set of dynodes
    - Efficiency ∝ length wave
    - Quantum efficiency (e- emitted by a incident photon) at most 25%.
    - Gain: $A = \delta^n$, n number of dynodes ar dynode emission coefficient: ~ 10^6-10^8
    - HV: 1-2 kV



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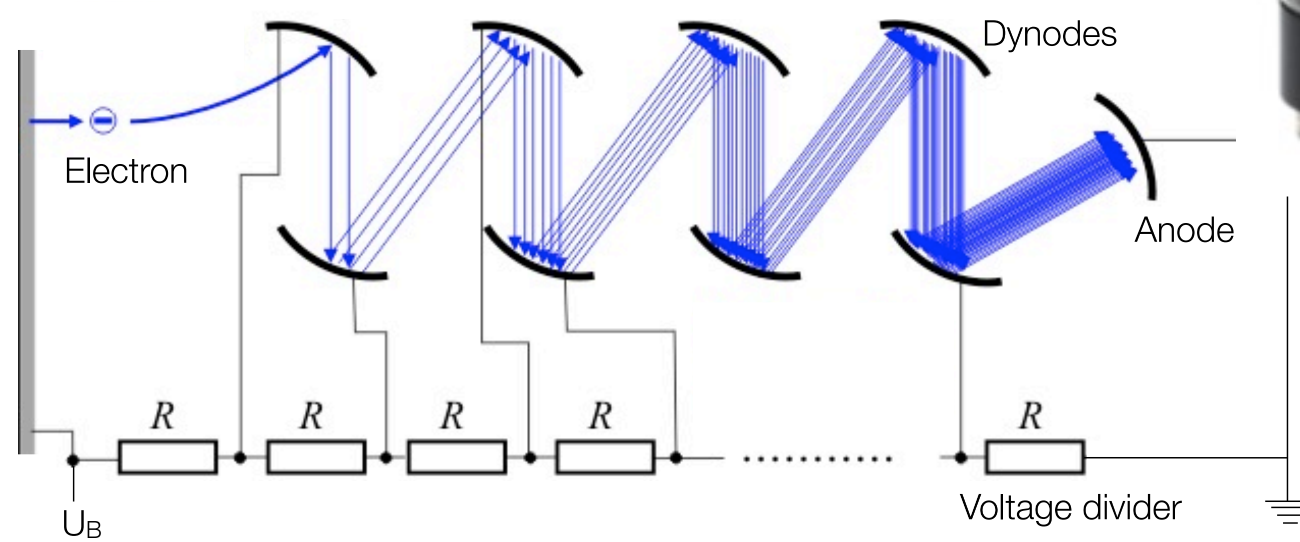
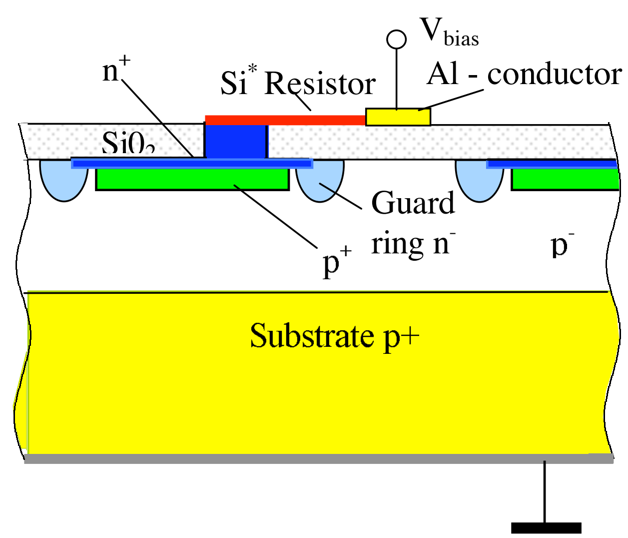
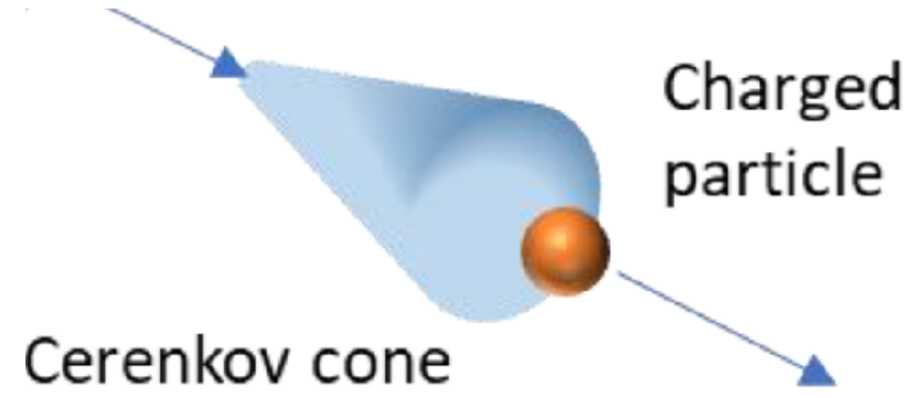


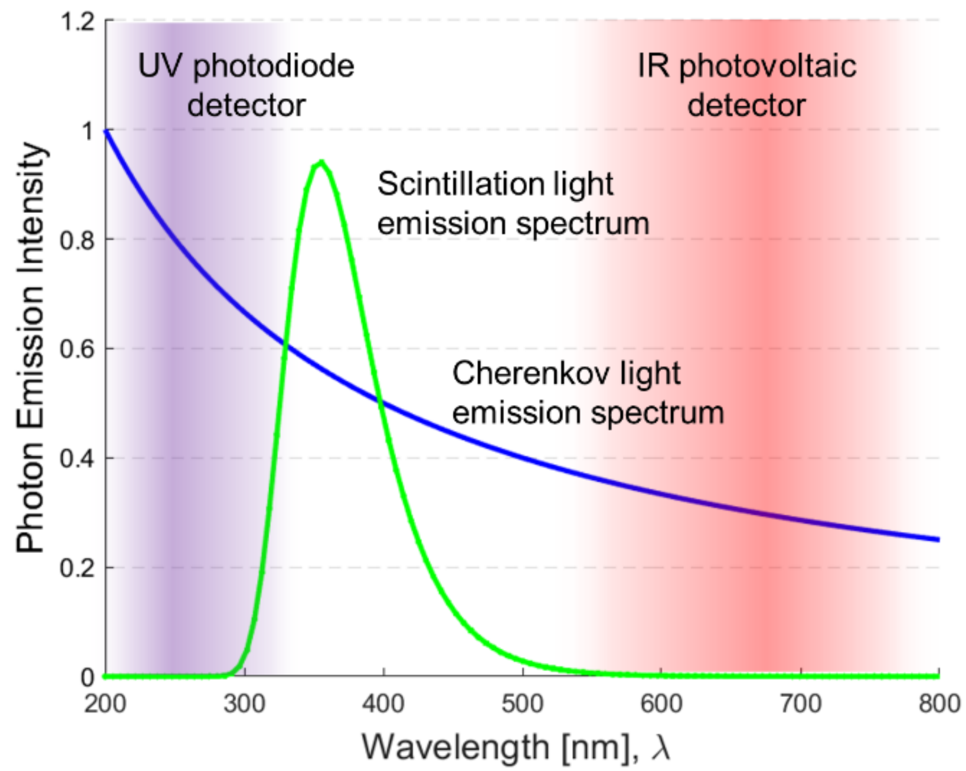
- Silicon photomultiplier (APD, SiPM, …):
  - Gain: ~ 10^6
  - HV: < 100 V
  - Not sensitive to magnetic field
  - Sensitive to temperature



Scintillator (vi)

- Cherenkov light in scintillator
  - Cherenkov radiation:
    - Happens when a particle velocity β > light speed in material
    - Light cone appears: $cos(\theta) = \frac{1}{\beta n}$ where *n* is the refraction index





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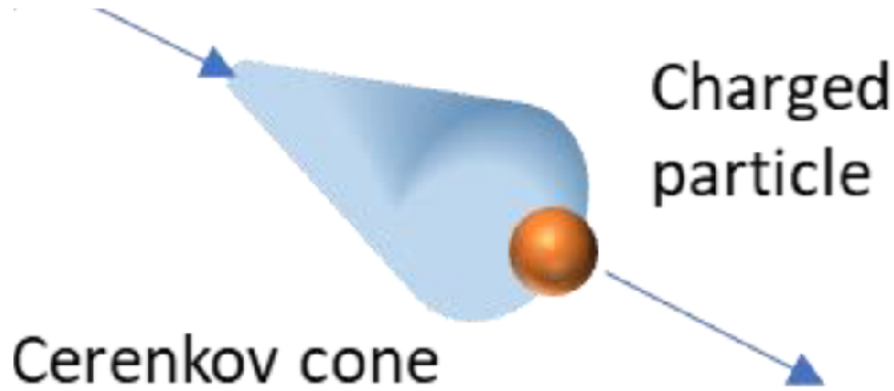

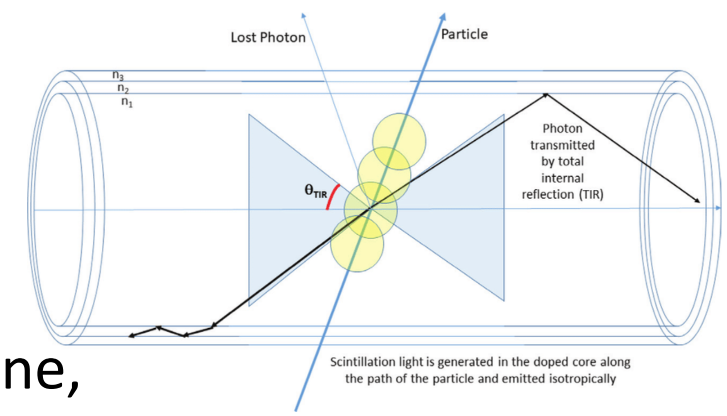

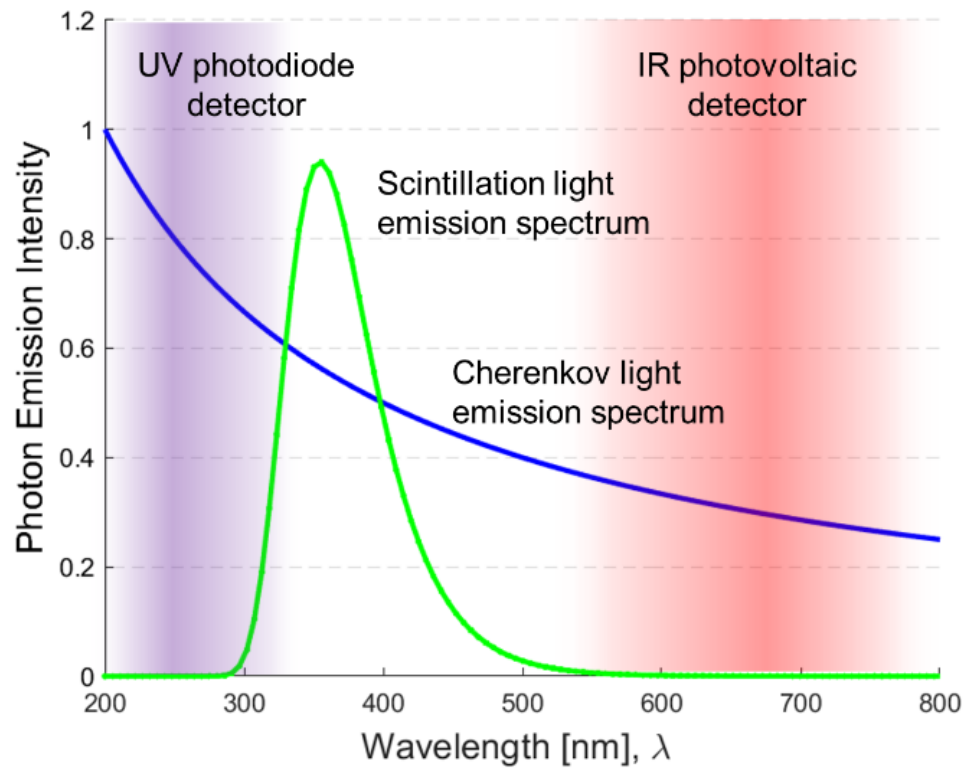

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- Scintillating fiber
  - Core: mainly polystyrene,
  - Cladding: PMMA, plastic, …
  - Very thin diameter could < 0.5 mm
  - Flexible

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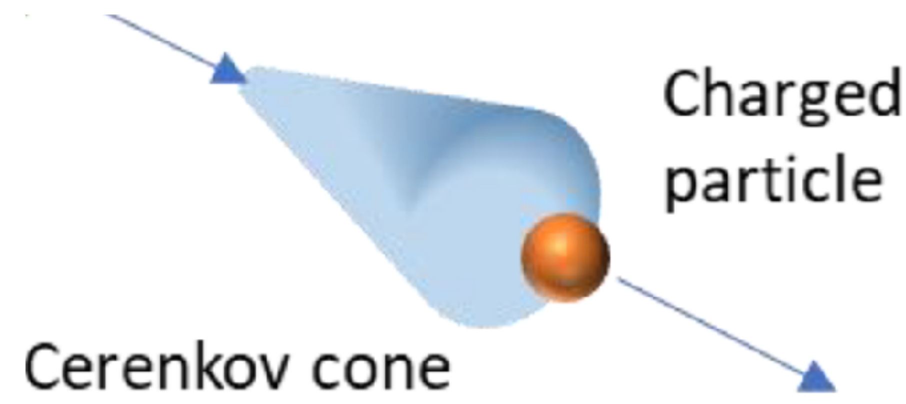

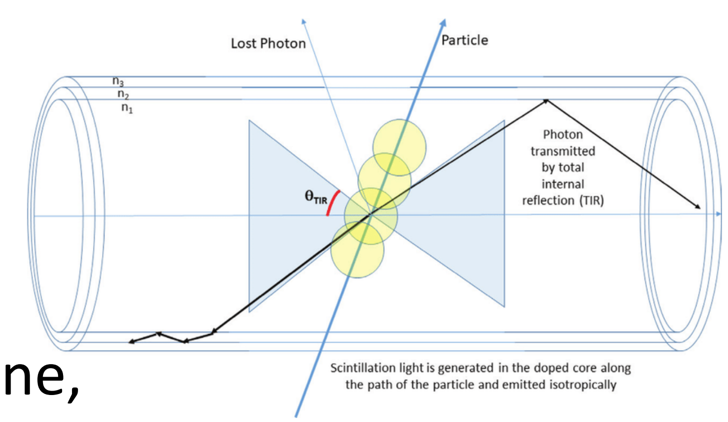

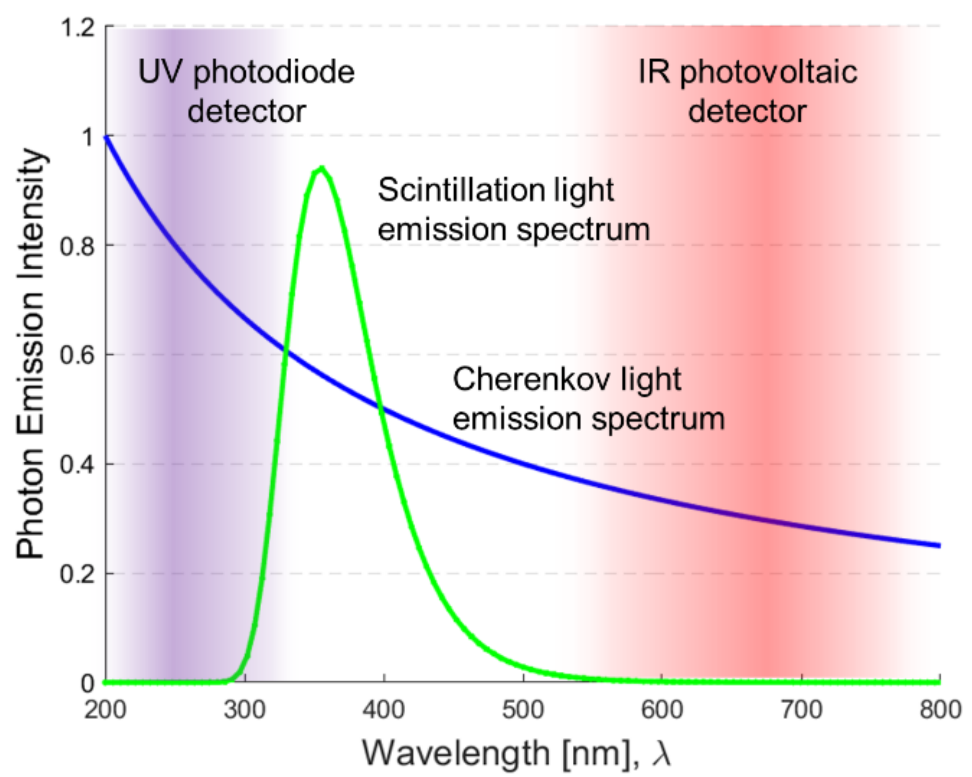

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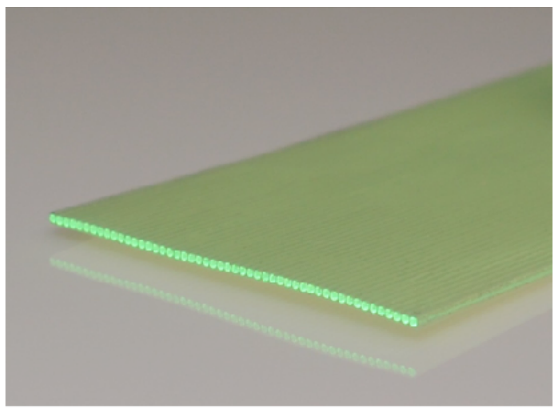
➡ Could be assembled in ribbons



Scintillator (vii)

❑ Scintillators comparison:

Scintillator Name	Density (g/cm^3)	Yield (photons/MeV)	Δ_E/E @ 662 keV (%)	Decay Constant (ns)
Polystyrene	1.05	10000	11	2.5
BGO	7.13	7500	12	300
YAG	4.60	8000	11	70
BaF_2	4.88	10000	9.0	0.8
$LYSO(Ce)$	7.10	32000	8.0	40
$CsI(Na)$	4.51	34000	7.5	630
$NaI(Tl)$	3.70	38000	6.0	230
$CeBr_3$	5.10	75000	4.0	20
$LaBr_3$	5.06	86000	3.0	16

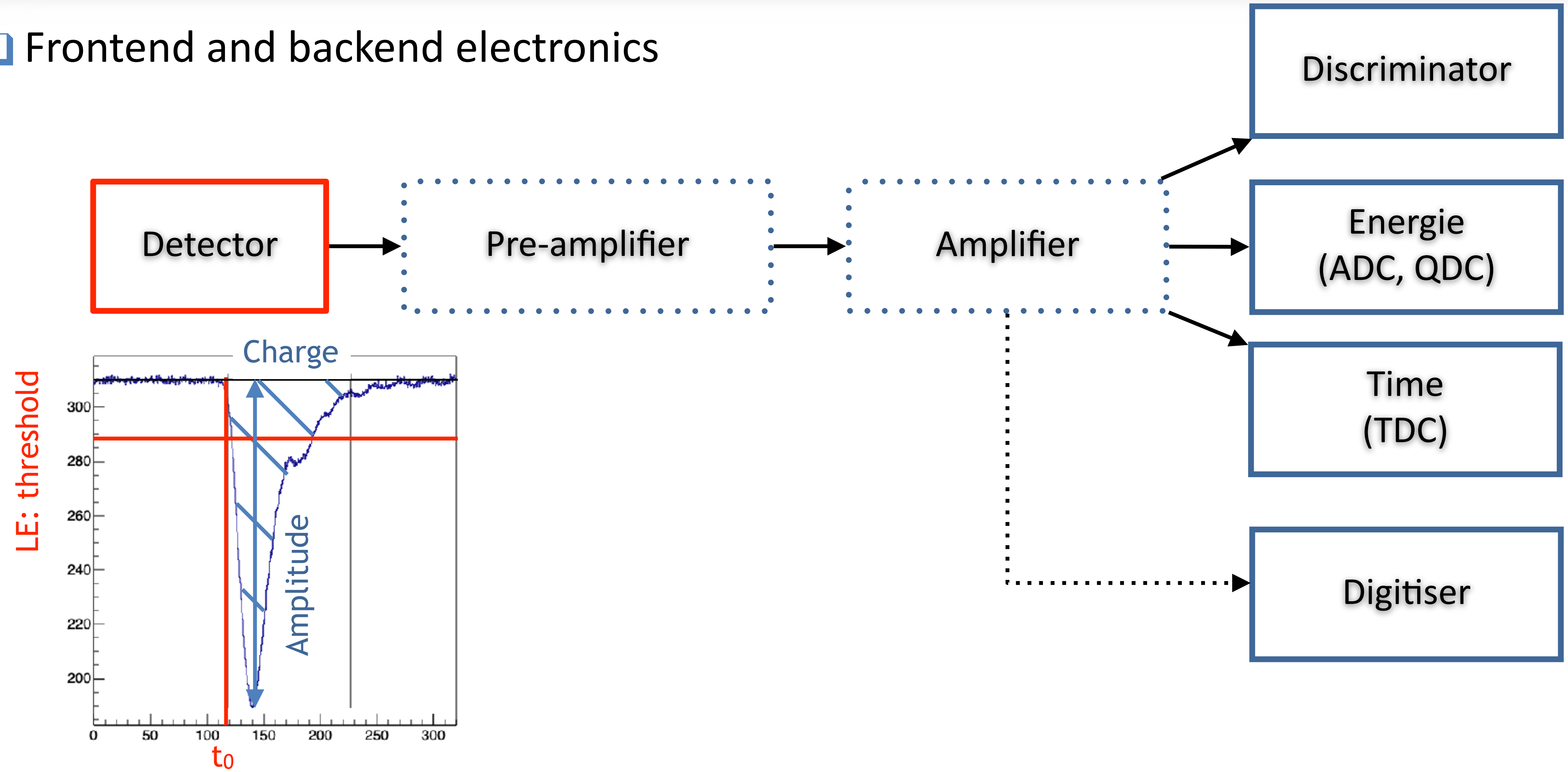
Plastic

➡ Efficiency proportional to density

➡ Energy resolution proportional to yield

Electronics chain

- Frontend and backend electronics



- Discriminator: compute start of signal t_0 (LE, CFD, etc… algorithms)
- ADC: Analog to digit converter, compute the amplitude of the signal
- TDC (TAC+ADC): time to digit converter, compute the time information
- QDC: charge to digit converter, compute the charge (integral) of the signal inside a give gate
- Digitiser (flash-ADC): compute the amplitude of the signal at a given frequency

Acquisition chain

❑ Acquisition modules

- Scheme

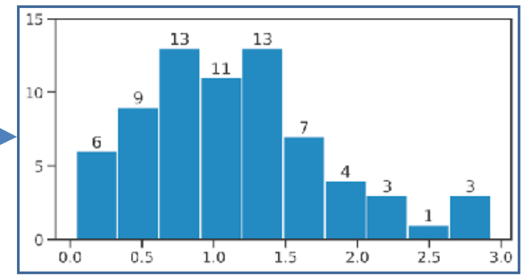
Discriminator → Counting rate

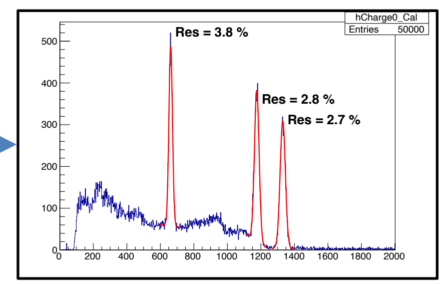
Time (TDC)

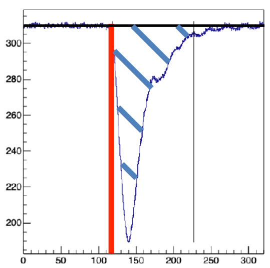
Energie (ADC, QDC)

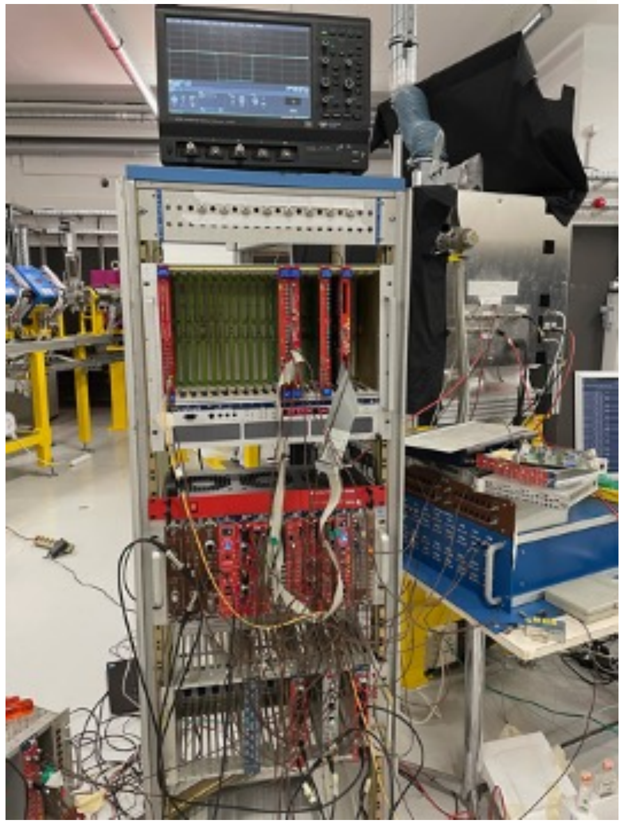
Time (TDC), Energie (ADC, QDC) → Multi-channel analysis

