PhotonDetectors

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Eurizon Detector School

eurizon
European network
for developing new horizons for RIs

Scientific Programme

The EURIZON Detector School is organized for training young scientists on state-of-the-art particle detection technologies in the fields of particle-, heavy-ion- and neutron-physics. The main program of the school comprises morning lectures by world experts in their fields, and hands-on exercises on various technologies in the afternoons. Social activities are organised during evenings and on the weekend.

The preliminary list of lecture topics:

- Calorimetry
- Characterization of detectors
- Communication in science, presentation skills
- Evolution of working detector systems from R&D to construction, operation and performance
- Gaseous detectors
- Neutron detectors
- Non-collider detectors
- Particle identification
- Photodetection
- Quantum sensing
- Readout- FPGA- trigger- DAQ- synchronization
- Silicon detectors
- Tracking

The school will also include practical courses that will allow the students to put their hands on various detectors and test them under the supervision of experts.

Students will be given opportunity to present their work. This activity will connect closely with the science communication tutorial.

Introduction to photon detection

- Detections of particles requires interaction with matter, which lead to its ionization or excitation.

- Choice of the material is extremely important:
  - Target particle.
  - Kind of interaction the particle has with matter.
  - Signature of the interaction.

- Some interactions of particles with matter produces photon as signature:
  - Scintillation.
  - Cherenkov radiation.

- Presentation topics:
  - Interactions which produce photons.
  - Photon detection principles.
  - Main photon detectors.
  - Some applications.

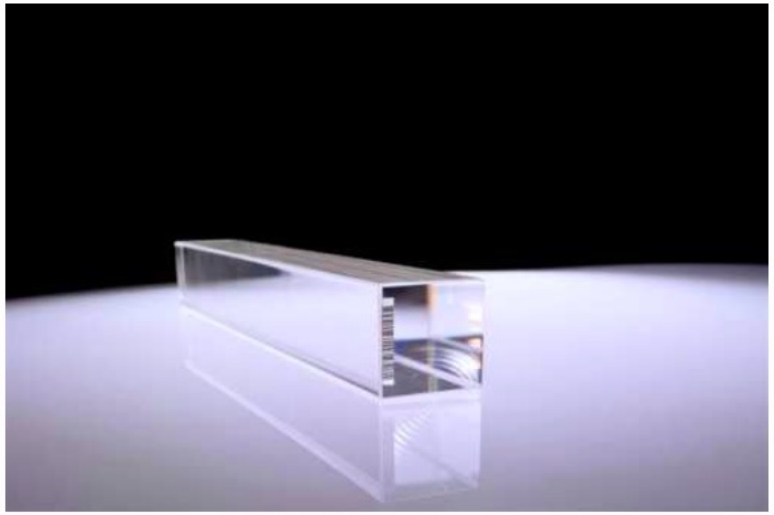
Principle of scintillation

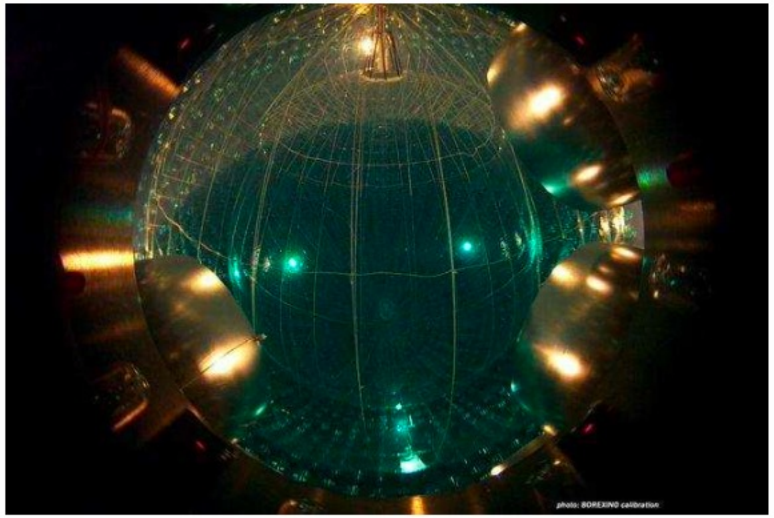
Some material can emit scintillation light when hit by a particle.

- dE/dx converted into detectable light.
- Light emission when hit by ionizing particles.
- Scintillator is transparent to scintillation light.