Digitiser → Waveform analysis









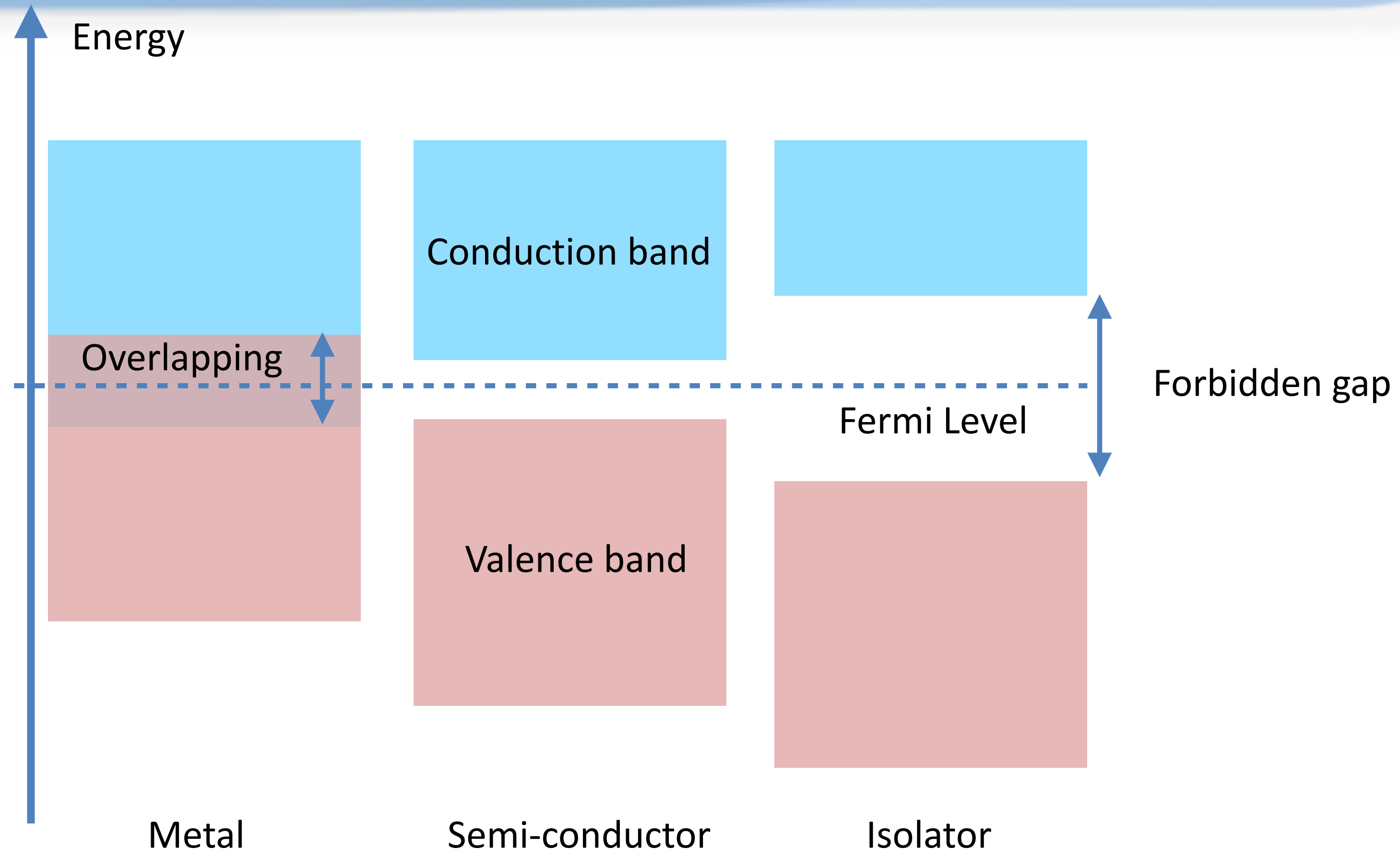
- Event building:
  - Build with data arriving in a given time (generated by dedicated detectors)
  - Trigger-less, a common clock provides the TimeStamp

  ➡ Build event offline

Semi-conductive detector (i)

❑ Properties (i):

- Principle:
  - Based on electronic band structure
  - Ionising leads e- to conduction band
- Extrinsic detector:
  - n doping brings an e- in valence band
  - p doping remove an e- in the valence band
- Intrinsic detector:
  - No doping, hyper pur crystal



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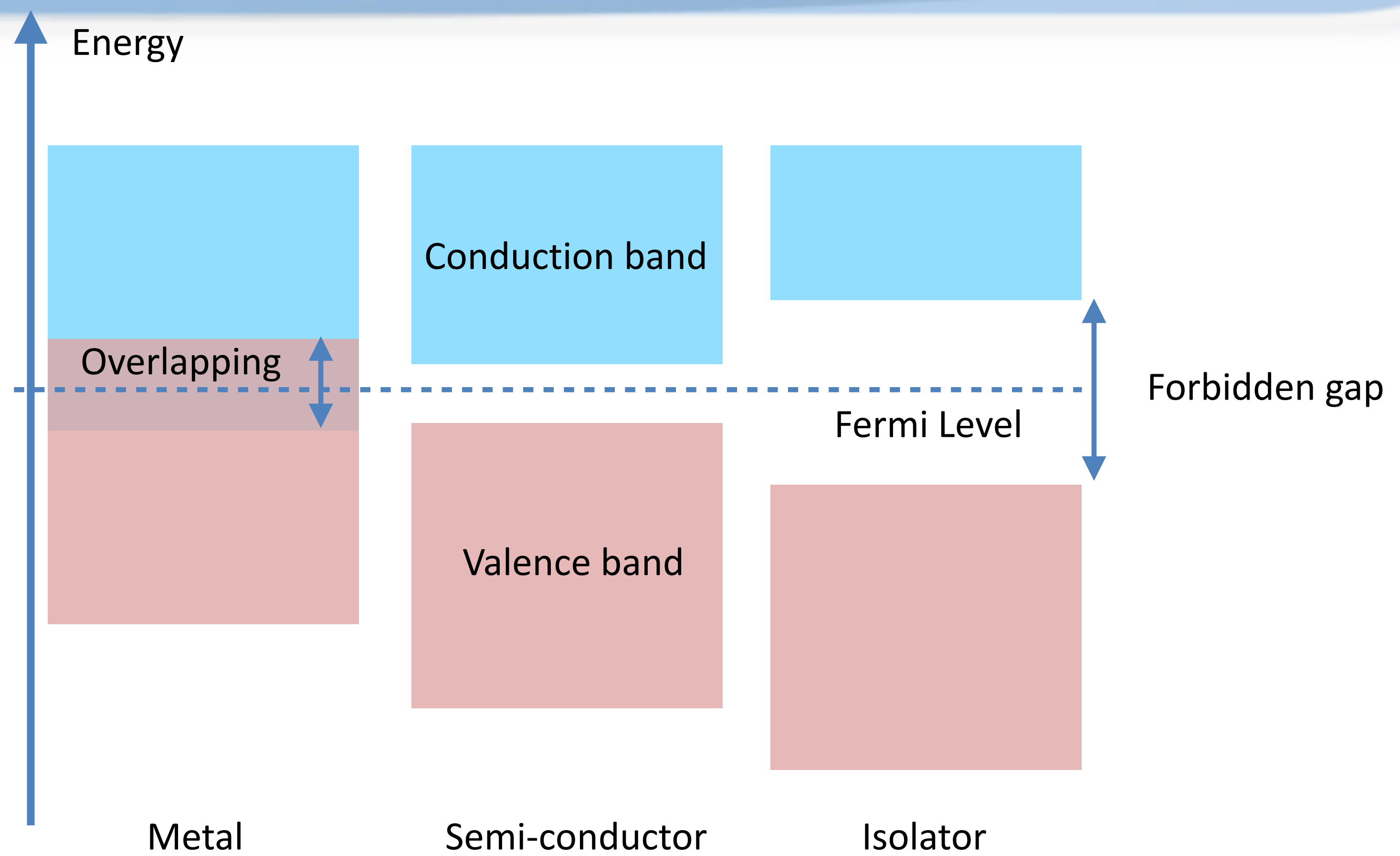
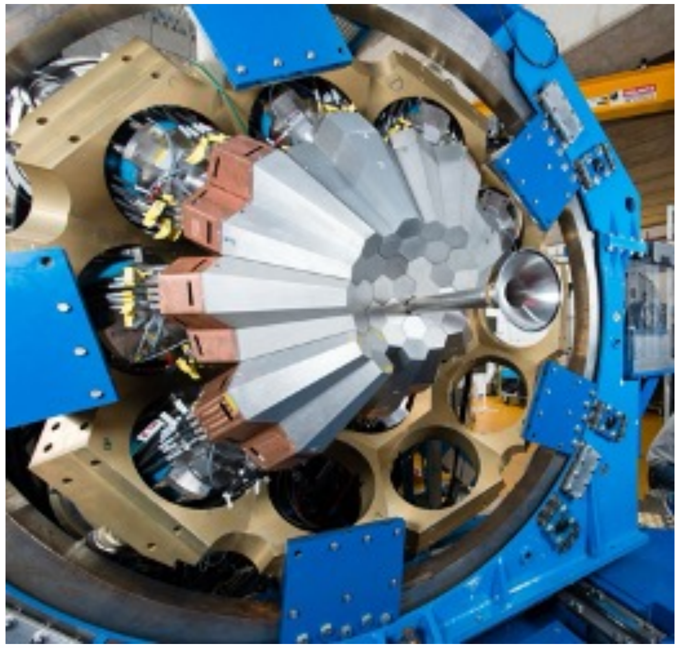


- Production pair (e- hole): $W_i \lesssim 3\,eV$

  ➡ ~10 times smaller than for gaseous detector

  ➡ Except for wide-bandgap detectors:

  SiC, GaN, ZnO ($W_i \gtrsim 2\,eV$), diamond ($W_i \lesssim 13\,eV$)
- Most used: silicon and germanium detector



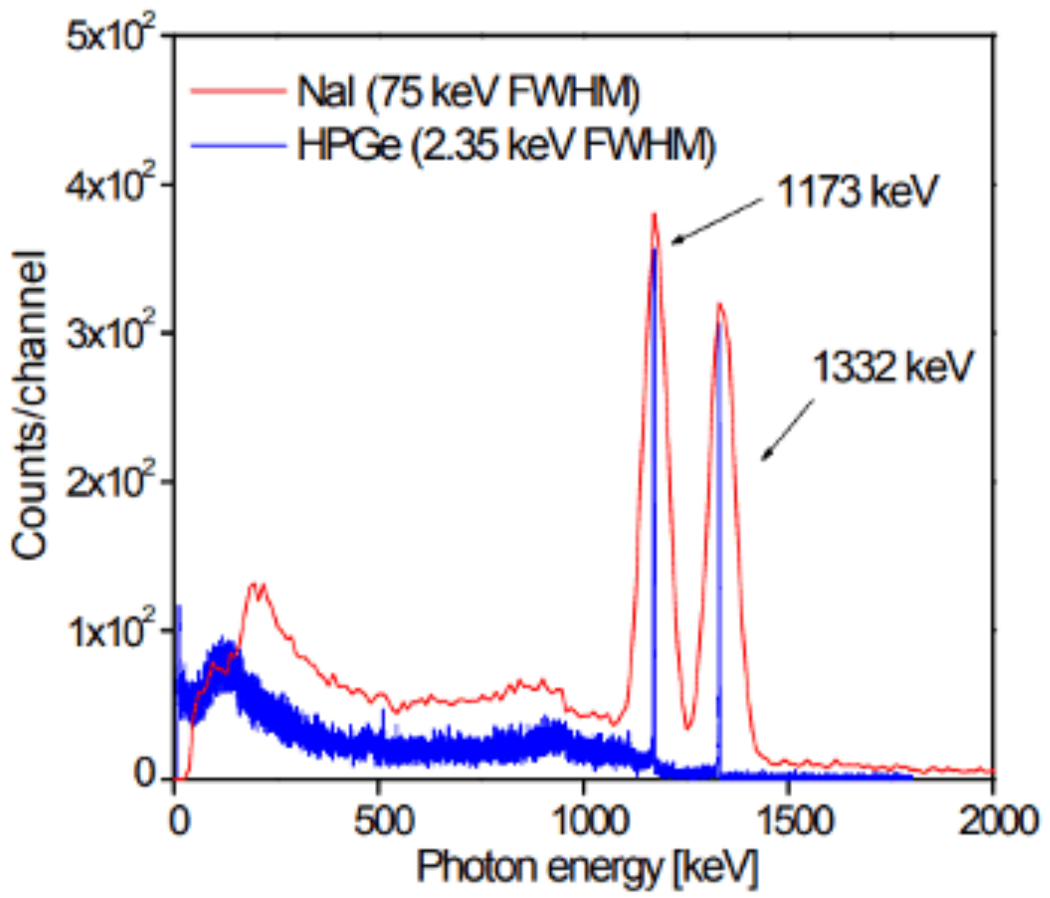
Semi-conductive detector (ii)

- Germanium detector:
  - Advantages
    - High energy resolution: ~ 0.1 %

➡ Use for E measurements

  - Drawbacks
    - Poor efficiency: ~ 50 % of NaI crystal
    - Slow charge collection: few ten of μs
    - Need to amplify the signal
    - Need to cool down cos $W_i = 2.62\,eV$ very low (77º K)
    - Very expensive for large volume (when possible)

➡ Not portable measurements



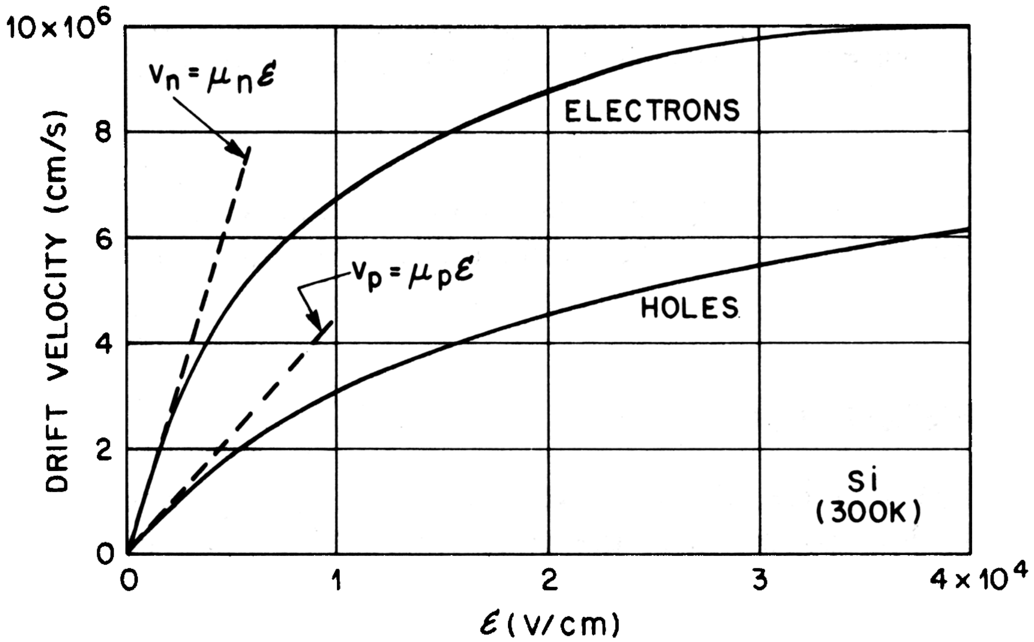
Semi-conductive detector (iii)

- Silicon detector:
  - Properties
    - Pair creation energy: $W_i = 3.69\, eV$
    - Mobility:

$$\mu_{(e,h)} = \frac{e}{2m_{(e,h)}} E \times \tau_{(e,h)}$$

E: electrical field

$\tau_{(e,h)}$: mean free time between 2 collisions (cf. gaseous detector)



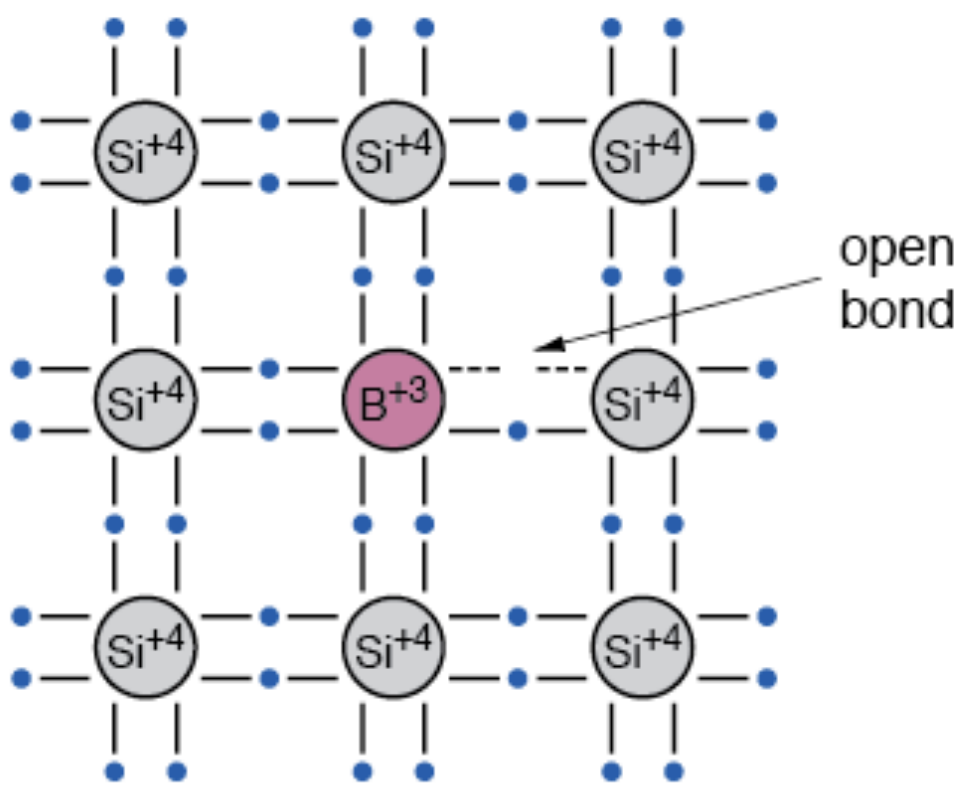
S.M. Suze, *Semiconductor Devices* , J. Wiley & Sons, 1985

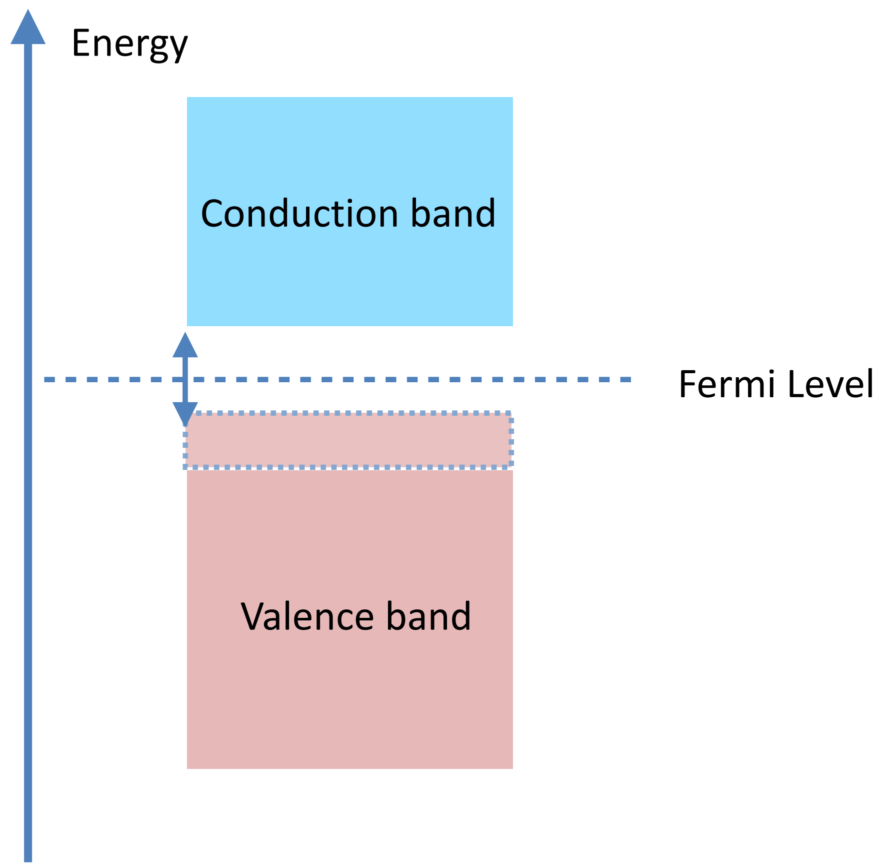
$$\mu_e(300K) \simeq 1450\, cm^2/V/s$$

$$\mu_h(300K) \simeq 450\, cm^2/V/s$$

Semi-conductive detector (iv)

- p-doping:
  - Doping 3 atom (e.g. B, Al, Ga, In). One valence bond remains open. This open bond attracts electrons from the neighbour atoms:

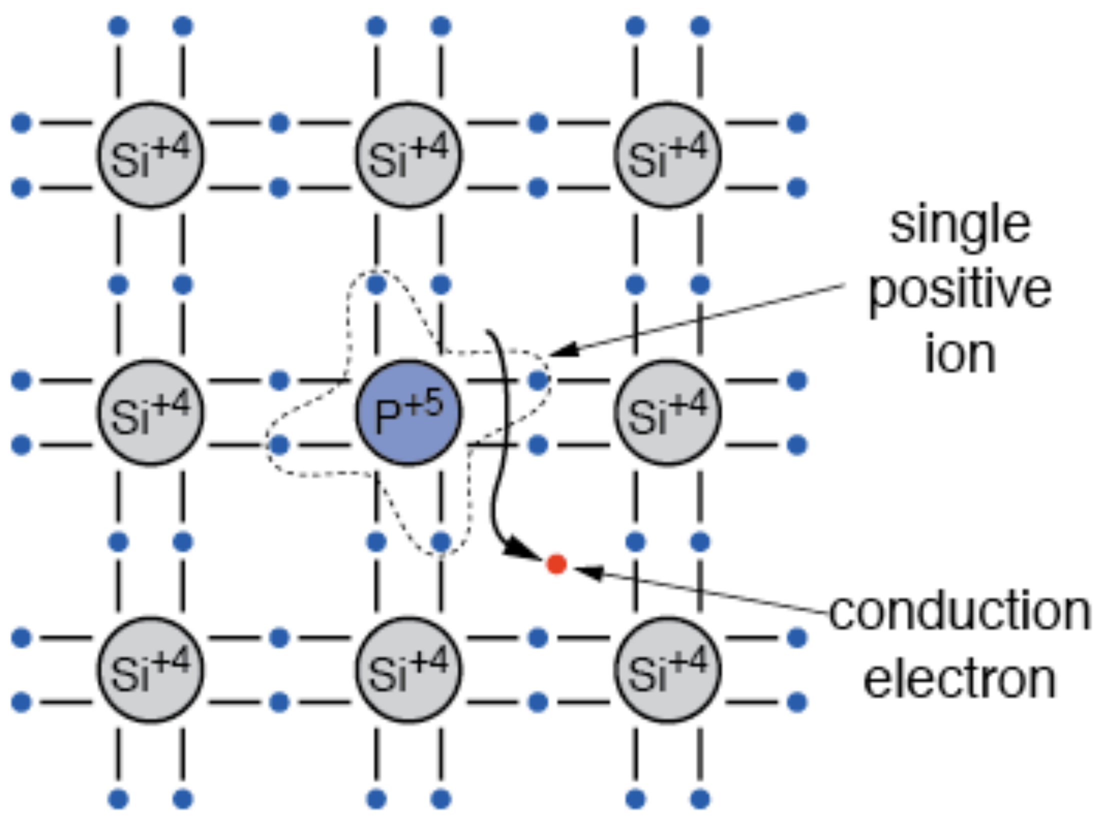


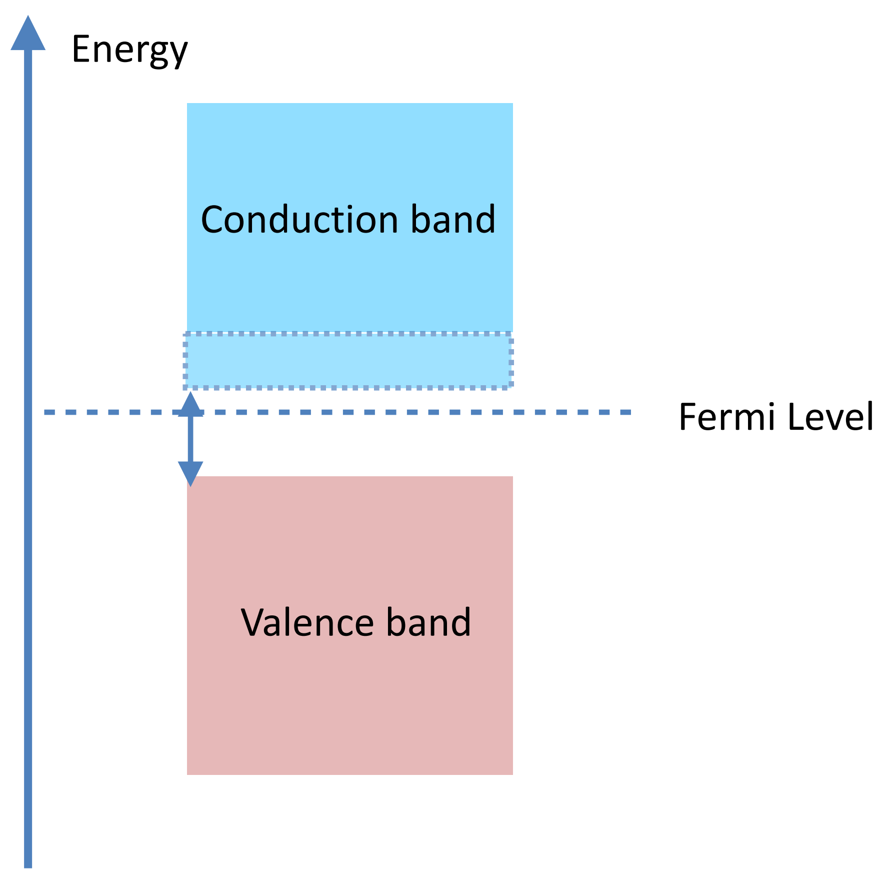


➡ Less electron density (acceptor of e)

Semi-conductive detector (v)

- n-doping:
  - Doping with 5 atom (e.g. P, As, Sb). The 5th valence electron is weakly bound:



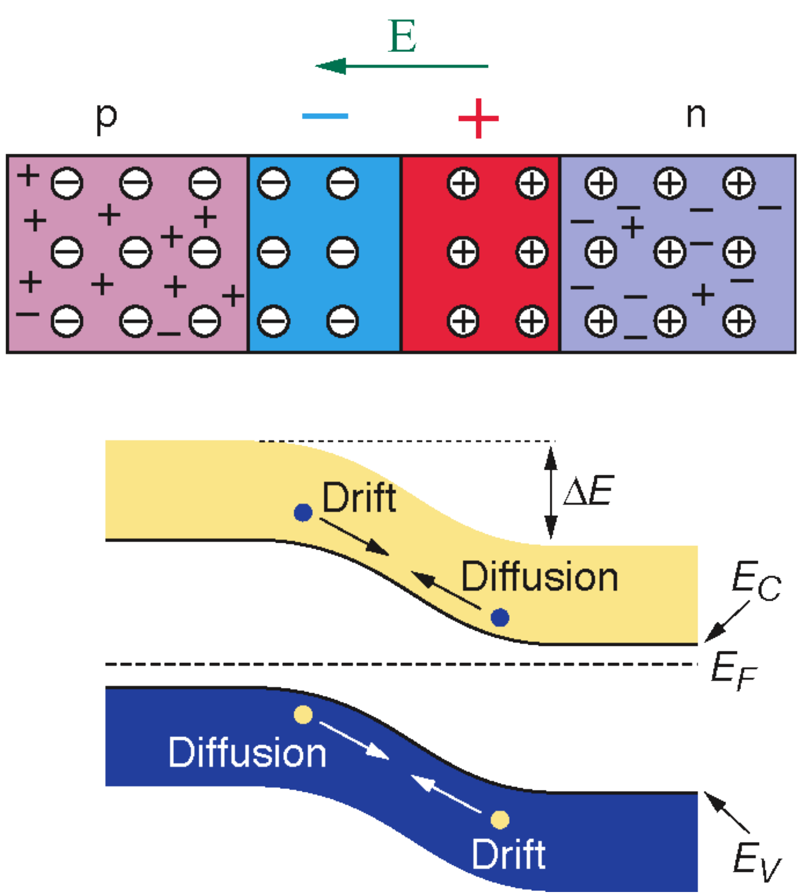


➡ Higher electron density (donor of e)

Semi-conductive detector (vi)

❑ The p-n junction

- At the interface of an n-type and p-type semiconductor:
  - Fermi level different: diffusion til ions space charge stops it
  - The stable space charge region is free of charge carries and is called the depletion zone



- Depletion width depend on electric field
  - Without external field:

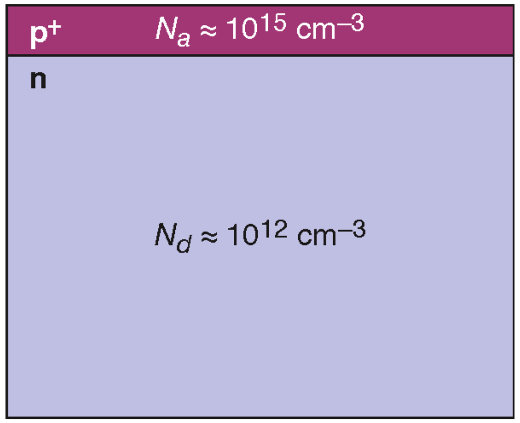
$$W_p = 0.02\,\mu m$$

$$W_n = 23\,\mu m$$

  - With external field:

$$W_p = 0.4\,\mu m$$

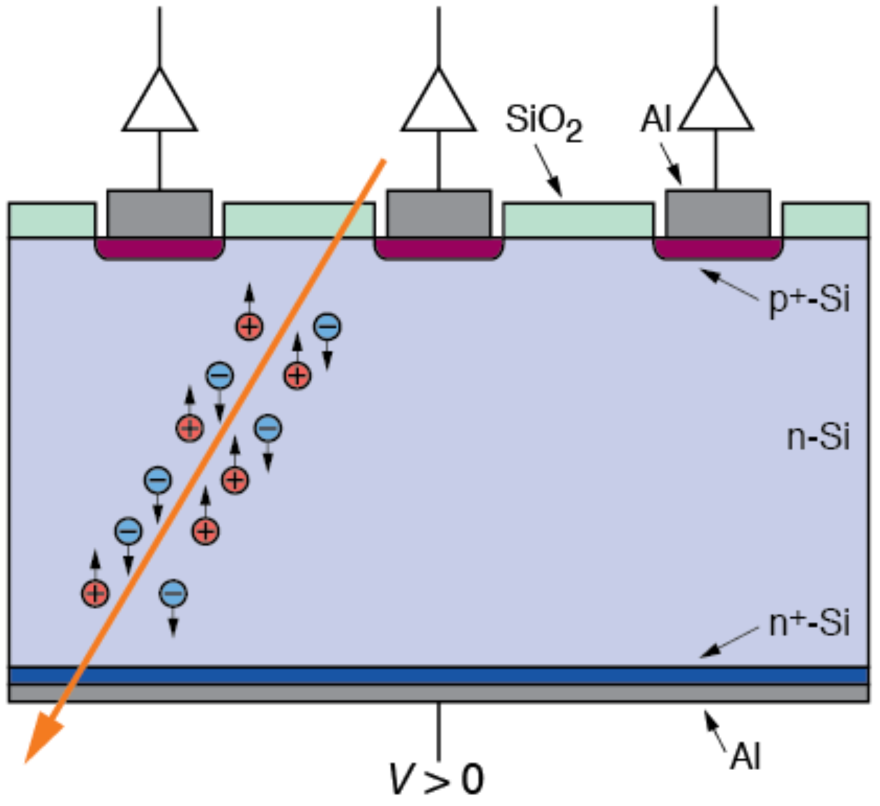
$$W_n = 360\,\mu m$$

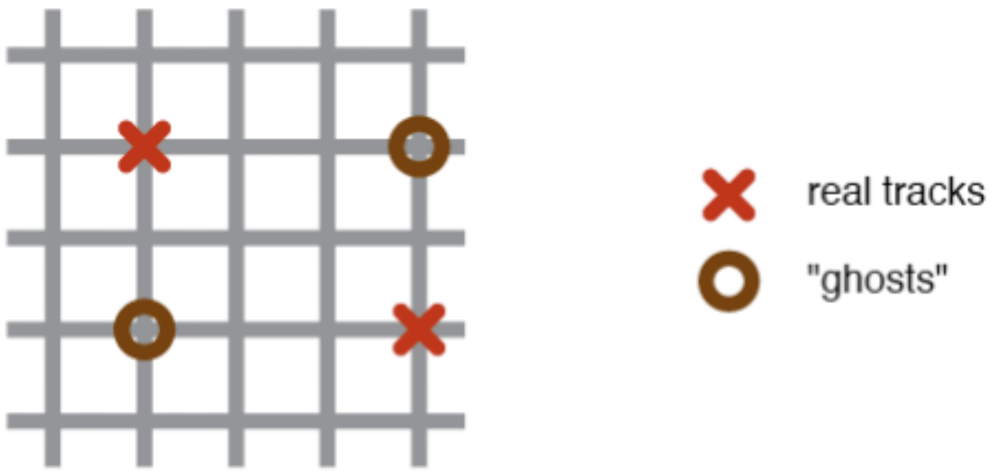


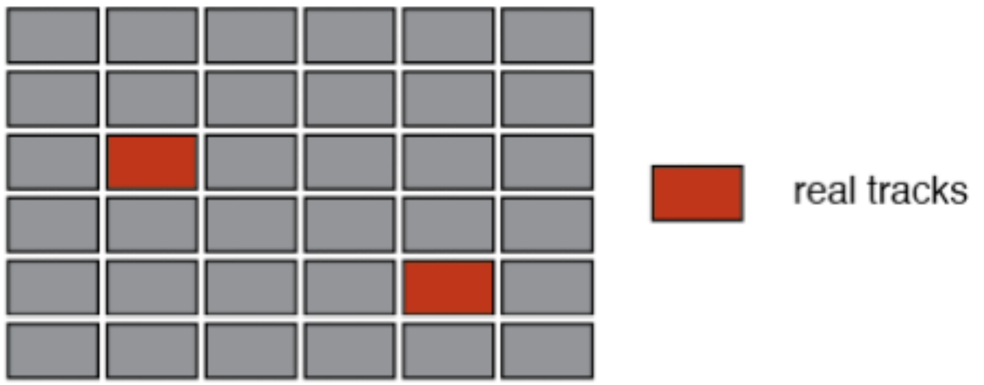
p+n junction

Semi-conductive detector (vii)

- p-n junction silicon detector
  - Impinging charged particles create e-h+ pairs in the depletion zone. These charges drift to the electrodes. The drift (current) creates the signal on each strip/pixel.
  - From fired strips/pixels possible position reconstruction.



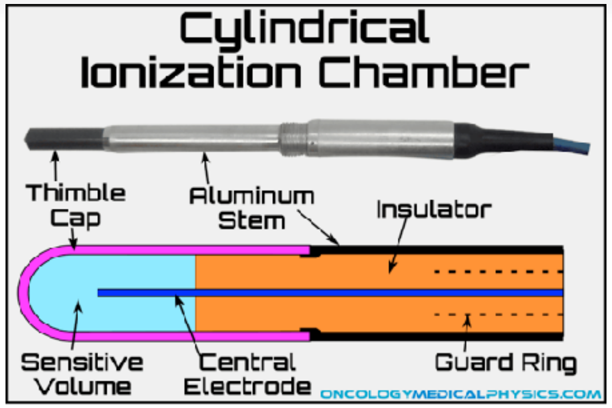


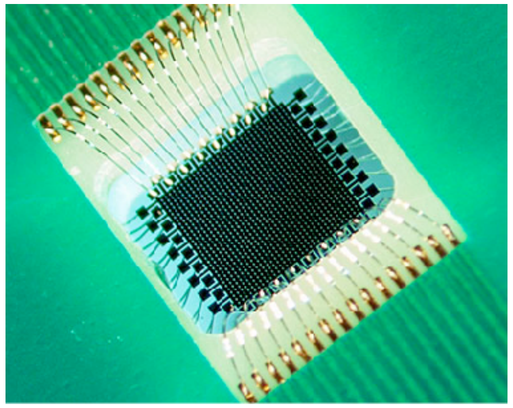


➡ Front/backend electronics mostly directly on the chip

Detectors for medical applications

- Beam monitoring:
  - Gaseous detectors
  - Semi-conductors





Detectors for medical applications

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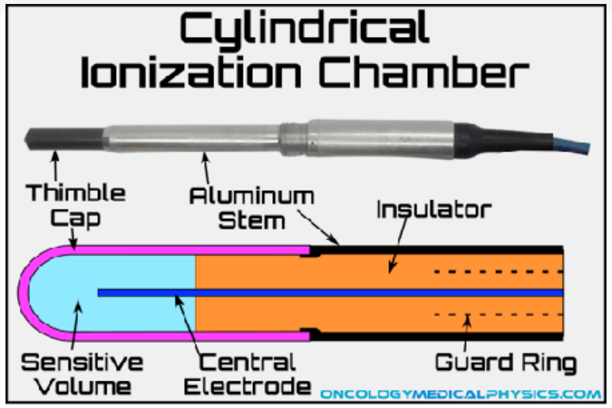
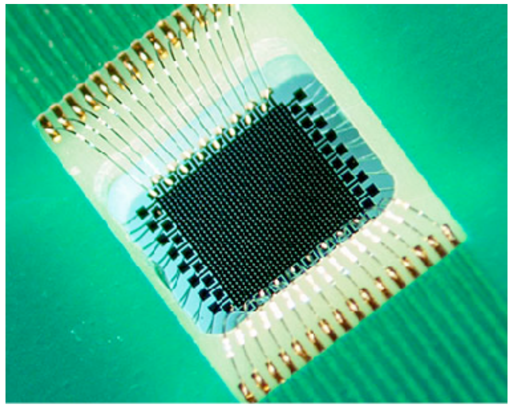
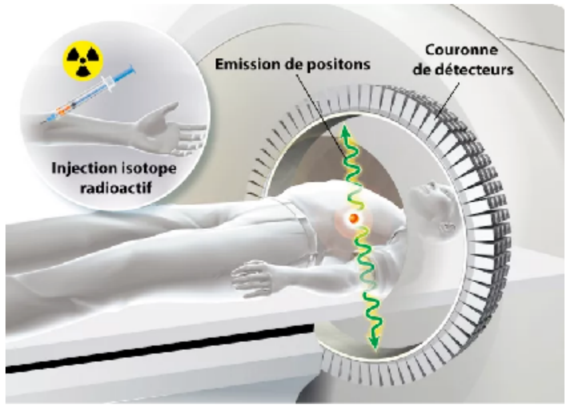




- PET-(SPECT)- pCT imaging:
  - Scintillators



Detectors for medical applications

❑ Beam monitoring:

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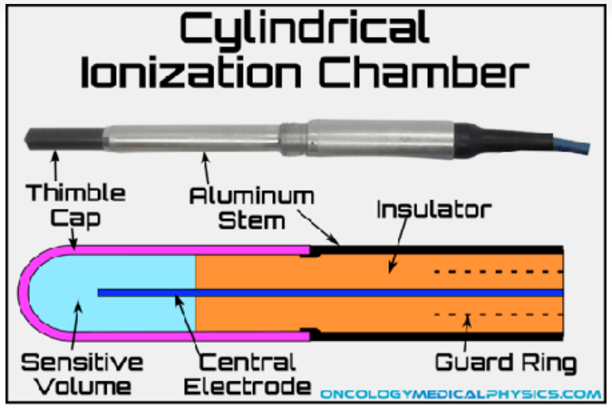

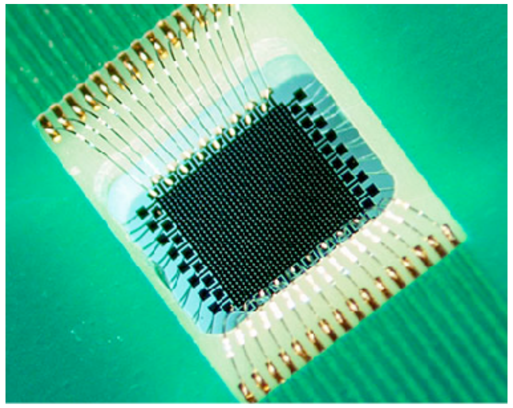

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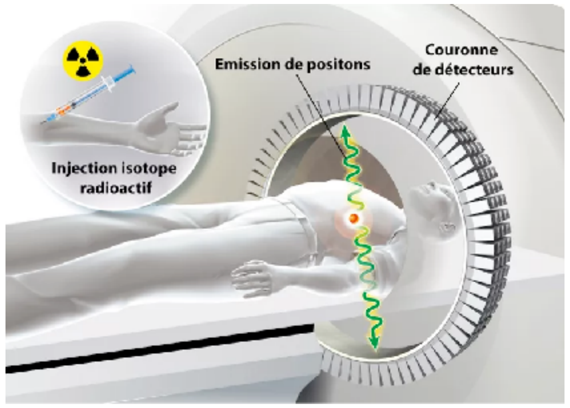
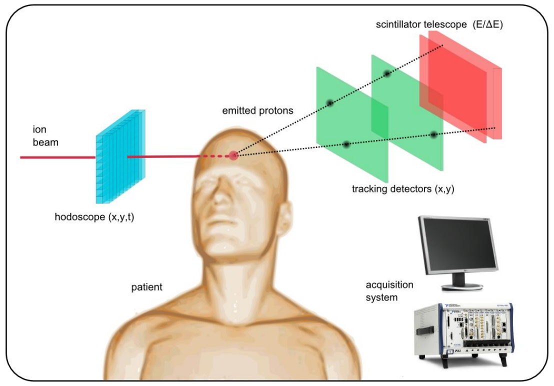
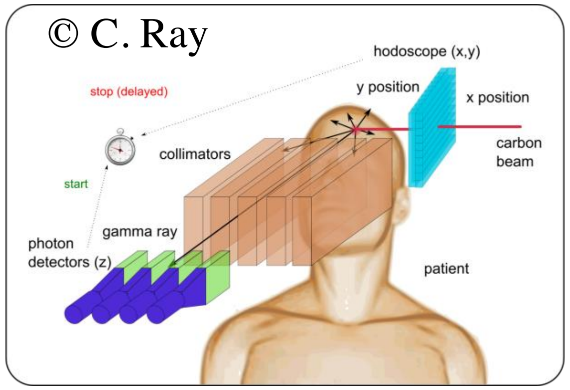


❑ Online dose control:

- Scintillators
- Silicon tracking devices





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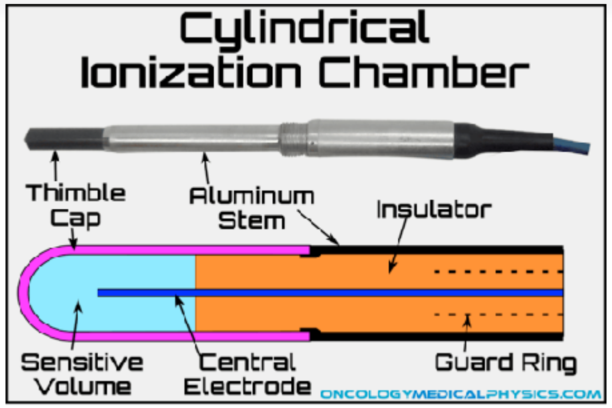

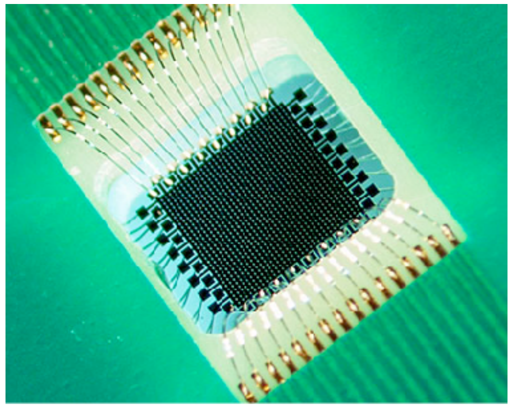

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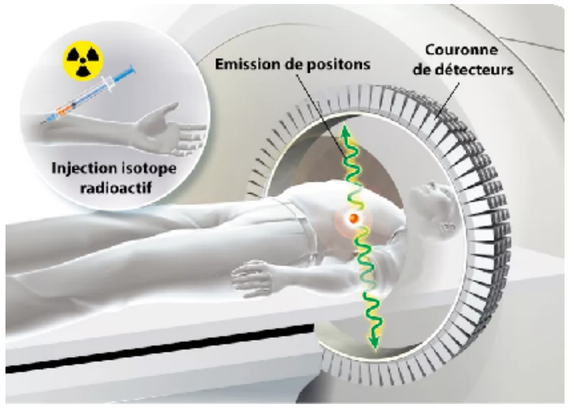

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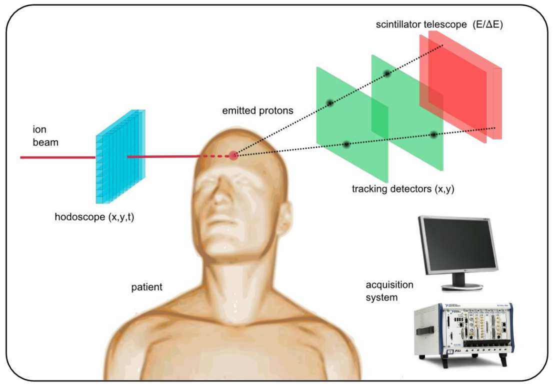
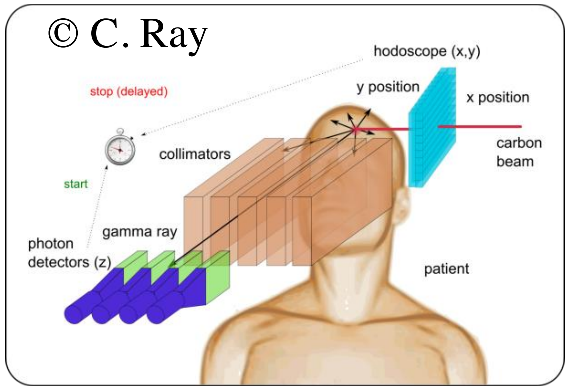
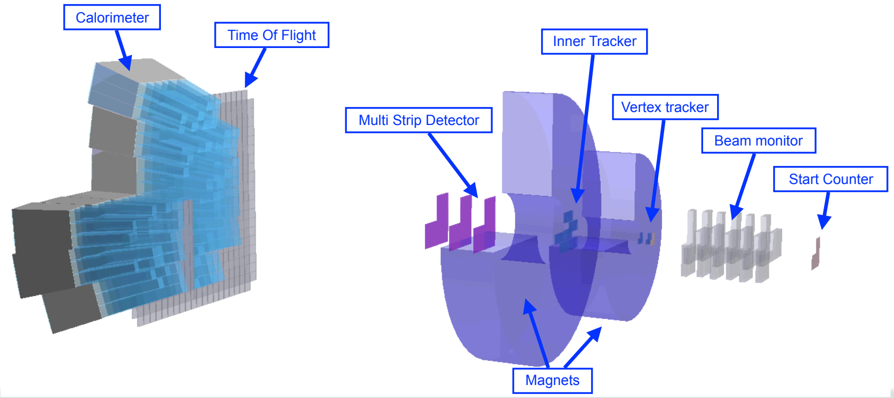




❑ Cross-section measurement:

- Scintillators (in-organic)
- Silicon tracking devices
- Gaseous detectors



Detectors for medical applications

❑ Beam monitoring:

- Gaseous detectors
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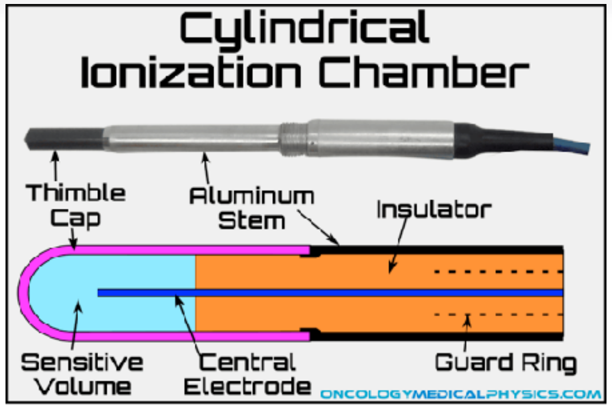

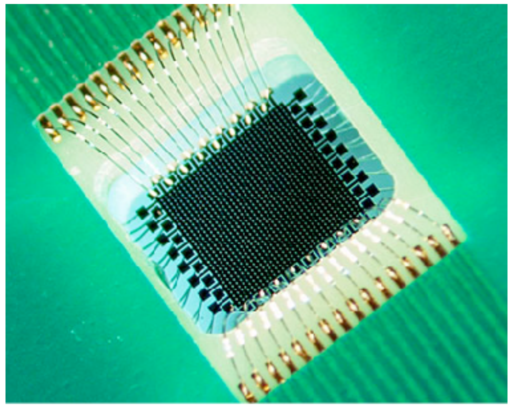

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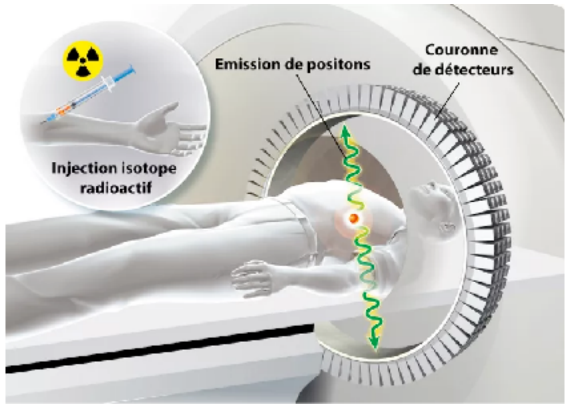

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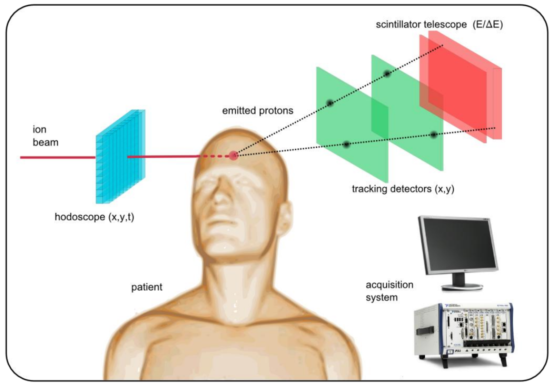