Main features:

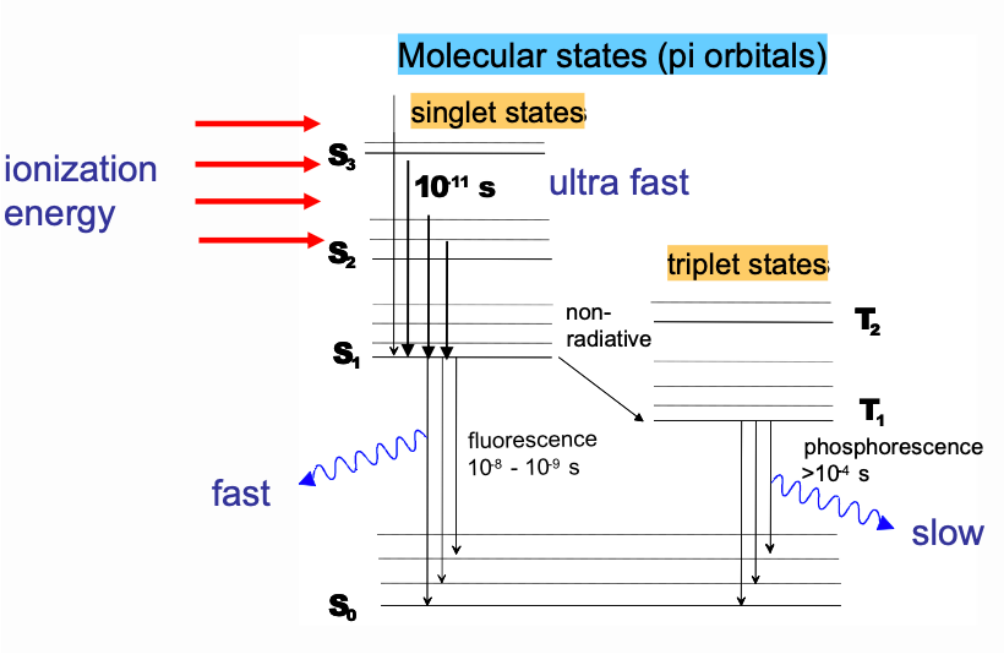
- Emitted light proportional to energy deposition (calorimetry).
- Fast-time respose (TOF, trigger).
- Response can depond on the particle type (PID).
- Large variety of materials (main classification organic vs inorganic).





Organic scintillators

- Aromatic hydrocarbon compounds (benzene ring)
- Scintillation light is due to **delocalised molecular electrons** in π-orbitals
- Two de-excitation mechanisms:
  - FAST: ground to excited state decaying to an **intermediate molecular state (~ps)** and subsequent decay to ground (ns).
  - SLOW: de-excitation of levels interacting with the **lattice** (>100ns).
- An intermediate state is necessary to make the material transparent to the de-excitation light.
- A small amount of a second fluorescent compound (wavelength shifter) is added to increase the overall visible light collection.
- Emission in the green-blue-UV spectrum.



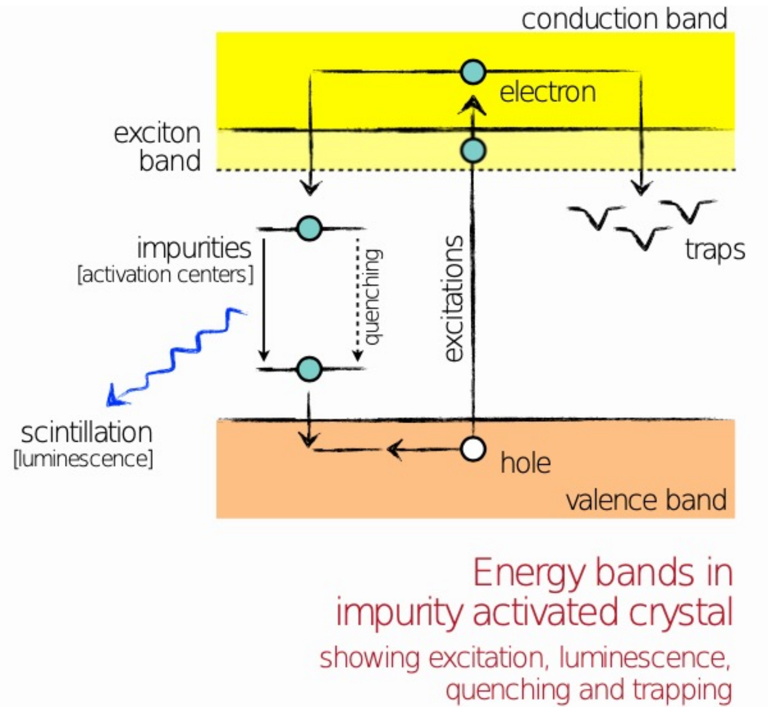
Main properties:

- Crystals, plastic or liquid solutions.
- Low Z, low density
- Up to 10k photons per MeV.
- ~ns decay time.
- Relatively inexpensive.
- Used in electromagnetic and hadronic calorimeters.