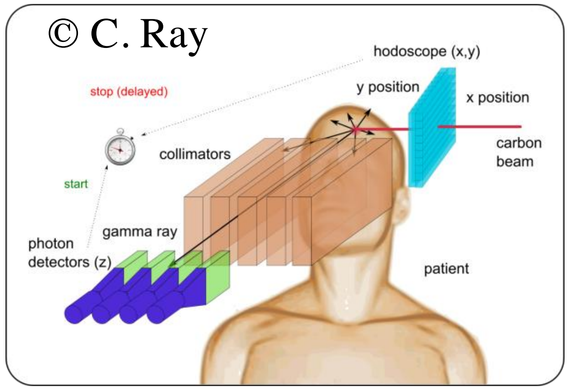

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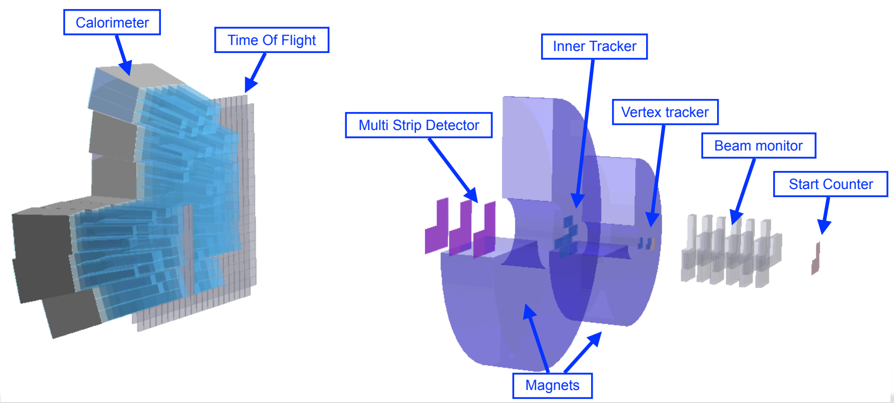


❑ Dosimetry:

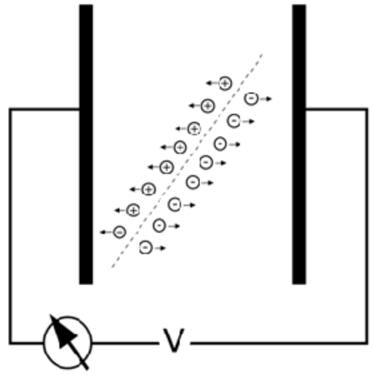
- Passive detectors
- Gaseous detectors
- Semi-conductors

Beam Monitoring (i)

- Gaseous detectors
  - Parallel plate Ionisation chamber
    - Gas at atmospheric (low) pressure
    - Applied HV ~ 100V
    - Simply read out a current

➡ Sustains high beam flux

➡ Need calibration



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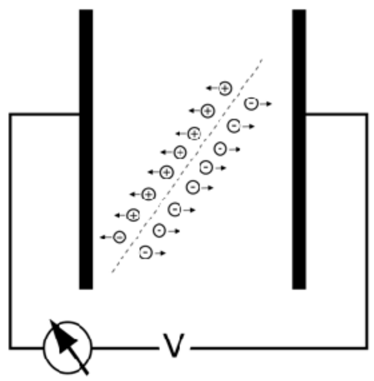
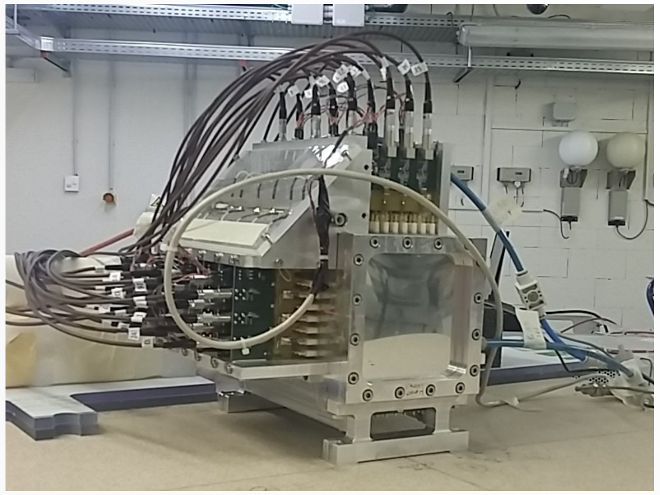
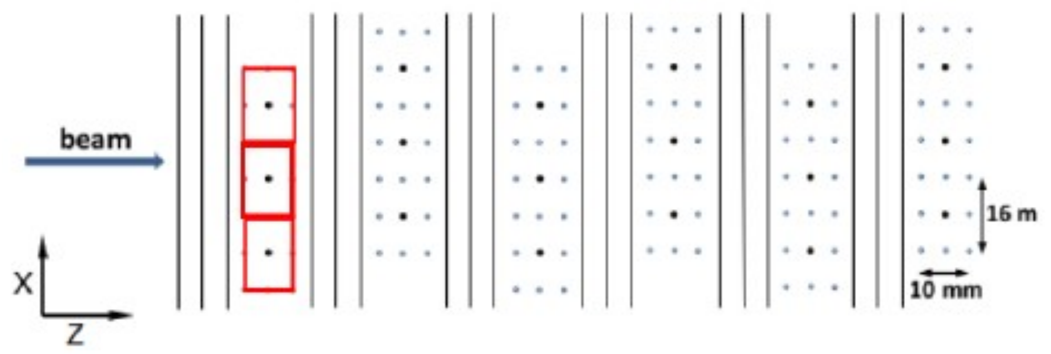




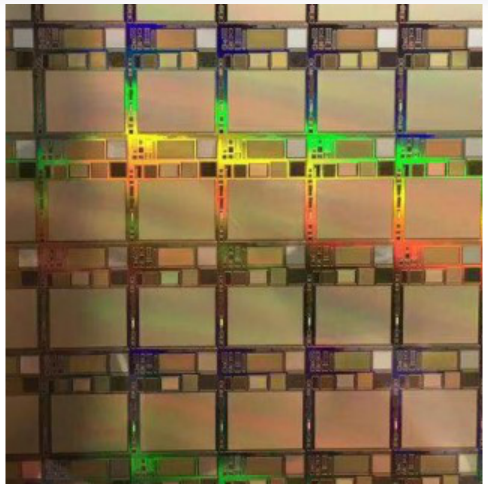
  - Drift chamber
    - Field wire at HV potential (~1-2kV)
    - Sense wire to read out the charge

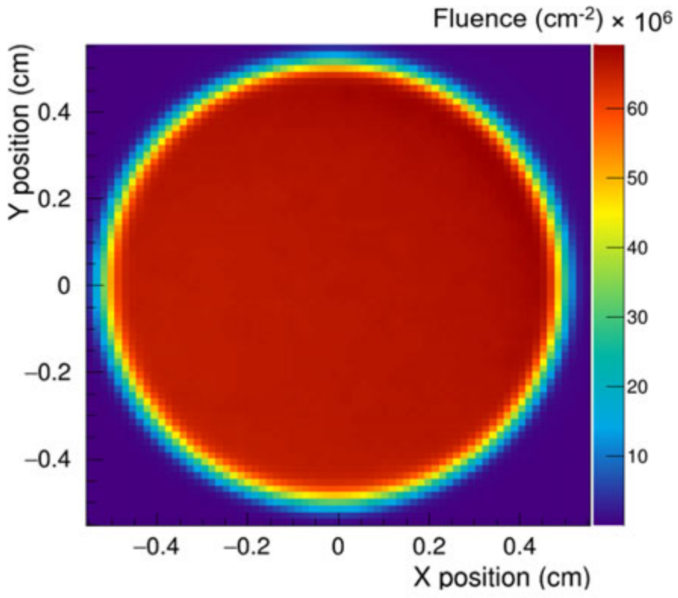


    - Gas mixture Ar+Iso/CO_2 (10-20%)
    - Beam profile resolution ~100-200 μm
    - ➡ Limited by beam flux ($\ll 10^4/cm^2/s$)
    - ➡ Need calibration for drift velocity

Beam Monitoring (ii)

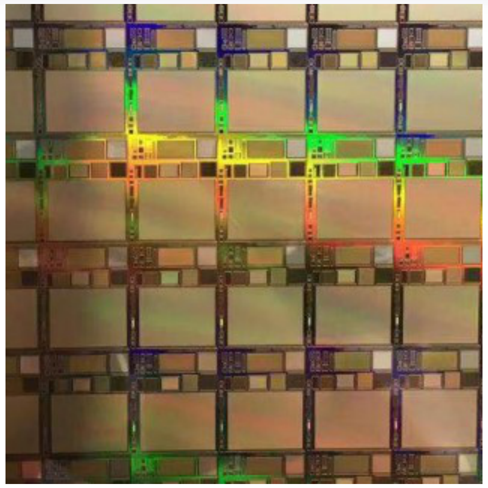
- Semi-conductors
  - Silicon detector
    - Bulk, strip or pixels
    - Good radiation tolerance
    - ➡ Charge resolution ~ 3-4%
    - ➡ Excellent beam profile resolution ($\ll 100\,\mu m$)
    - ➡ Limited beam flux tolerance ($\ll 10^7/cm^2/s$)

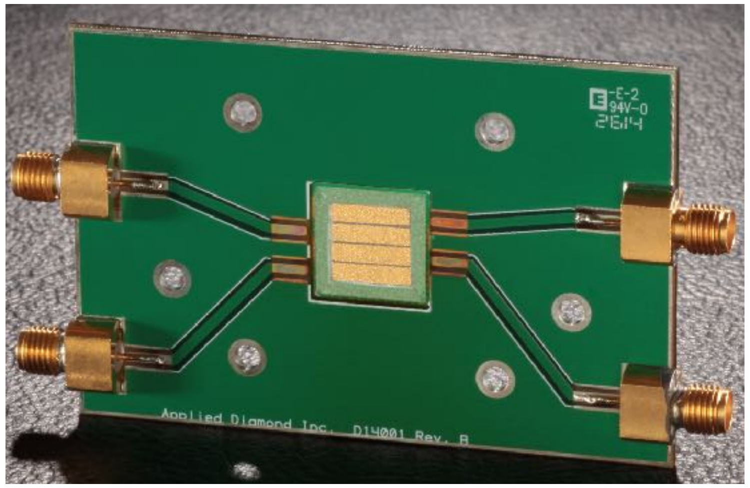




Beam Monitoring (ii)

- Semi-conductors





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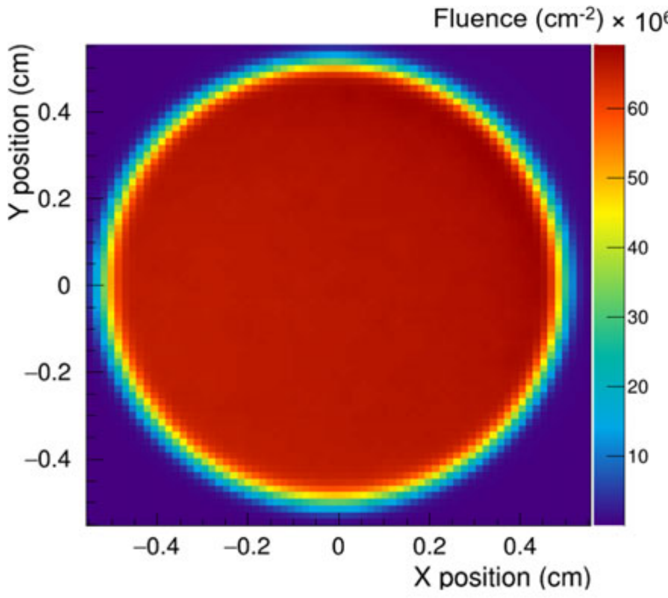

- Diamond detector
  - Wide-bandgap (low noise)
  - Very good radiation tolerance
  - Fast time response (< 2 ns)
  - ➡ Excellent beam profile resolution ($\ll 100\,\mu m$)
  - ➡ Good beam flux tolerance ($\sim (10^9 - 10^{12})/cm^2/s$)

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    - Bulk, strip or pixels
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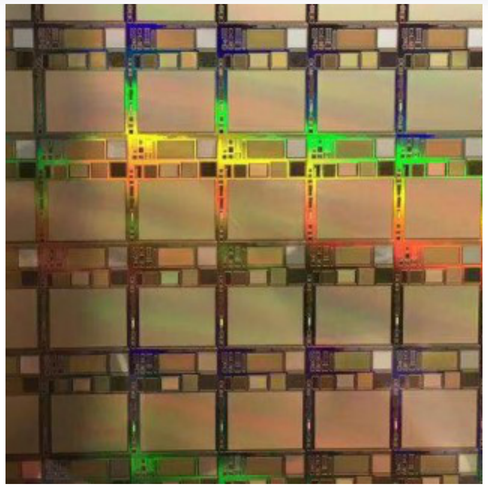

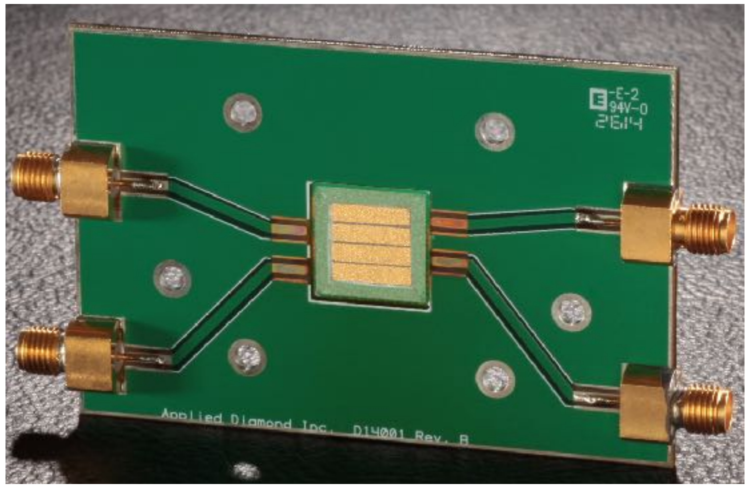

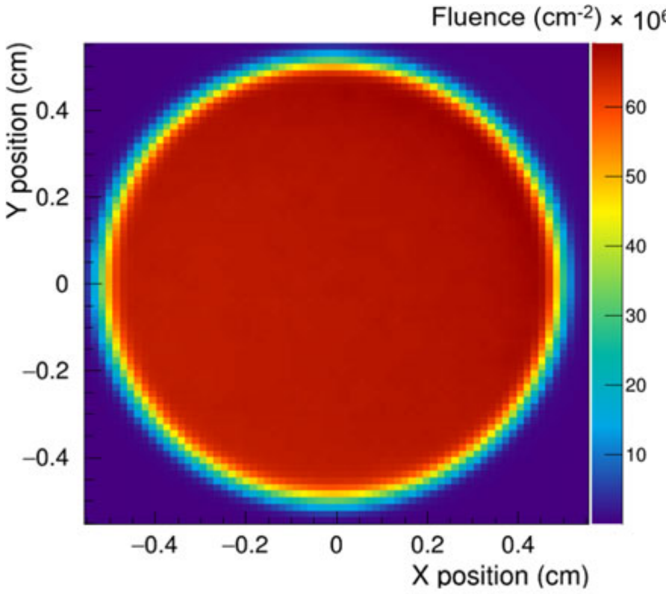

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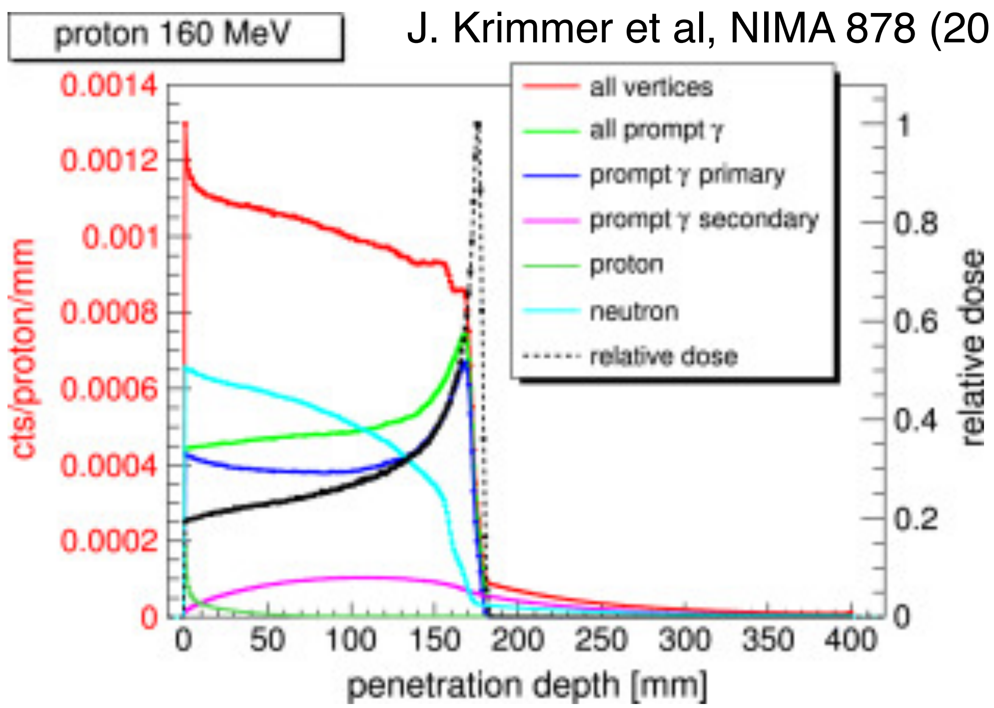
➡ Also other detectors exist: PEPITES, FastPix, micromegas, GEM, plastic, fibres, etc….

Online dose control (i)

- Mostly three techniques used, correlation btw Bragg preak and nuclear reactions
  - Prompt gamma method reconstruction

J. Krimmer et al, NIMA 878 (2018)



S. Jan et al., IEEE (2012)

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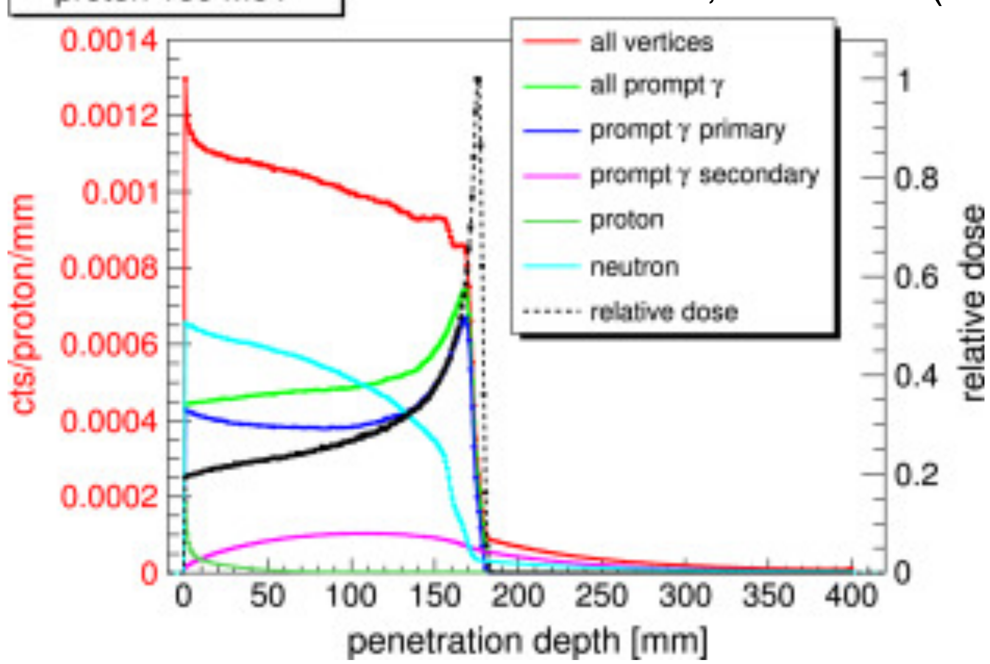

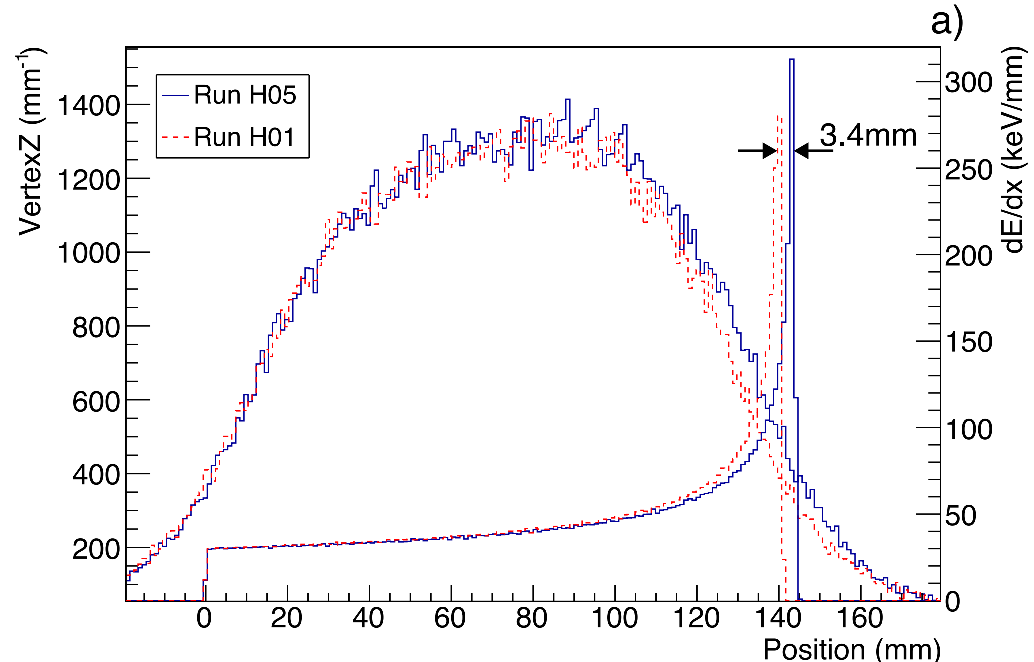

Ch. Finck et al, PMB 62 (2017)

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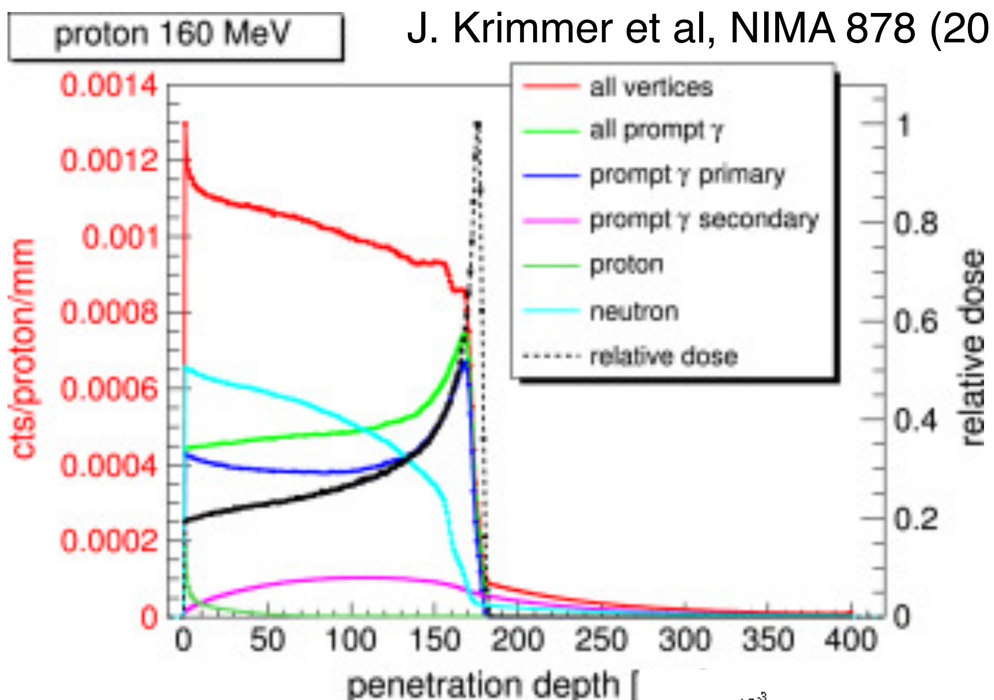
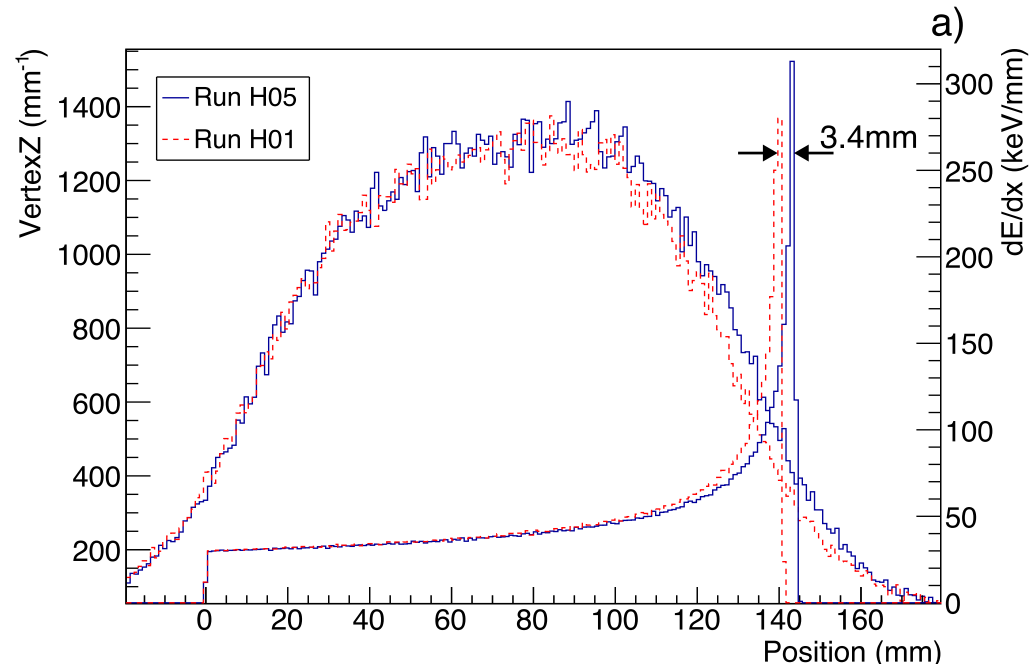
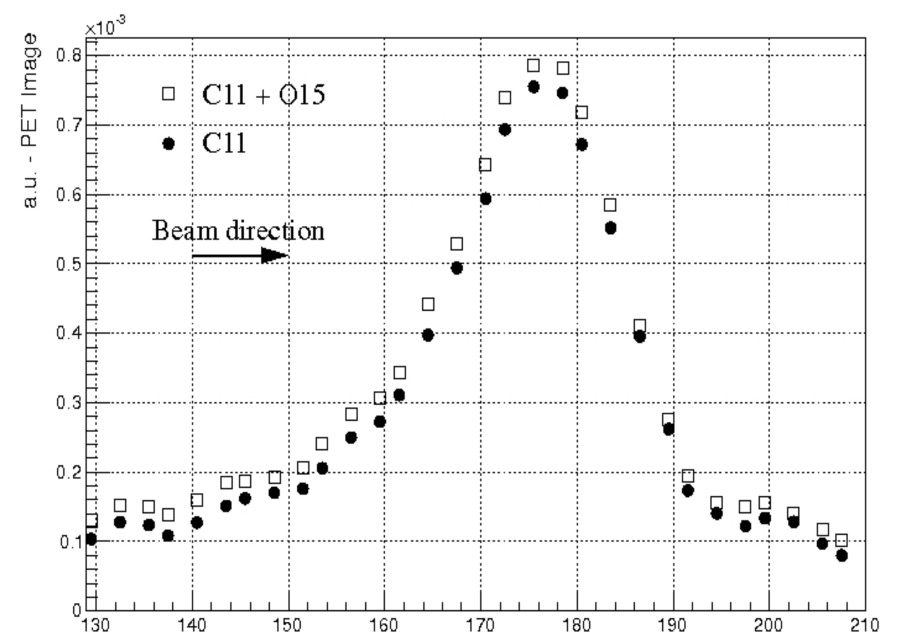


J. Krimmer et al, NIMA 878 (2018)



Ch. Finck et al, PMB 62 (2017)

- Inline PET reconstruction



S. Jan et al., IEEE (2012)

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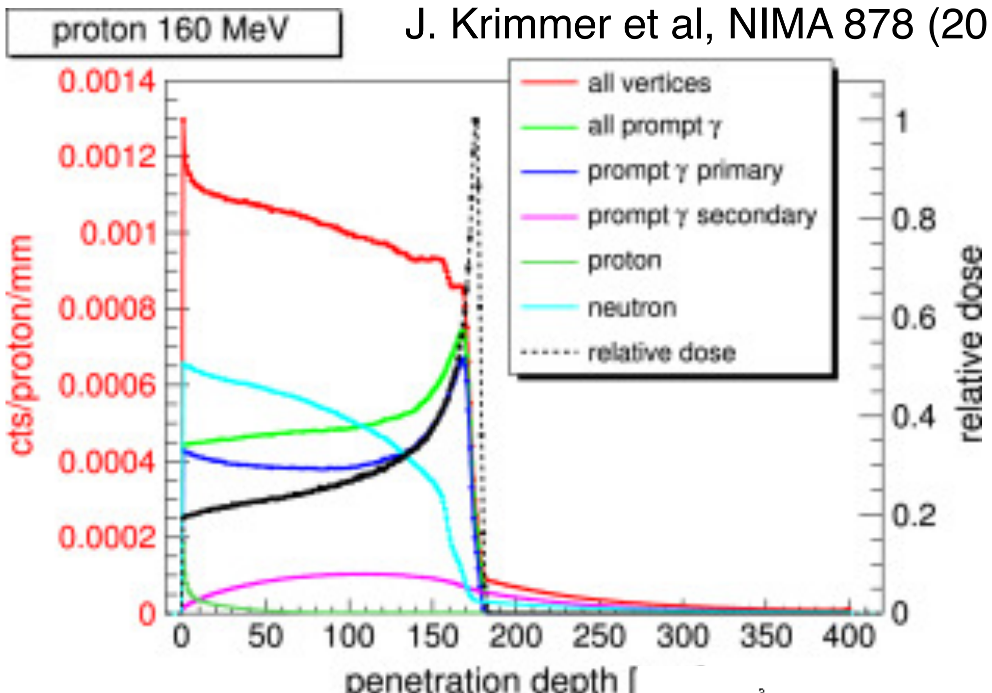
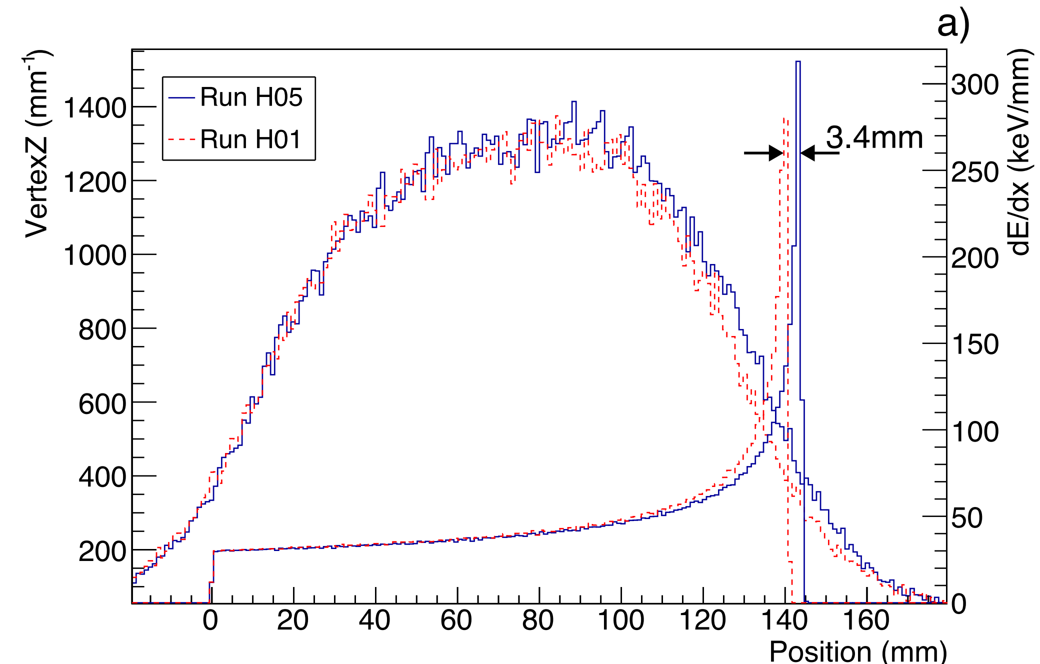


J. Krimmer et al, NIMA 878 (2018)

  - Secondary particle vertex reconstruction



Ch. Finck et al, PMB 62 (2017)

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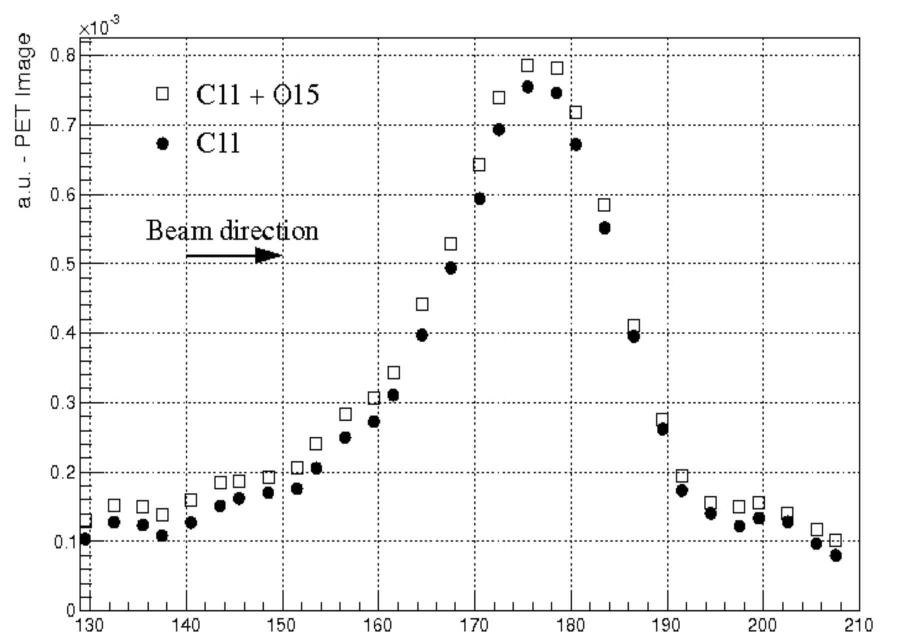
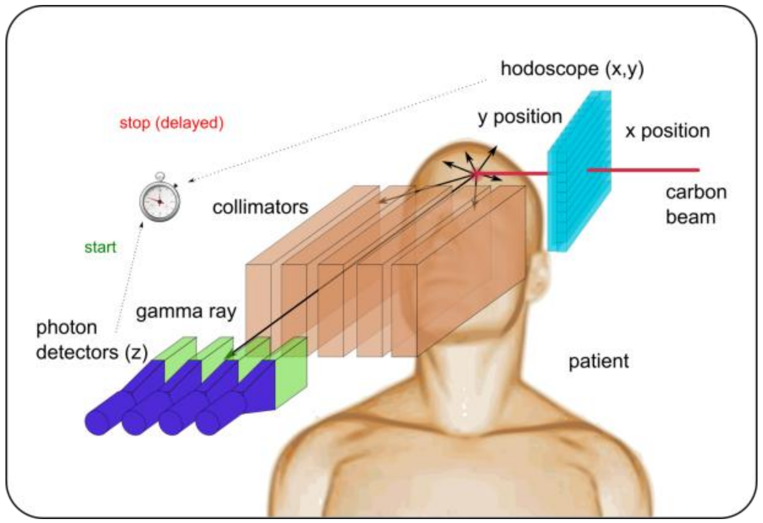


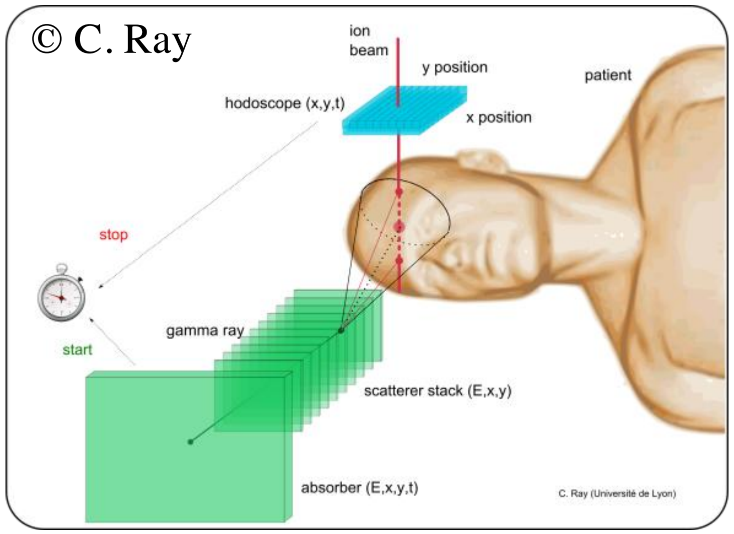
S. Jan et al., IEEE (2012)

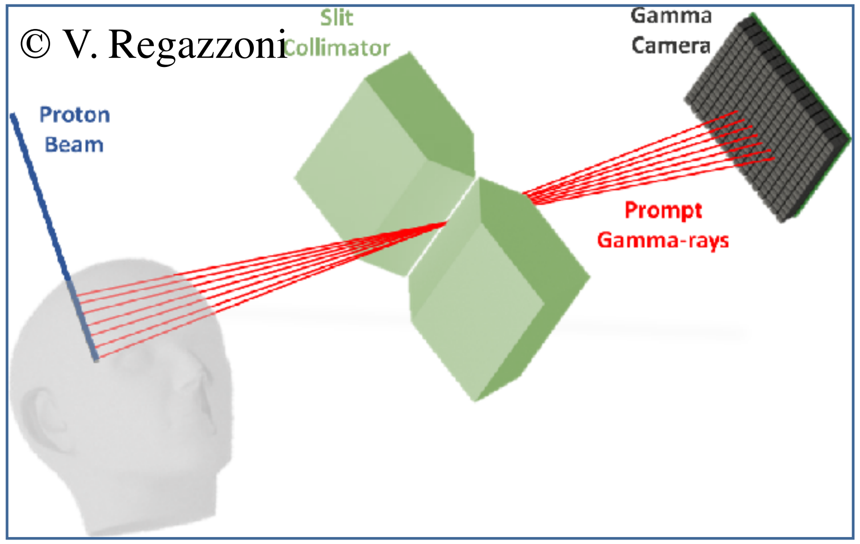
➡ Tag the Bragg peak at best ≳ 1 mm

Online dose control (ii)

- Prompt gamma method reconstruction
  - Collimated, slitted devices or Compton camera







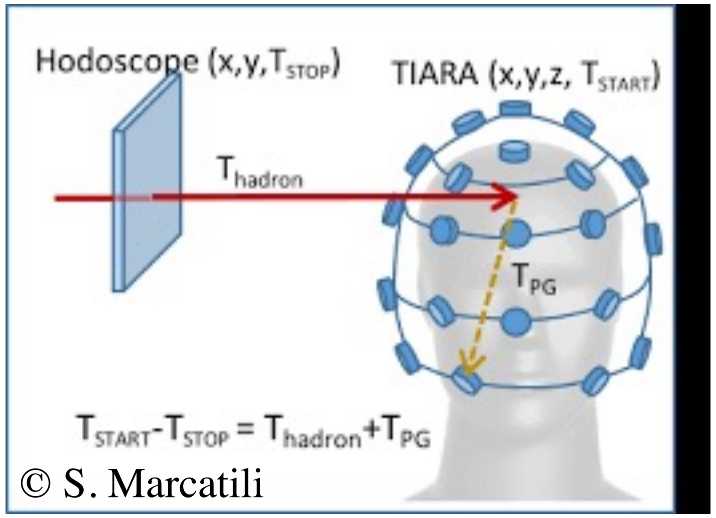
➡ Since low statistics need efficient crystal

➡ Fast time response if time gating

➡ Good energy resolution if ray tagging

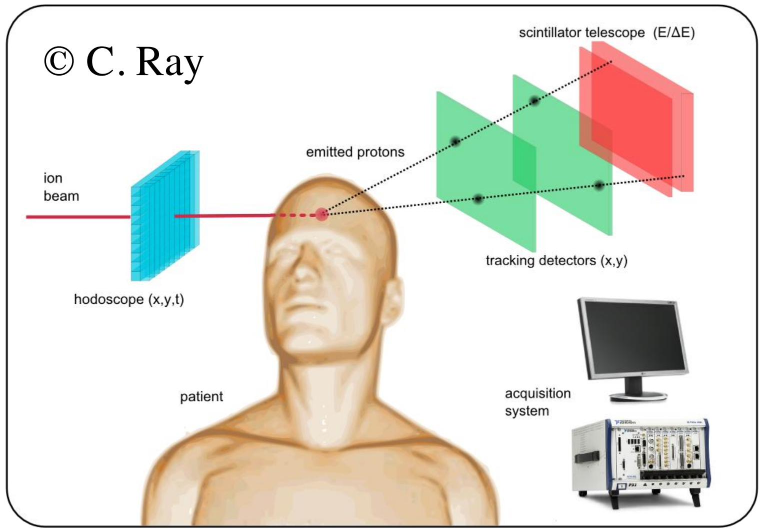
➡ Mostly used: NaI, LYSO, most recently PbF_2

➡ good comprise btw properties and prices



Online dose control (iii)

- Secondary particle vertex reconstruction
  - Using silicon tracking device to reconstruct vertices



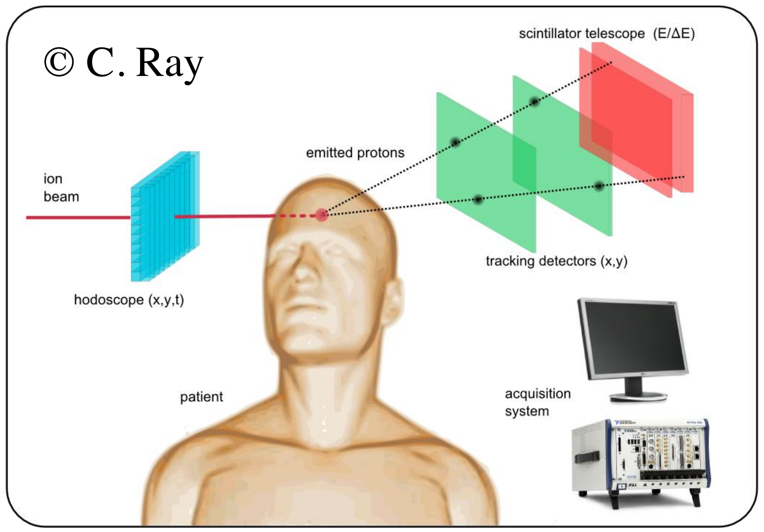
➡ Since low statistics need efficient sensor

➡ Good spatial resolution

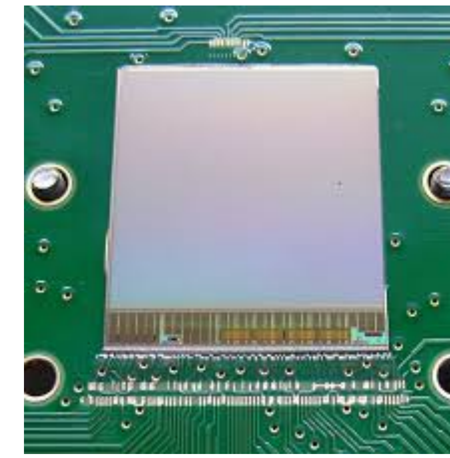
➡ Pixelised silicon detector

Online dose control (iii)

- Secondary particle vertex reconstruction
  - Using silicon tracking device to reconstruct vertices



- Example M28
  - Area 2x2 cm²
  - 1 Mpixels
  - Efficiency > 99 %
  - Spatial resolution $\ll 10\,\mu m$



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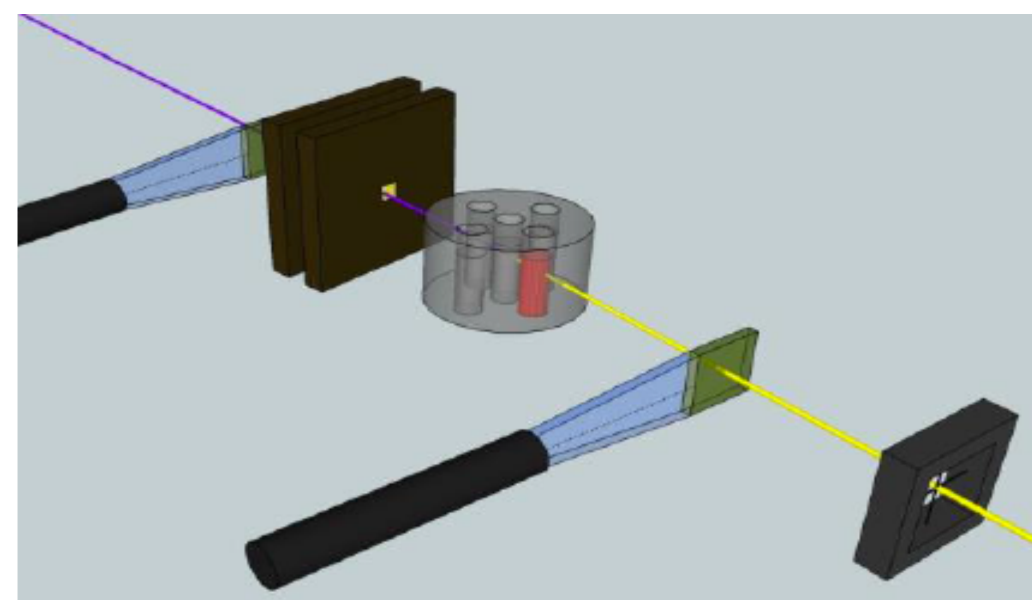
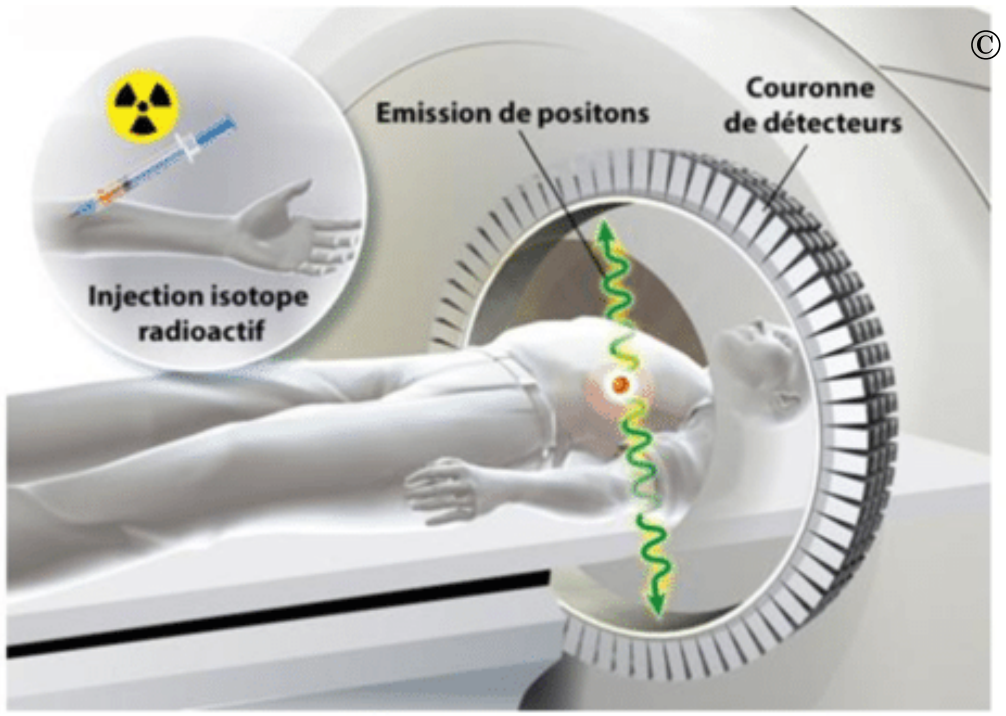


Online dose control/PET-Imaging

- Inline (offline) Positron Emission Tomography reconstruction
  - Using the 511 keV γ-rays from annihilation β-decay with medium



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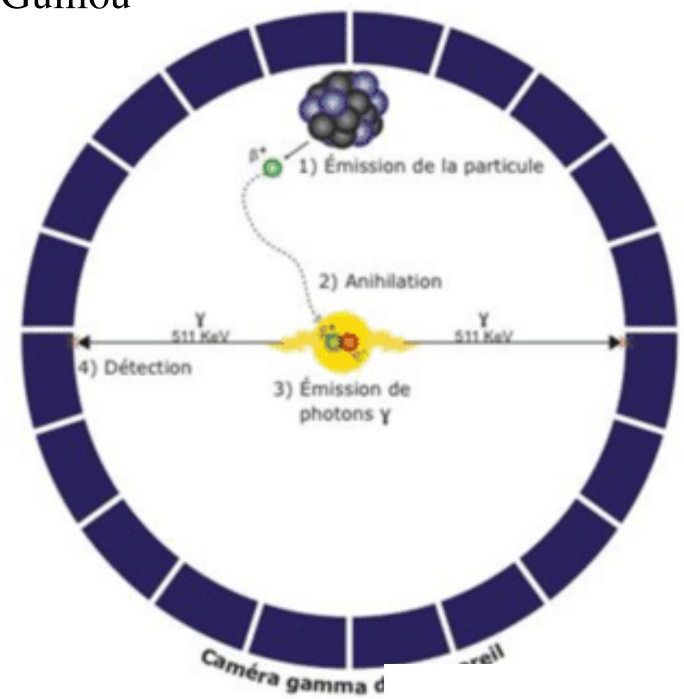
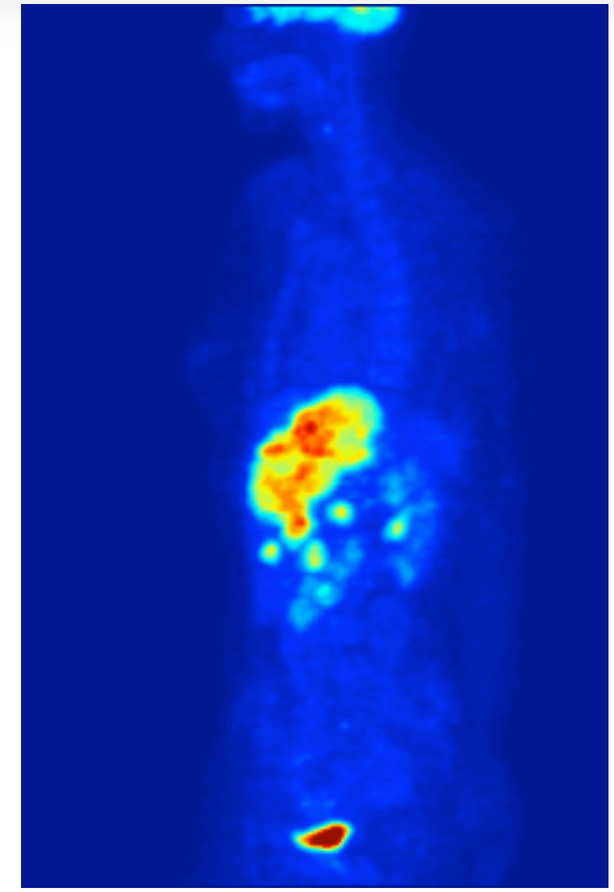
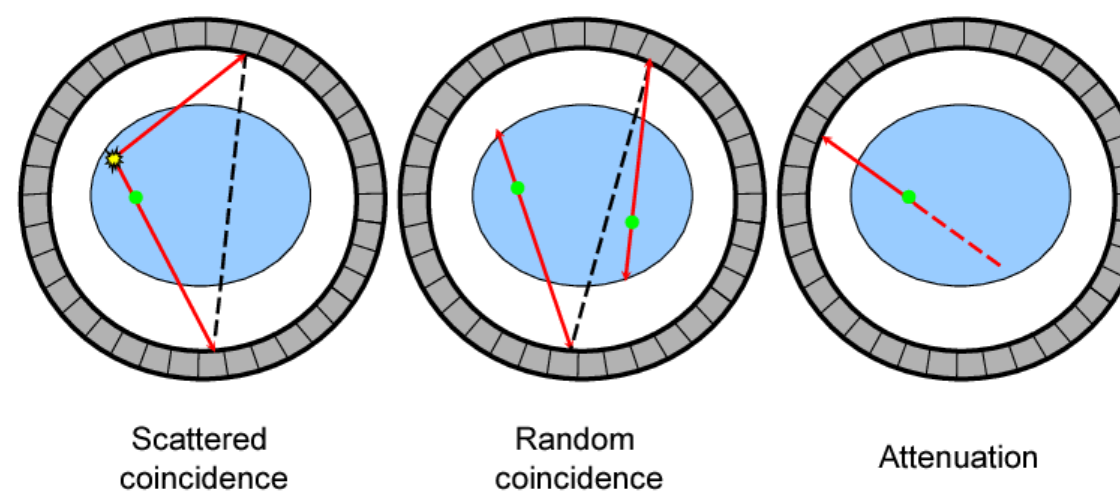