Inorganic scintillators

- Typically alkaline **non-conductive crystals with a small amount of fluorescent dopant**: NaI, CsI, …
- Non-alkaline species: Barium fluoride (BaF2), …
- Scintillation mechanism related to the **crystal lattice bands**:
    - energy deposition by ionisation.
    - energy transfer to impurities.
    - radiation of scintillation photons.

- Fast component due to recombination from activation centres (ns to μs).
- Slow component due to de-excitation from traps.
- Emission in the green-blue-UV spectrum.



Main properties:
- higher light yields (up to 70000 ph/MeV)
- High Z, high density
- Relatively expensive
- Used in electromagnetic calorimetry

Cherenkov radiation

- Cherenkov light produced when a charged particle is moving though a medium at a speed which is greater than the speed of light in the medium.

- **Asymmetric polarization and coherent waveform** produced, only at a specific angle θ, which depends on the particle v.

$$\cos\theta_c = \frac{1}{\beta n(\lambda)}$$

- Intensity inversely proportional to wavelength: characteristic blue light.

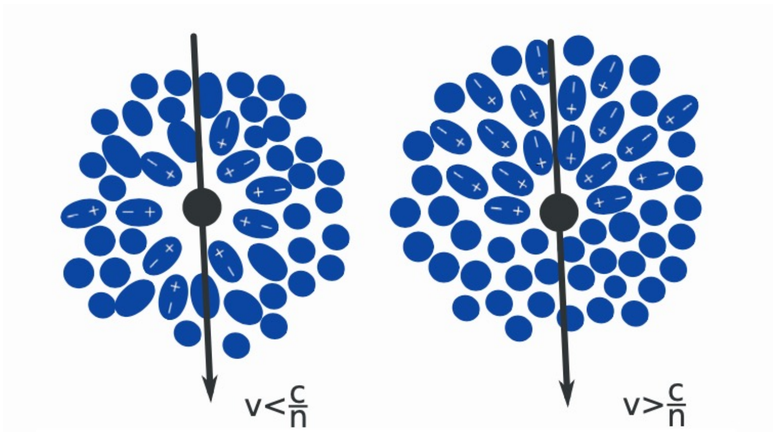
$$N_{photons} \propto \frac{1}{\lambda^2}$$

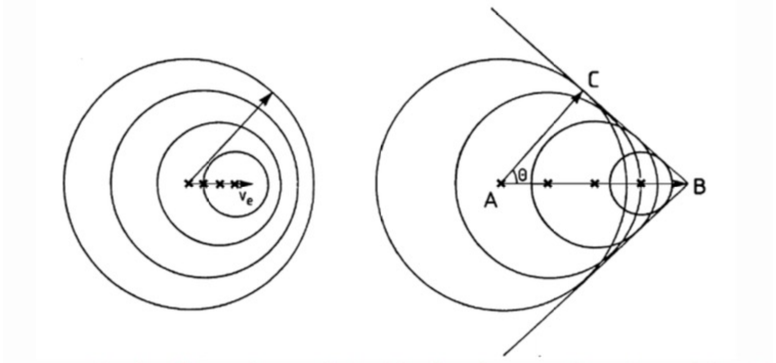
- Low number of Cherenkov photons (low energy loss from the particle).

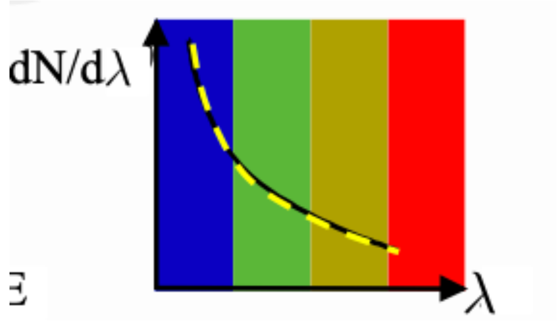
$$d^2N/dEdx \approx 370 \sin^2\theta_C(E)\ [\mathrm{eV}^{-1}][\mathrm{cm}^{-1}]$$

- Natural employment in particle physics for **particle identification detectors.**