- Need to reconstruct the road of the two γ-rays
- Good timing resolution to avoid false reconstruction
- Wash out phenomena
- Need a 3D reconstruct (could take time)



➡Mostly used: LYSO, good comprise btw properties and prices

pCT-Imaging

- Proton(carbon)-computed tomography
  - Using same particle for treatment and imaging (avoid conversion)

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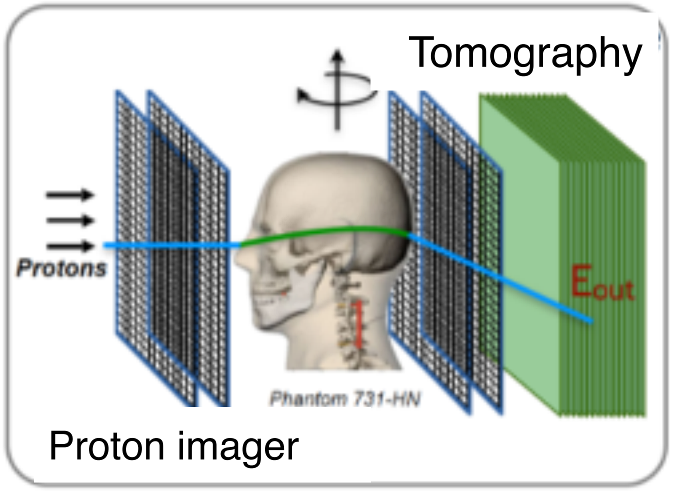
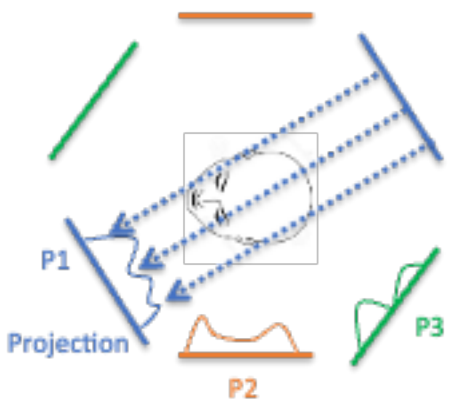
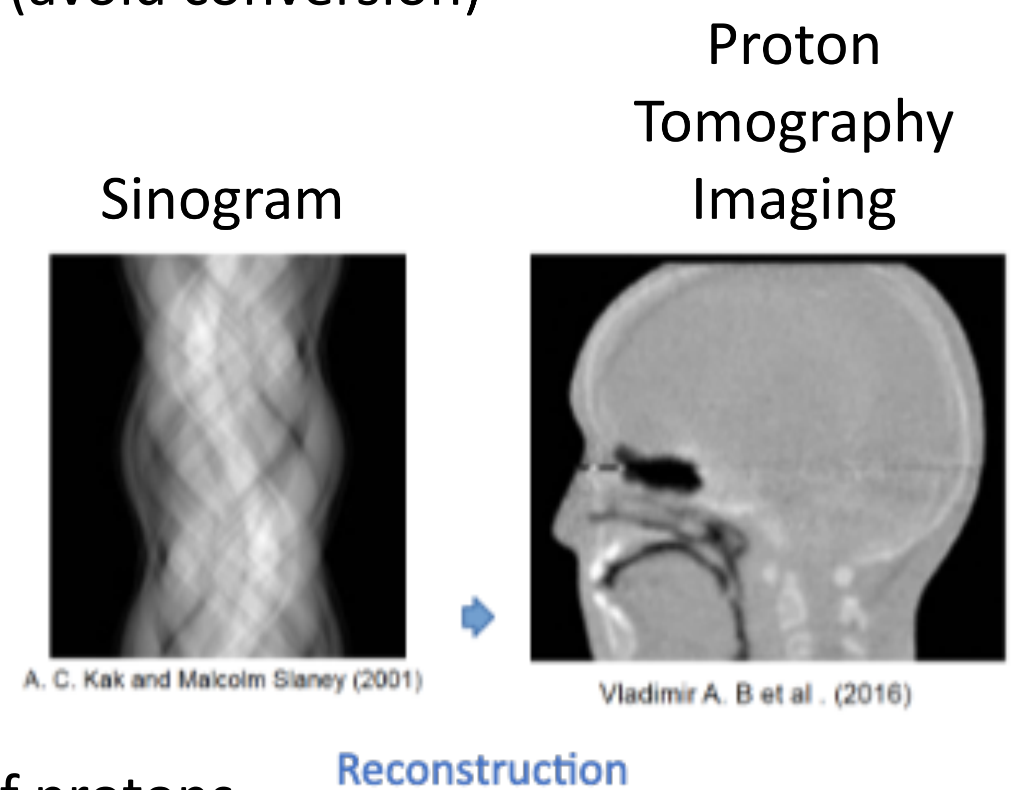




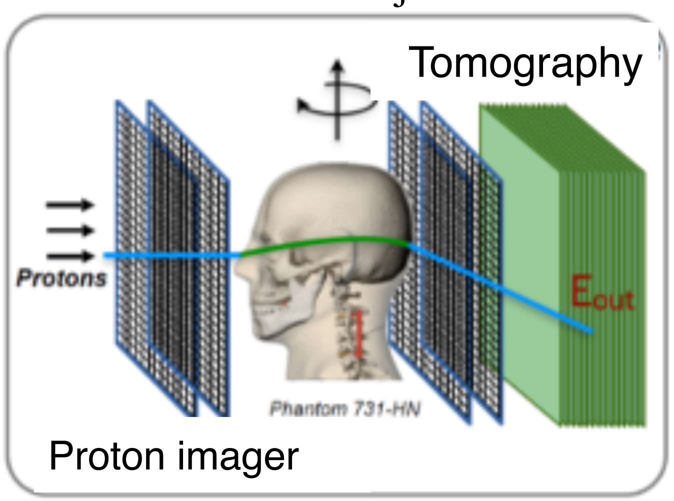


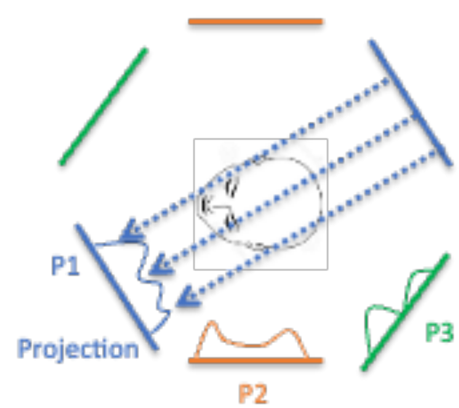
- Need to reconstruct the most probable part of protons
  - ➡ Fast tracking system
  - ➡ Good resolution on energy or path

pCT-Imaging

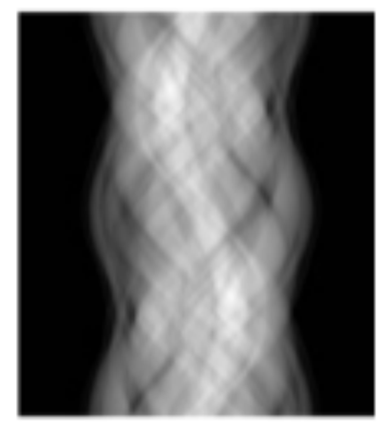
- Proton(carbon)-computed tomography
  - Using same particle for treatment and imaging (avoid conversion)

© Y. Karakaja





Sinogram



A. C. Kak and Malcolm Slaney (2001)

Proton Tomography Imaging

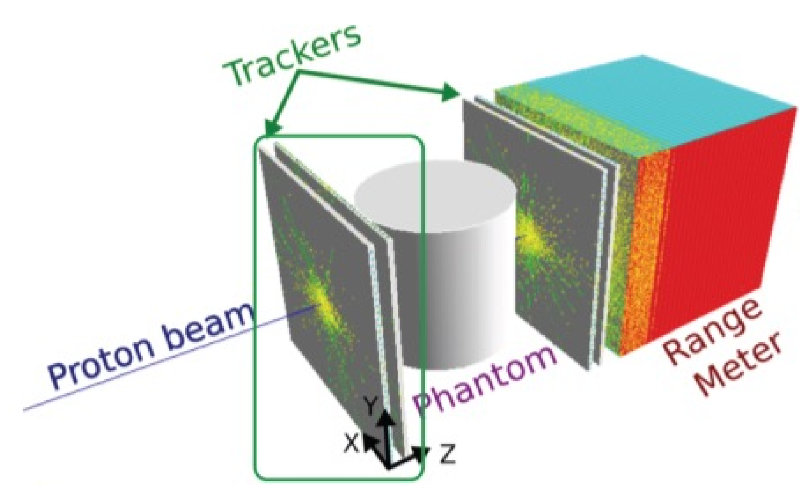
Vladimir A. B et al . (2016)

Reconstruction

- Need to reconstruct the most probable part of protons
  - ➡ Fast tracking system
  - ➡ Good resolution on energy or path

➡ Mostly proposed:

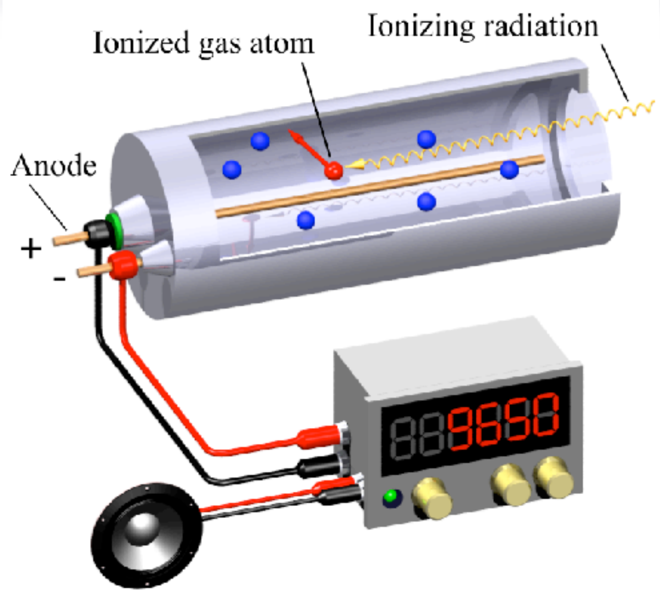
- Tracking: Scintillating fibers diameter < 1 mm
- Residuals: (stack of) scintillators for energy or range-meter



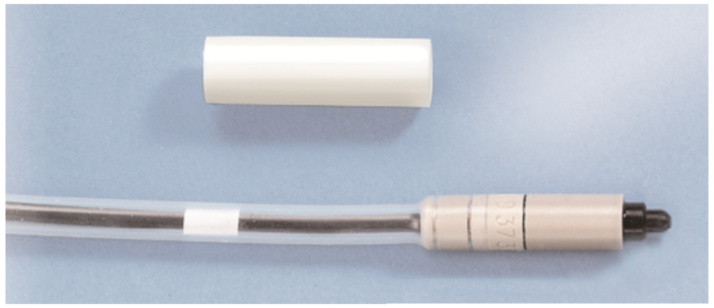
Geant4 simulation

Dosimetry

- Using different type of detector for different purpose
  - Geiger-Müller counter
    - Simple ionisation wired tube
    - Count number of interaction (wide range in energy/particle)

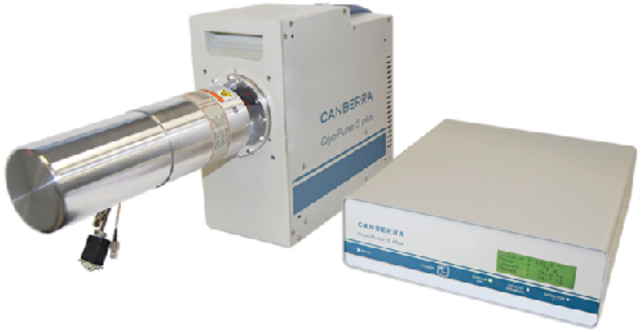


  - Ionisation chamber (see before)
    - Give an good dose measurement
    - Wide dynamic range



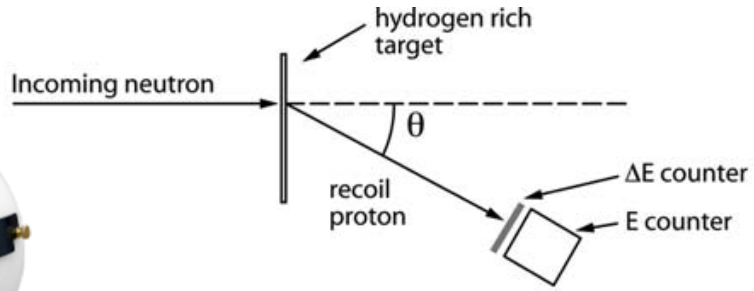
  - Etc…

  - Semi-conductors
    - Use for γ-spectroscopy (isotope identification)
    - Accurate energy resolution



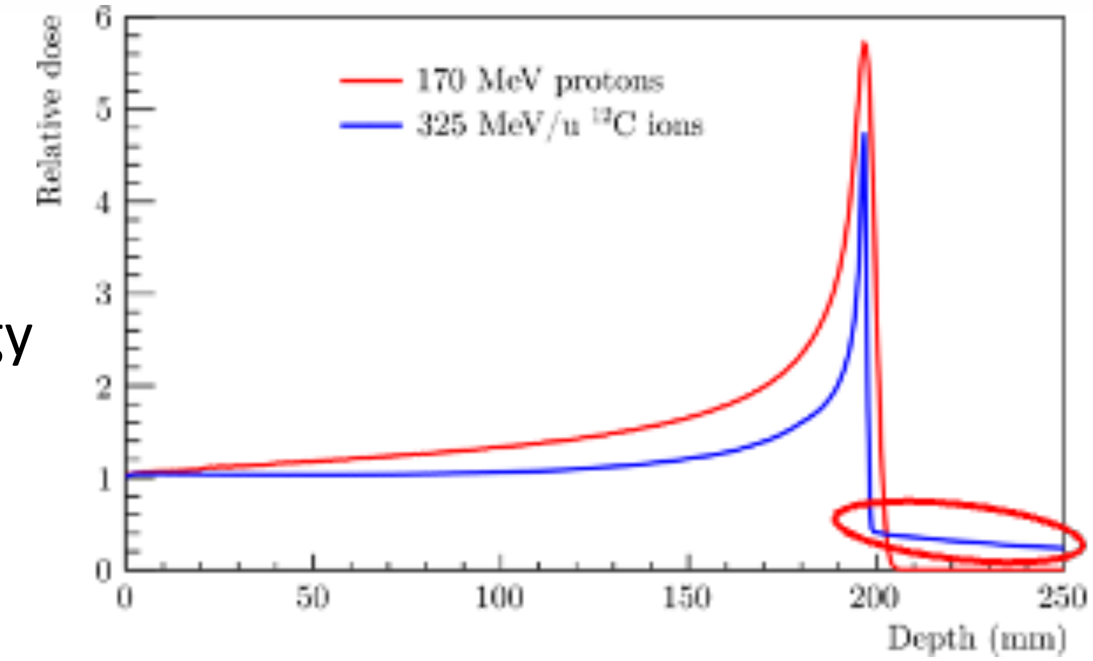
  - Proton recoiled neutron detector
    - Using a converter (hydrogenated)
    - Detect the proton to reconstructed neutron properties:

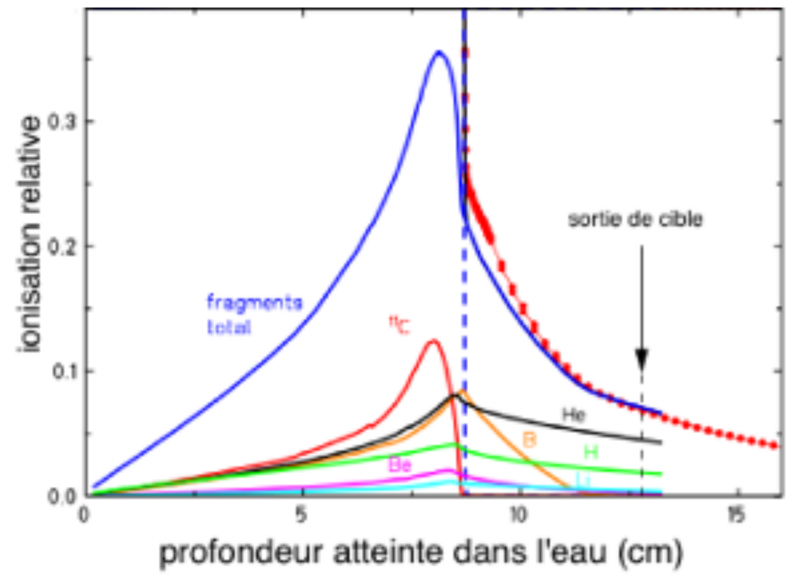
$$E_n = E_p / cos^2(\theta)$$



Cross-section measurement (i)

- Nuclear reactions during hadrontherapy (^{12}C and ^{16}C)
  - During treatment ~50% of beam loss due to reactions
  - Extra dose after Bragg peak
  - Need to measure cross-section as function of angle/energy





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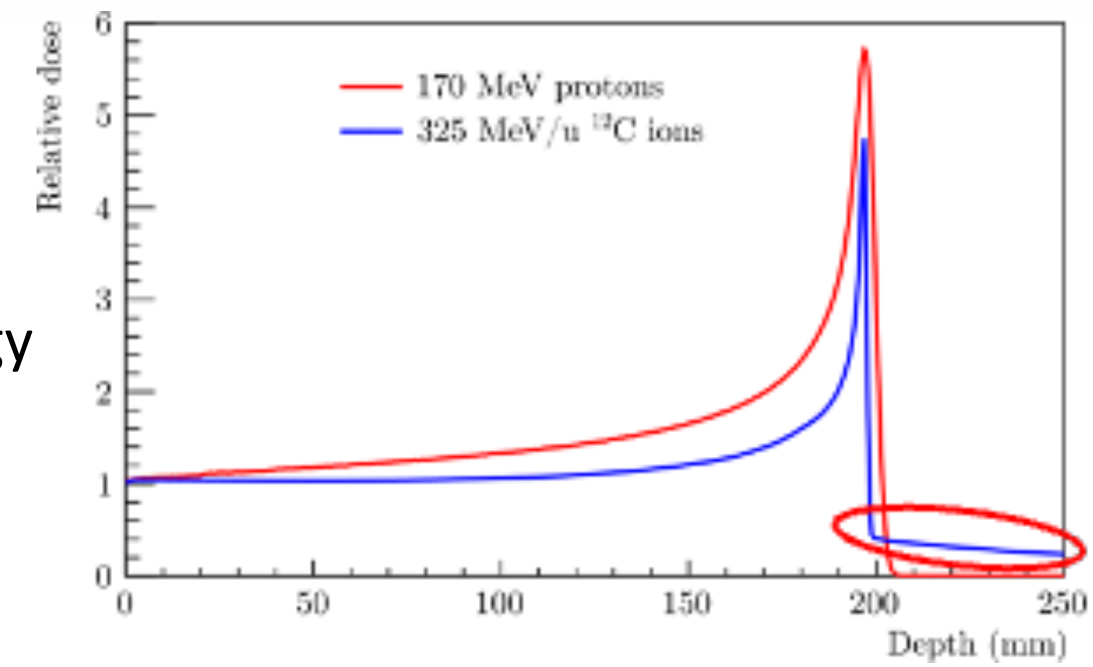
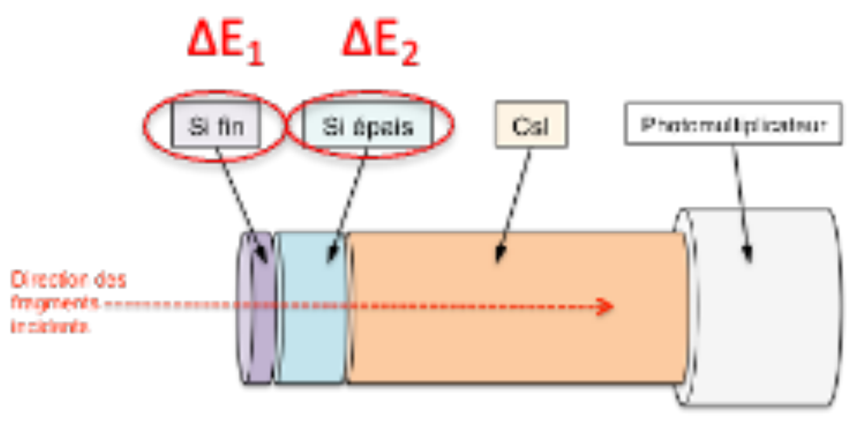
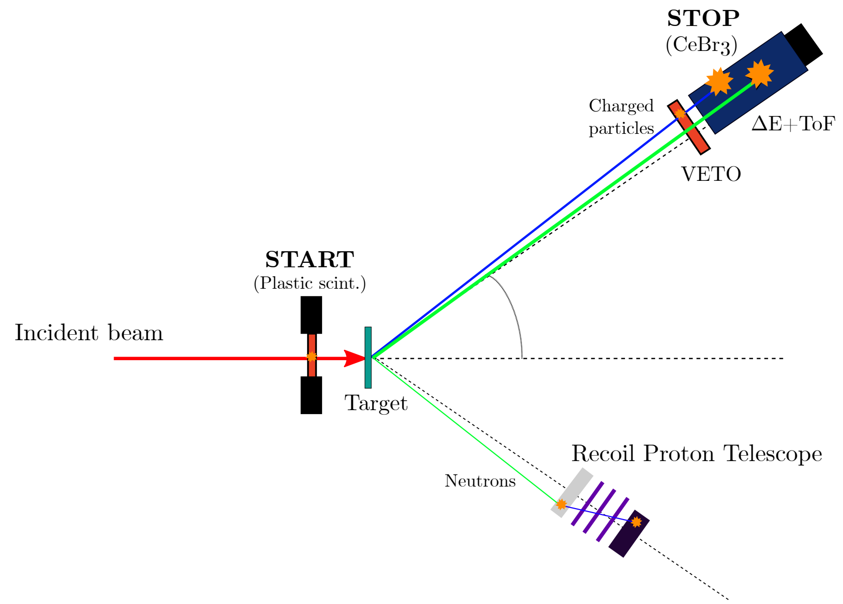


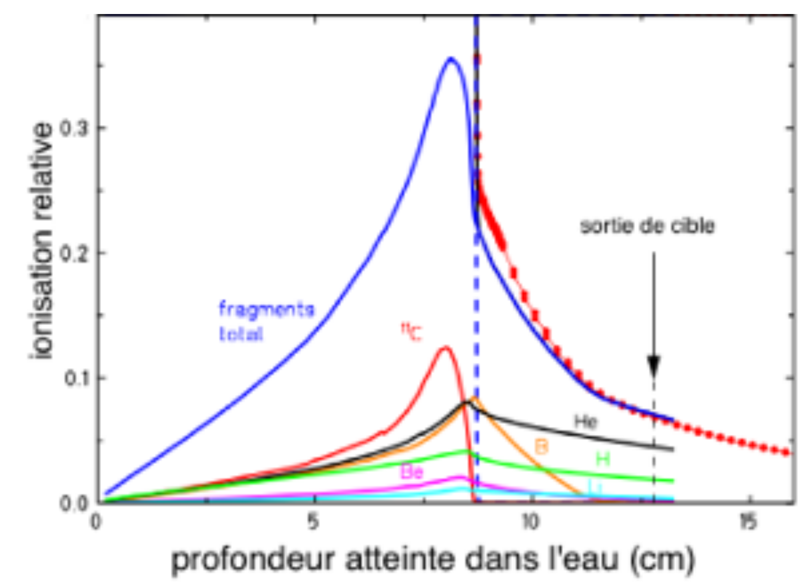
- Exclusive measurements (i)
  - Placing detector at given angles
  - Using ΔE_1(-ΔE_2)-E telescope or ΔE-ToF telescope for isotope Id