Asymmetric polarization



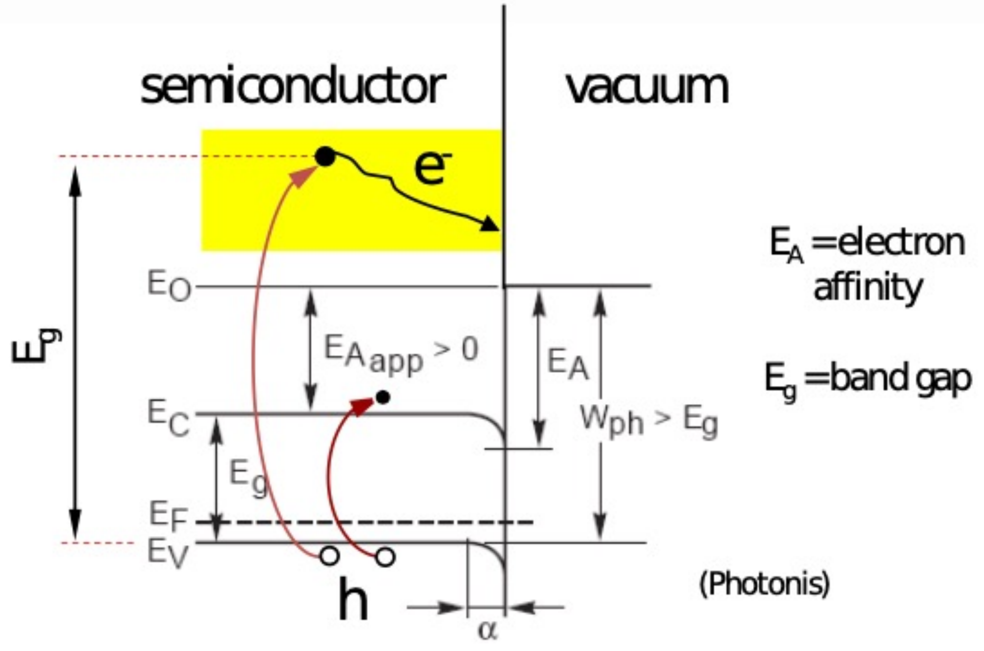




Photon detectors principles

Transformation of light into detectable electric signals.

Principle: photons hit a **cathode** and are converted to electrons via **photoelectric effect**; electric signal is then collected at the **anode**.



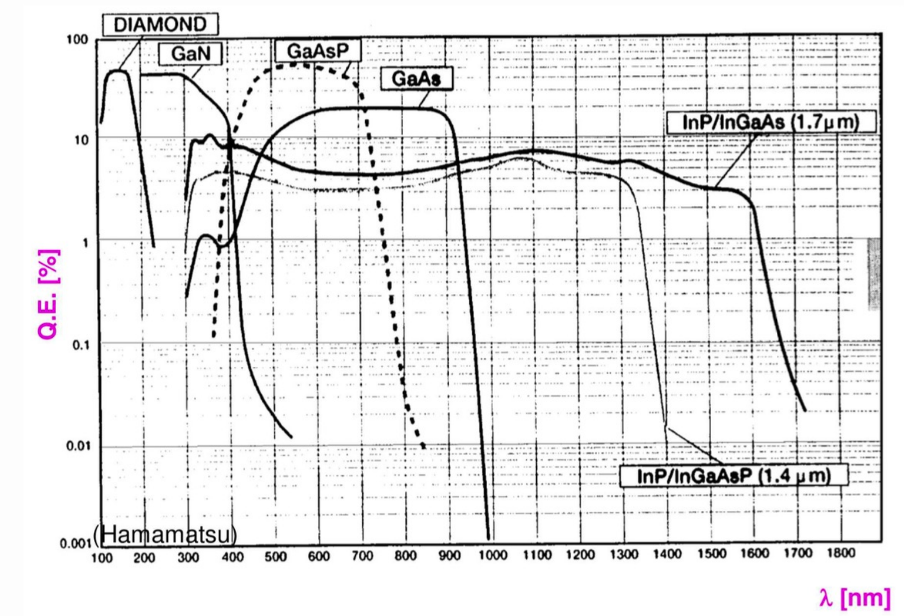
Multiple steps:

- Photo-ionisation: electrons lifted from valence to conduction band (internal photoelectric effect).
- Electrons drift in photocathode: energised electrons diffuse through the material (losing E).
- escape into vacuum: only electrons with sufficient excess energy escape from the photocathode (external photoelectric effect).