E600 experiment @ Ganil

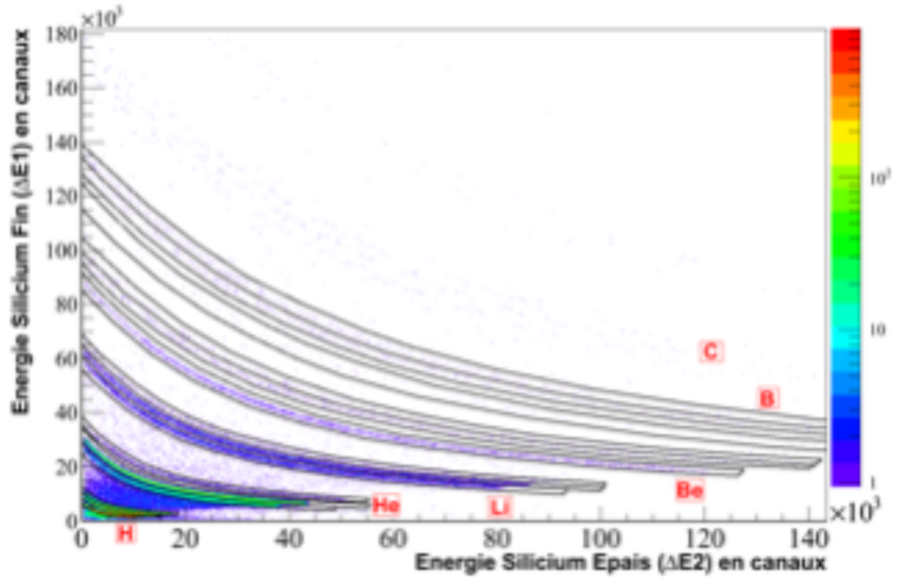


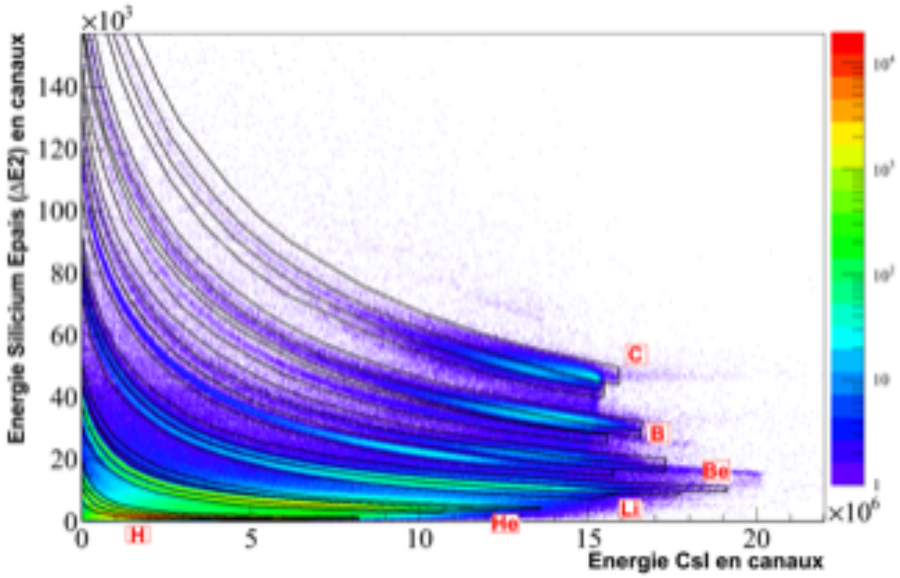
CLINM experiment @ CNAO

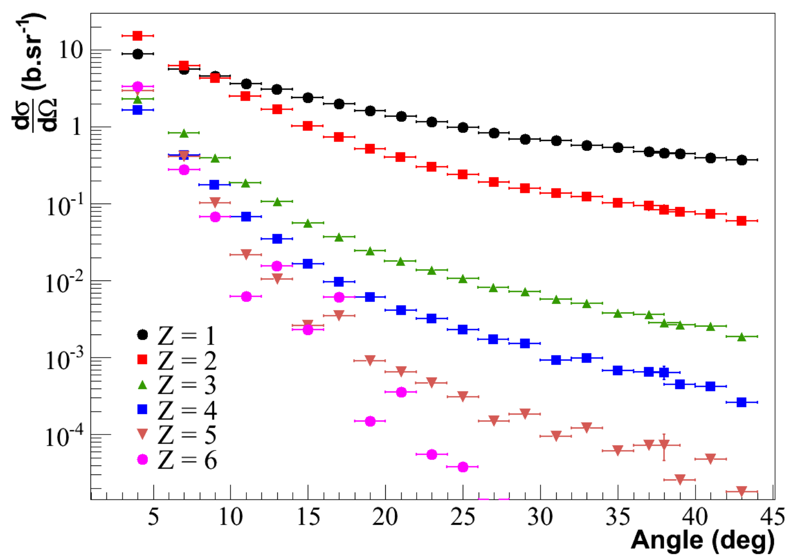


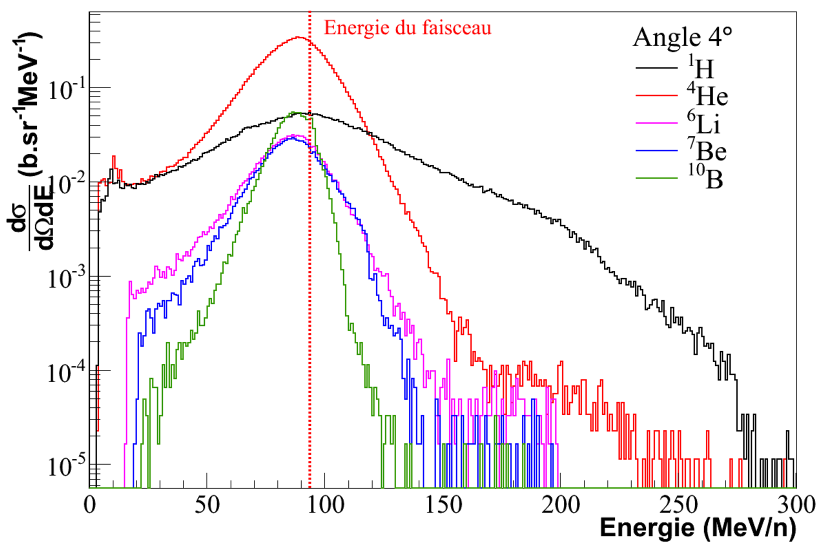
Cross-section measurement (ii)

- Exclusive measurements (ii):
  - Results (highlights):







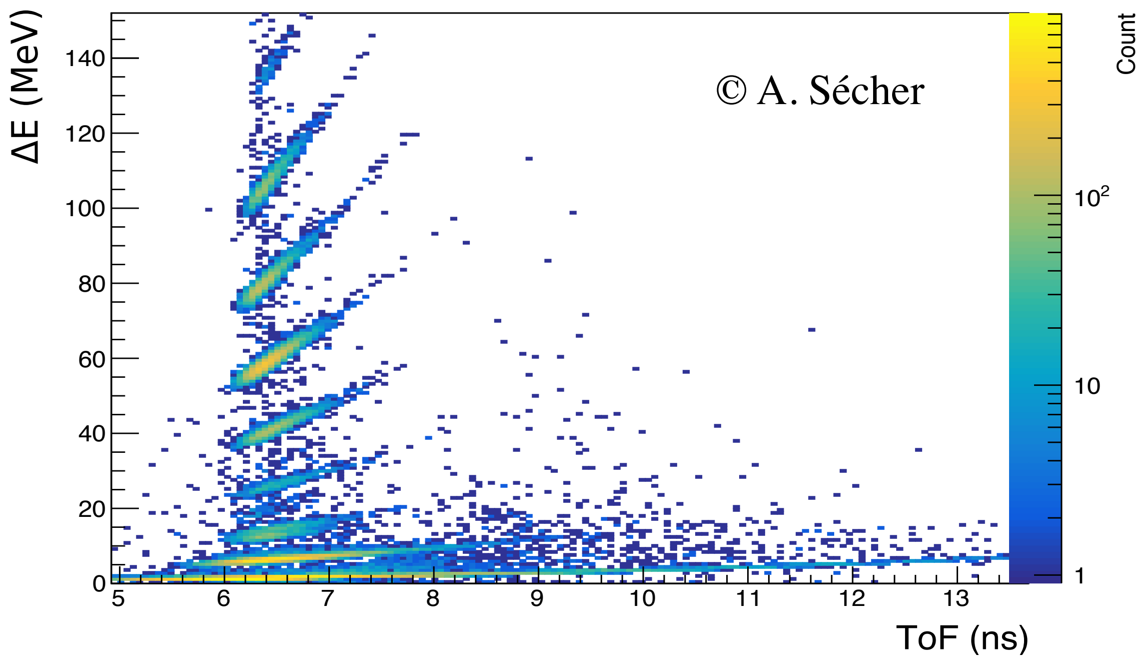


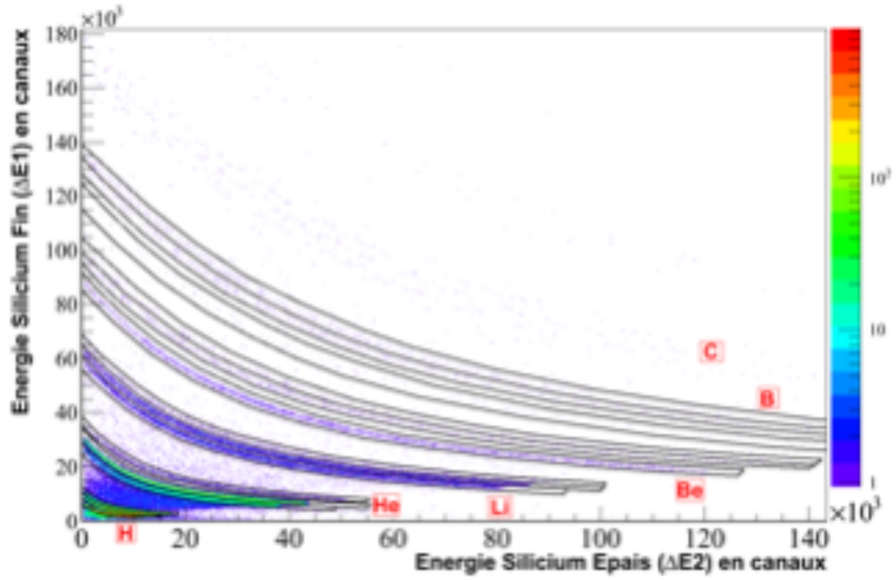
E600 experiment @ Ganil (D. Juliani)
$^{12}C+^{12}C$ @ 95MeV/u

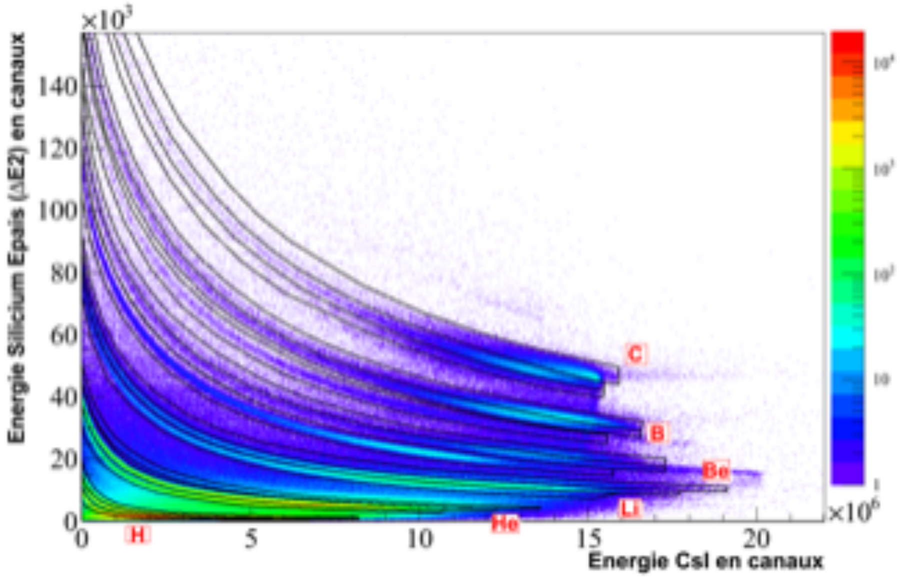
Cross-section measurement (ii)

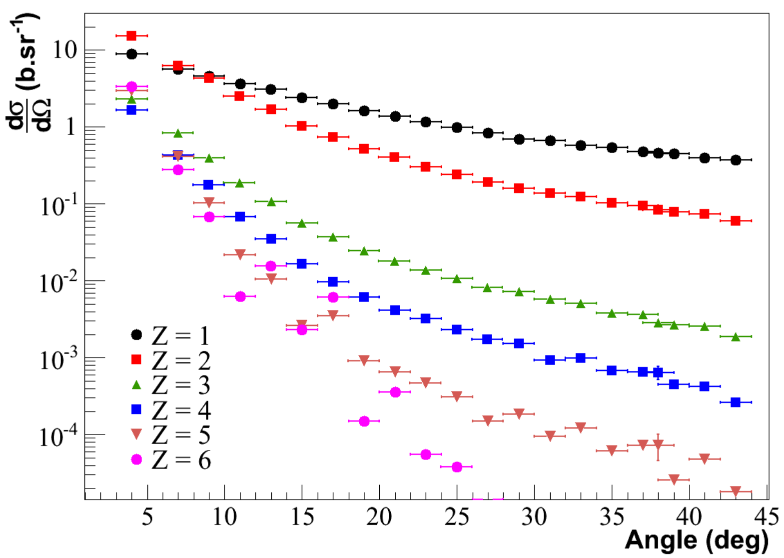
- Exclusive measurements (ii):
  - Results (highlights):

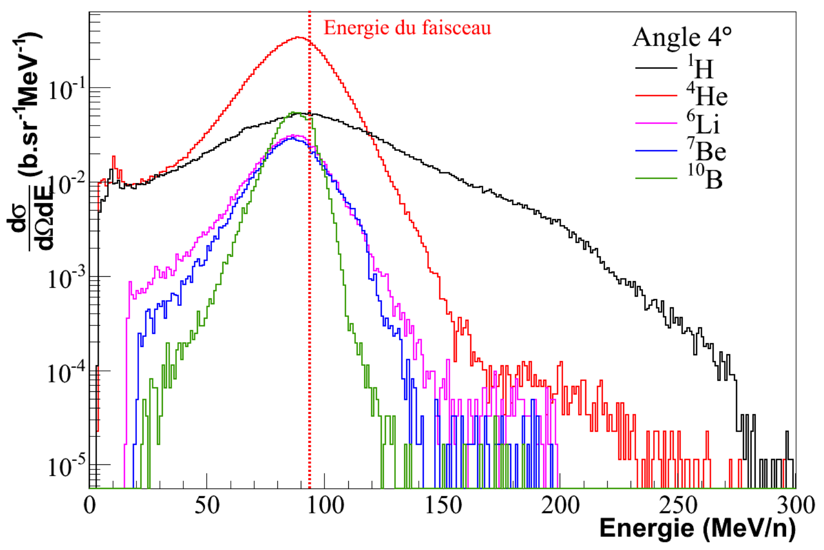
CLINM experiment (Geant4 simulation)









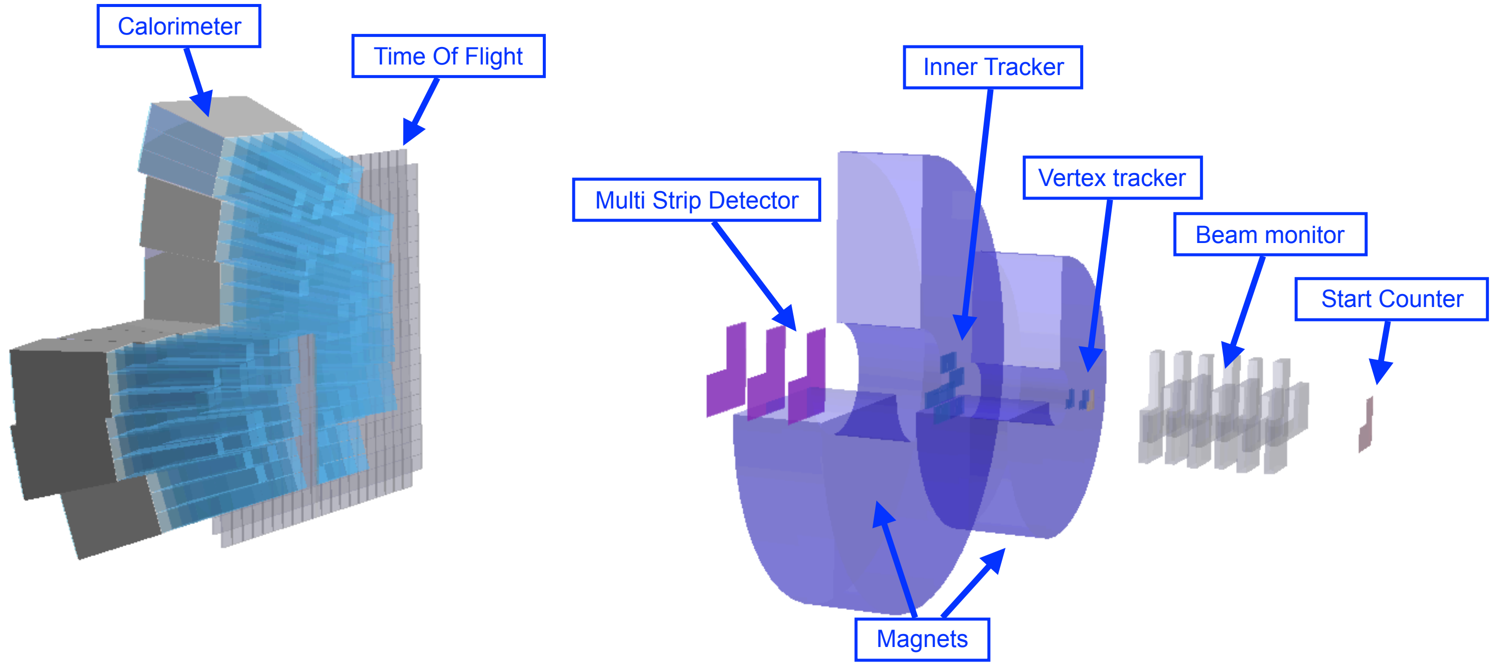


E600 experiment @ Ganil (D. Juliani)
$^{12}C+^{12}C$ @ 95MeV/u

Cross-section measurement (iii)

- Inclusive measurements:
  - Full coverage for a given angular acceptance
  - Need different type of detector

FOOT experiment @ CNAO



- Beam monitoring: drift chamber
- Tracking system: silicon pixel and strip detector
- Momentum reconstruction: Permanent magnet
- Time of flight: plastic scintillators
- Calorimeter: BGO crystal

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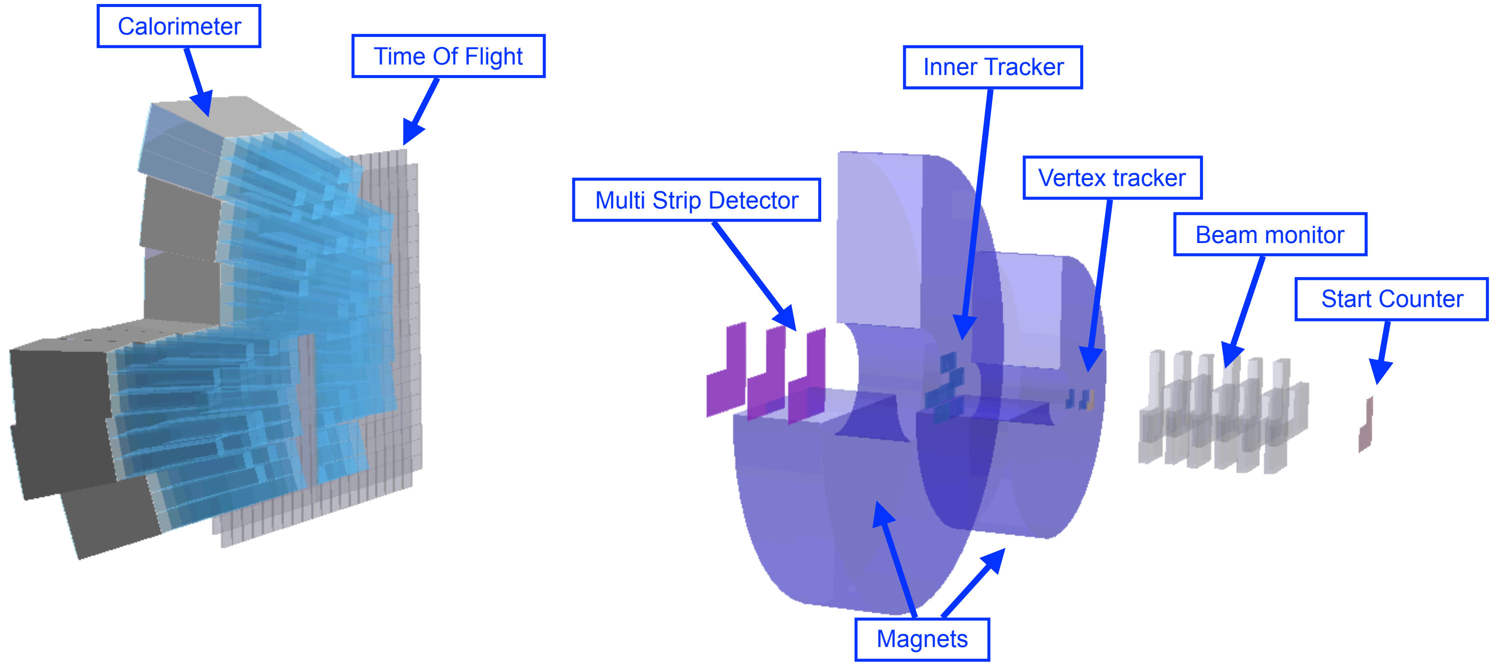
FOOT experiment @ CNAO



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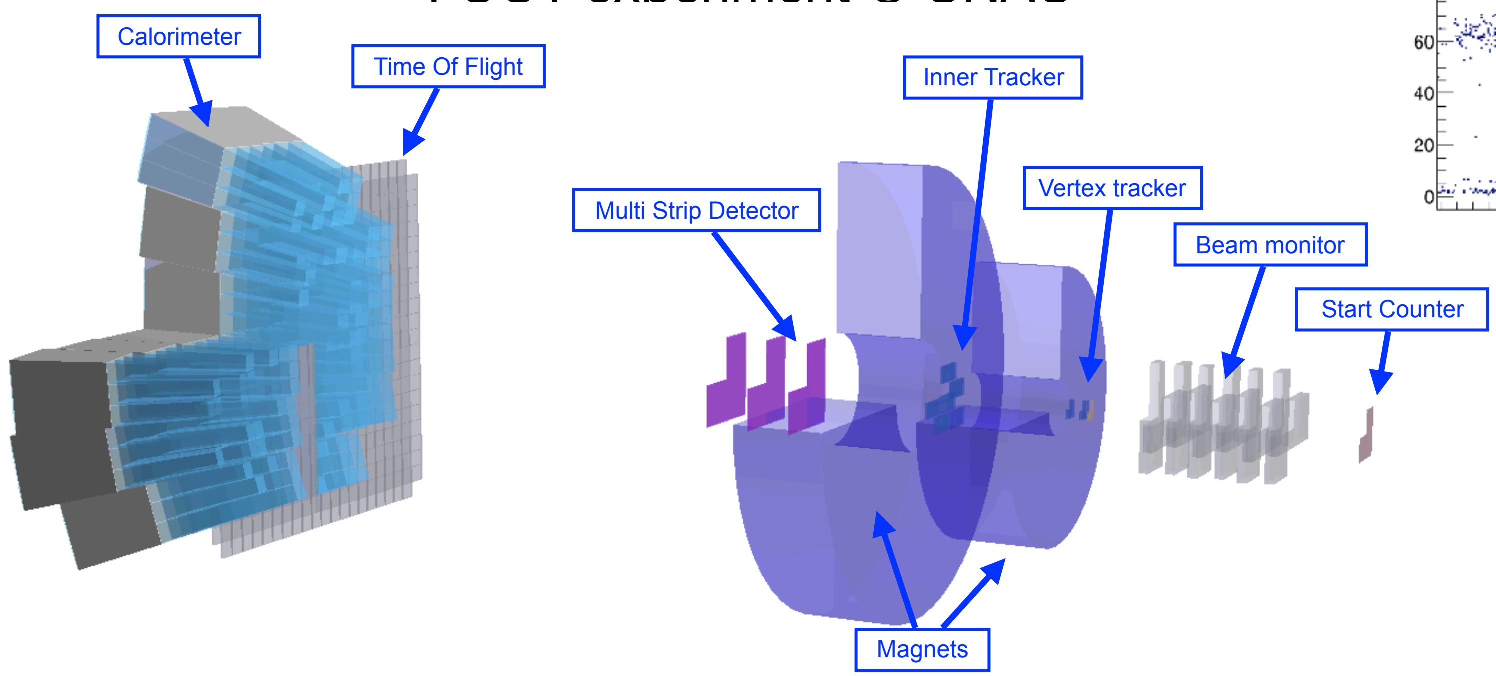

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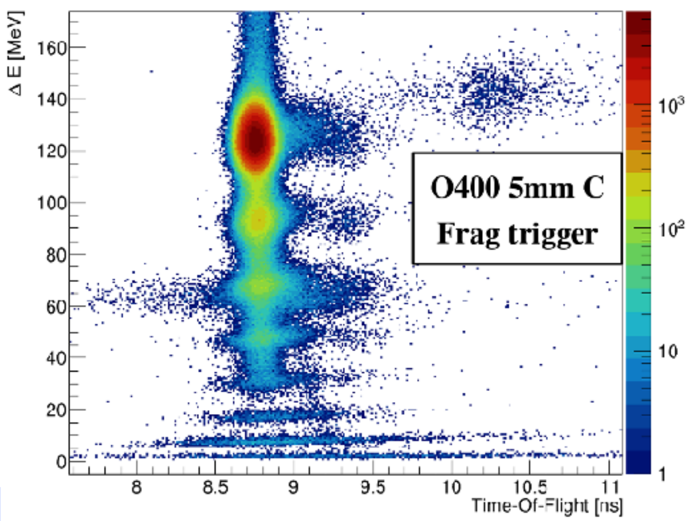

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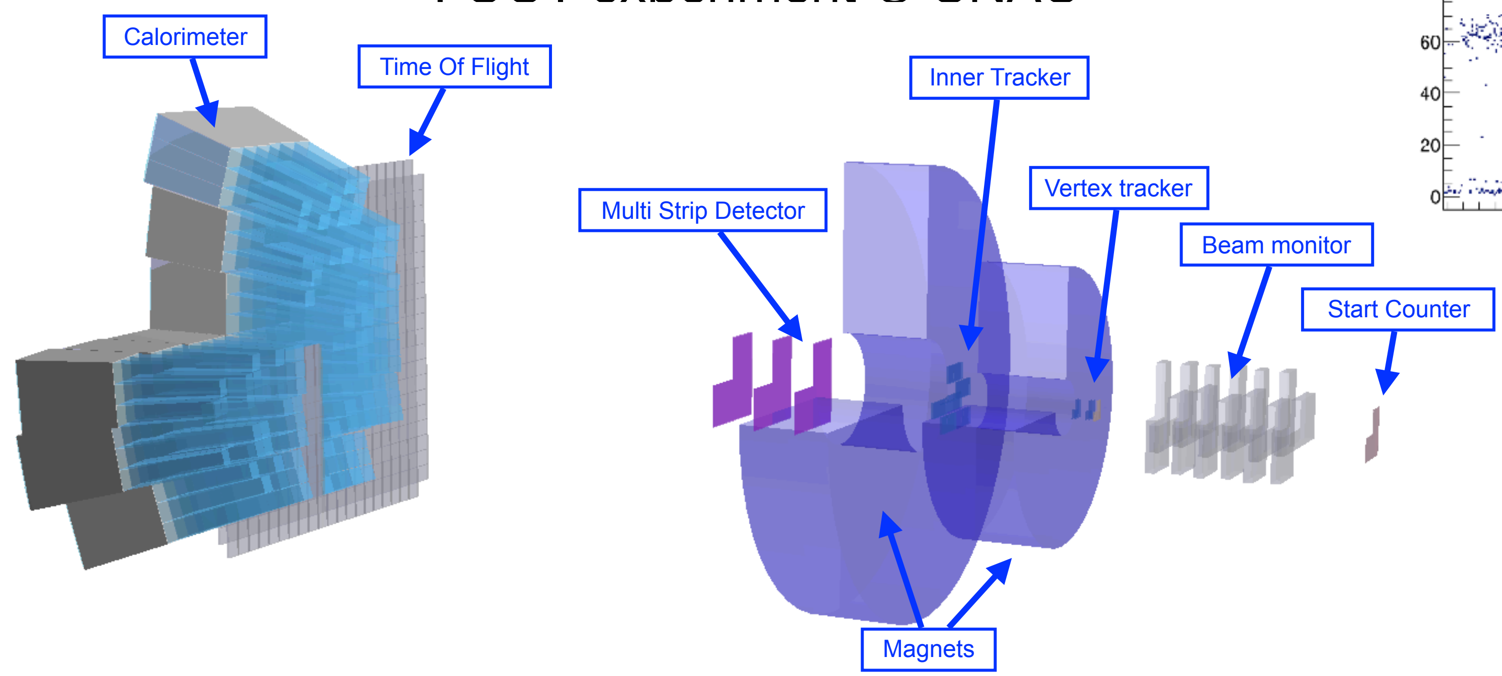

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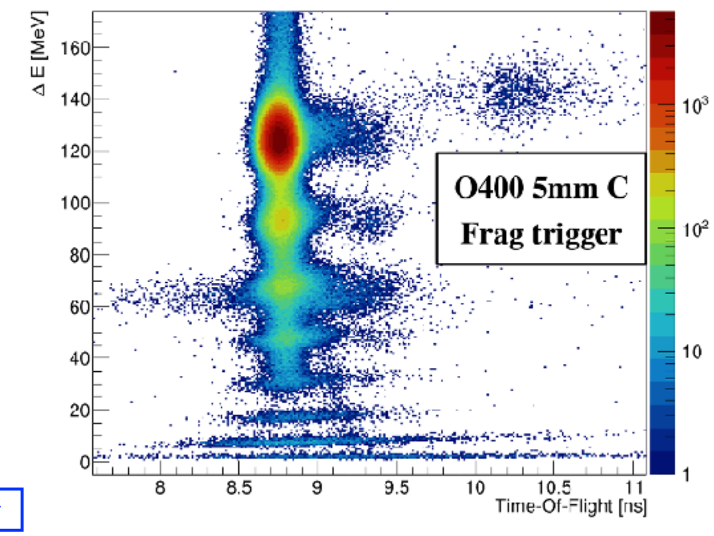

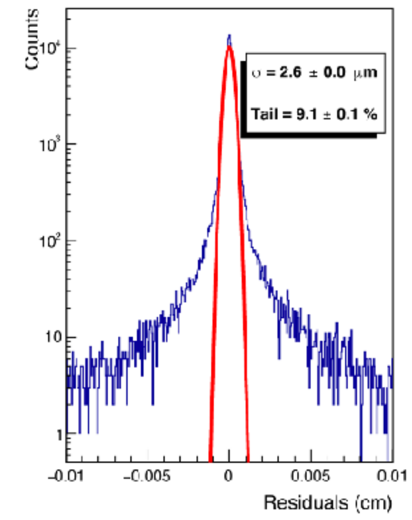

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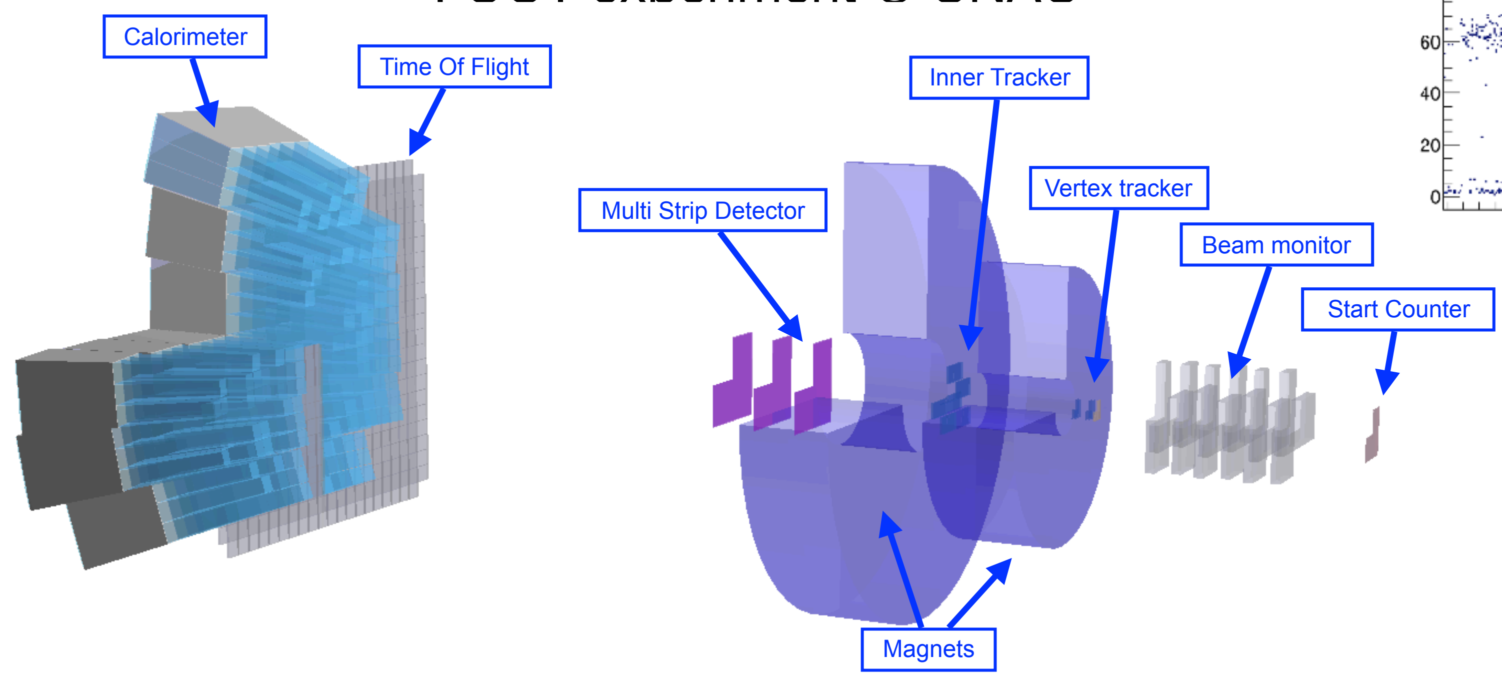

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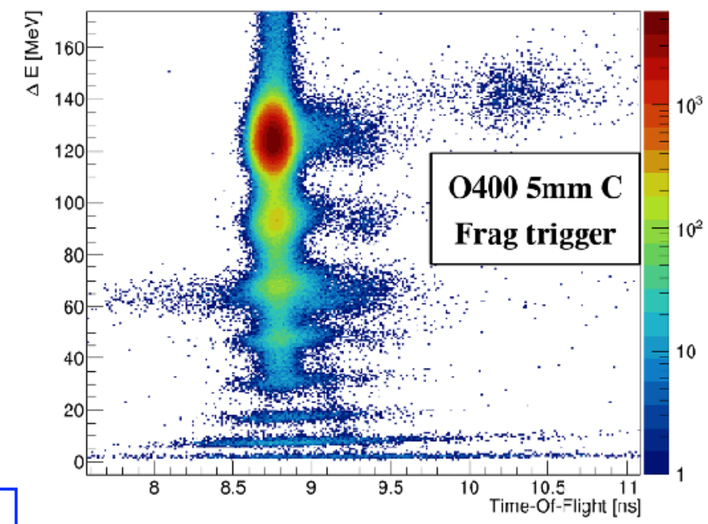

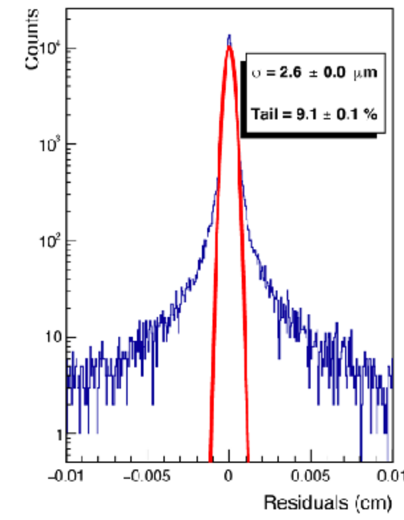

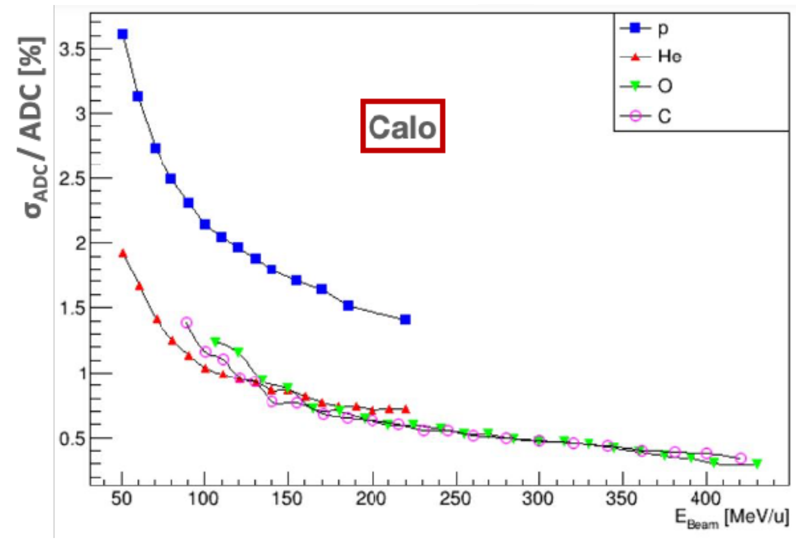

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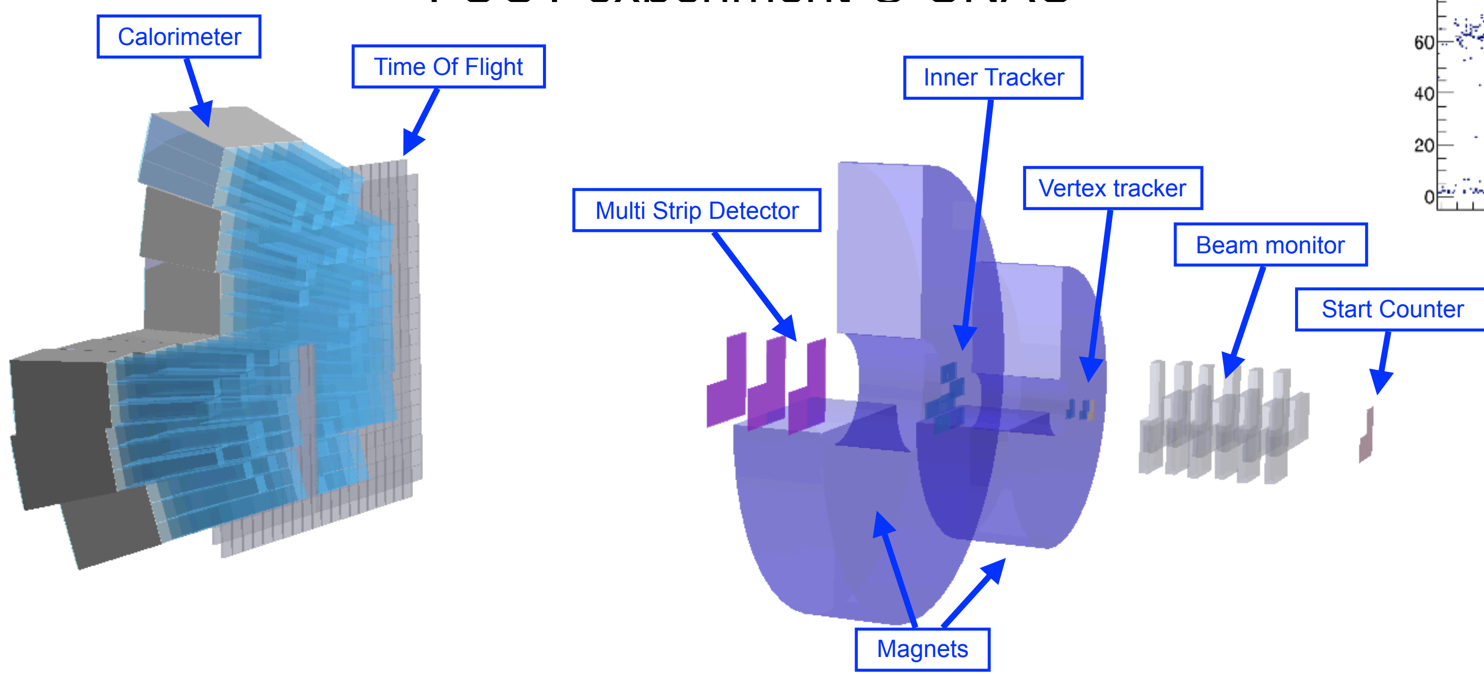

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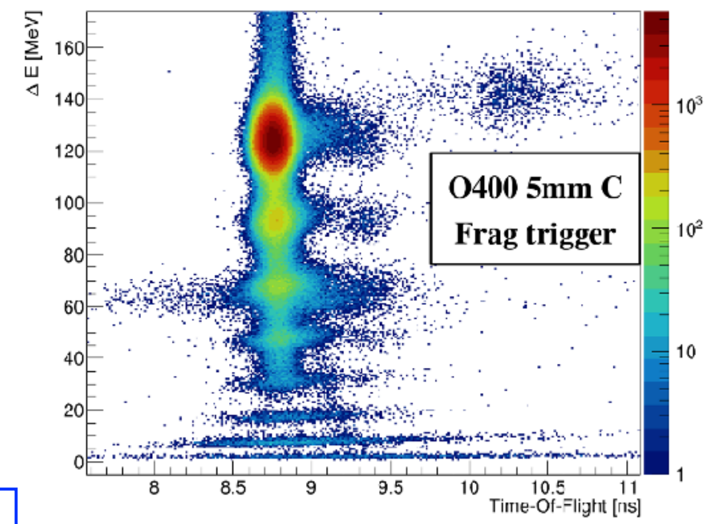
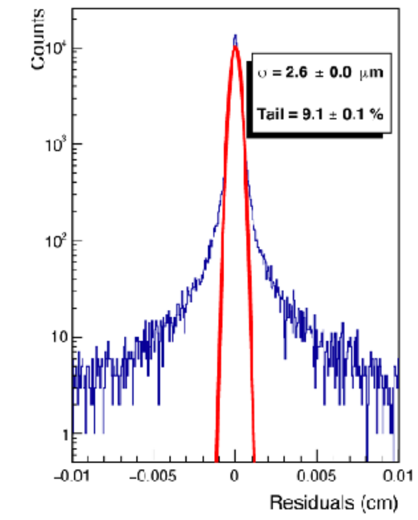
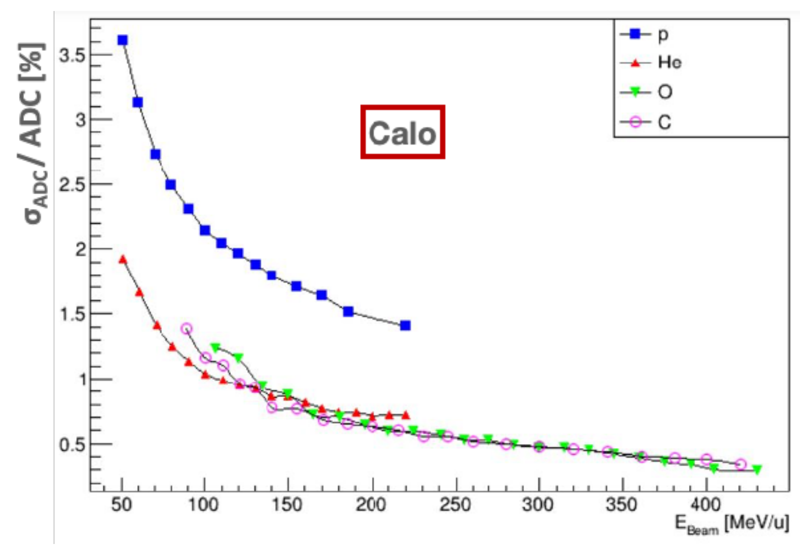






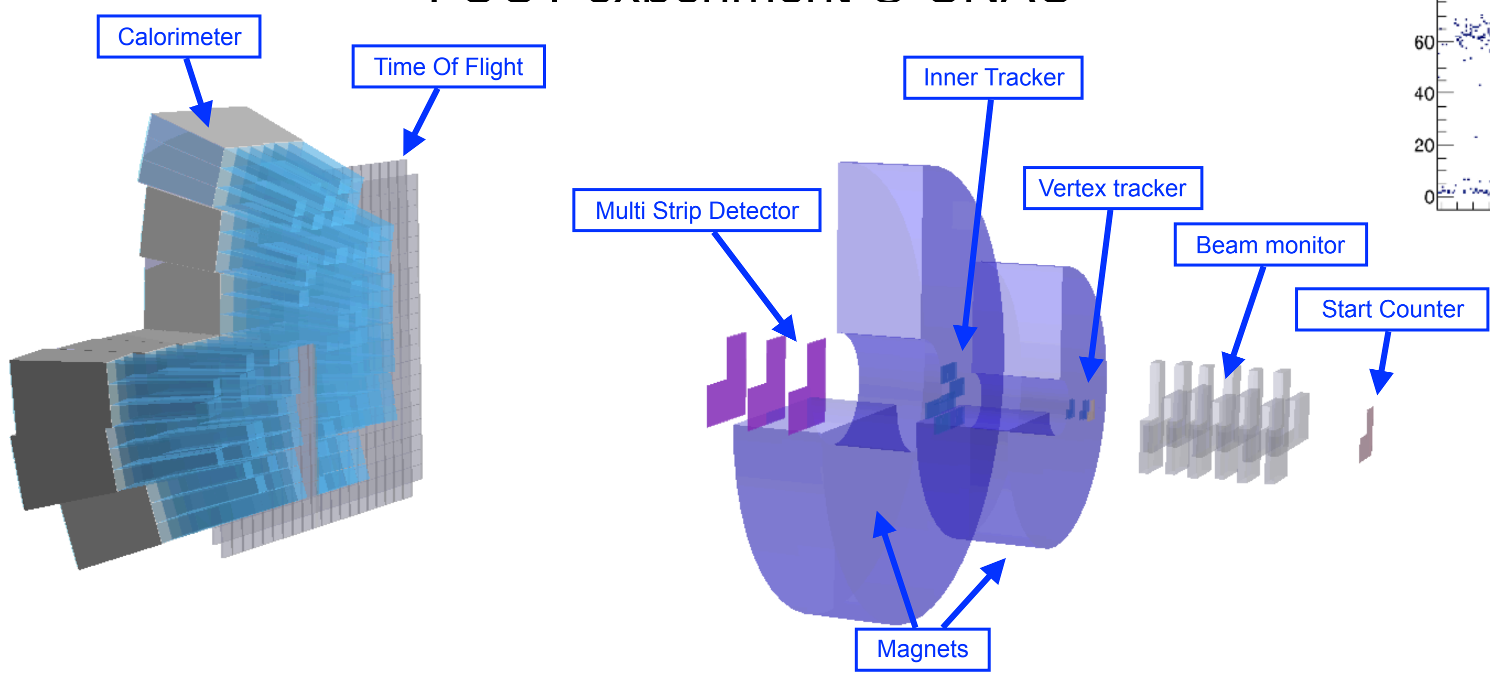
- Required performances:
  - $\sigma(p)/p < 5\,\%$
  - $\sigma(\Delta E)/E < 5\,\%$
  - $\sigma(ToF) < 50\,ps$

Cross-section measurement (iii)

❑ Inclusive measurements:

- Full coverage for a given angular acceptance
- Need different type of detector

FOOT experiment @ CNAO



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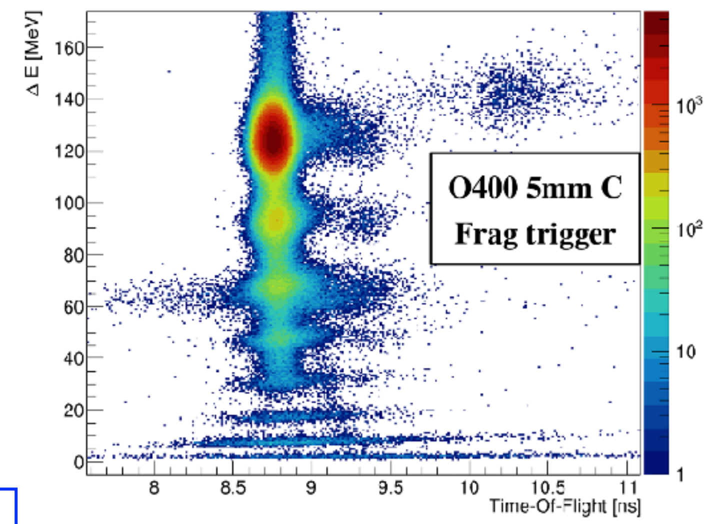
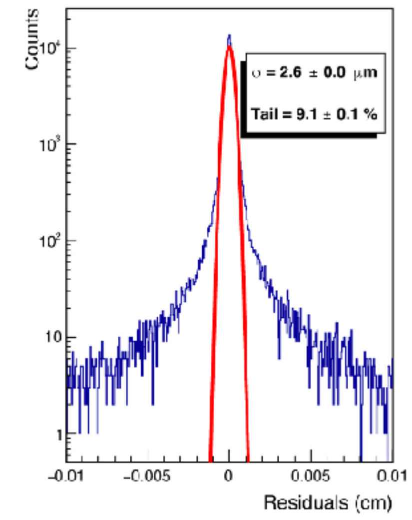
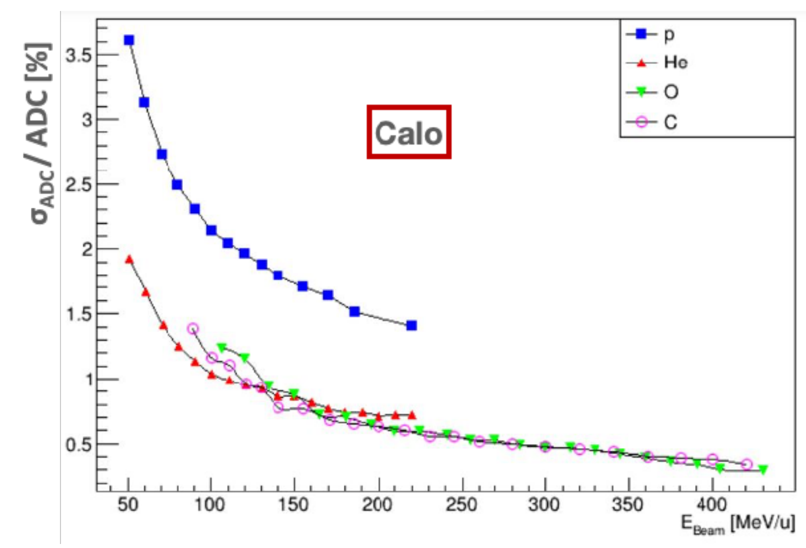
• Results (highlights)







• Required performances:

- $\sigma(p)/p\ < 5\,\%$
- $\sigma(\Delta E)/E\ < 5\,\%$ ➡Analysis ongoing
- $\sigma(ToF)\ < 50\,ps$

Conclusions

- In many fields (not all covered here) in medical applications, nuclear physics detectors are used
  - Beam monitoring
  - PET-SPECT-pCT Imaging
  - Cross-section measurement
  - Online dose control
  - Dosimetry
  - Etc….

Outlooks

❑ Also many fields were still improvement and development are need to face existing or forthcoming chalenges:

- Beam monitoring: flash therapy

  ➡Sustain high flux in a short time (40-100 Gy/s)

- PET-pCT Imaging:

  ➡increase time resolution and decrease acquisition time

- Online dose control:

  ➡ Increase Bragg peak correlation resolution (new technique / new detectors ?)

- Cross-section measurement:

  ➡Increase the number of measurements, including the existing data in TPS

- Dosimetry:

  ➡Increase sensitivity (neutrons for instance) and decrease acquisition time

- Etc....

Backup