Photon detectors parameters (1/3)

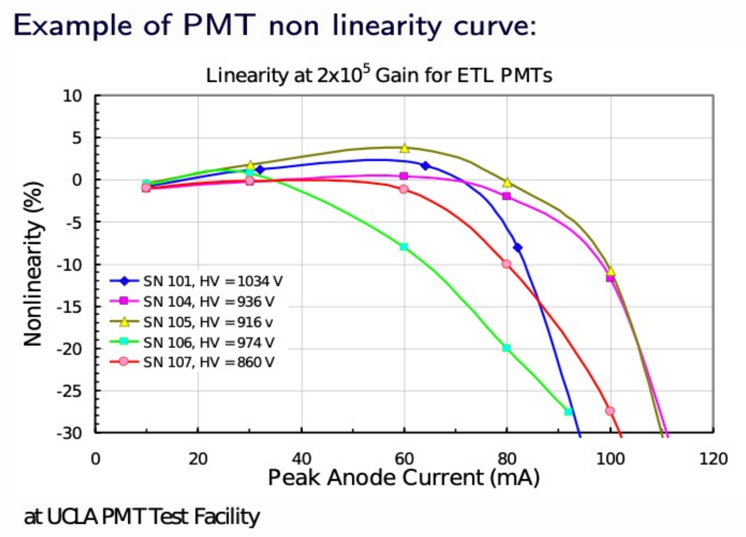
Sensitivity

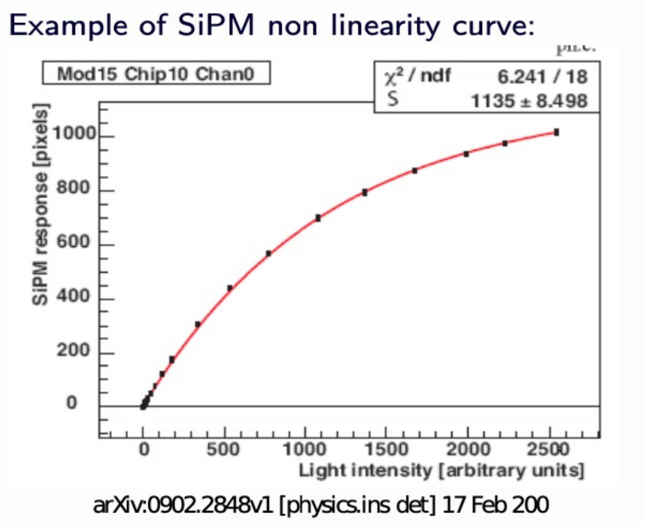
- Expressed as Quantum Efficiency $QE[\%] = \frac{N_{pe}}{N_\gamma}$
- Photon Detection Efficiency $PDE = \epsilon_{geom} \cdot QE \cdot \epsilon_{photondetection}$
- It depends on the wavelength (material of the photocathode).
- High sensitivity required for Cherenkov detectors (UV/blue) and HEP calorimeters (blue/green)



Linearity

- How linear is the photocurrent response with the incident radiation over a wide range.
- Linearity studies for calibration.





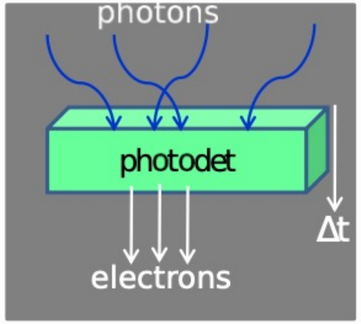
Photon detectors parameters (2/3)

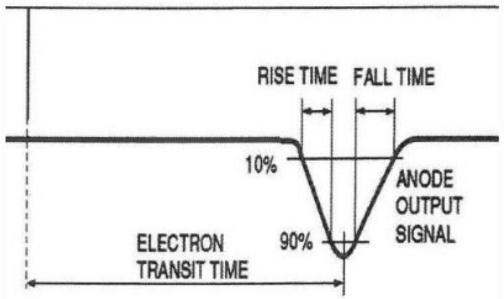
Signal fluctuation

- Most of the detectors characterized by a gain (~10^6Me) obtained from multiplication of the photoelectrons produced.
- Statistical fluctuation of the multiplication – excess noise factor $ENF = \frac{\sigma_{out}^2}{\sigma_{in}^2}$
- Impact on low light measurements and energy resolution.

Time response

- Rise and fall time, duration (time over threshold).
- Transit time and transit time spread (TTS, **time resolution**).
- Good time resolution needed in high intensity application for particle identification.





Rate capability

- Inversely proportional to the time needed, after the arrival of one photon, to get ready to receive the next.

Photon detectors parameters (3/3)

Dark counts rate DCR

- Electrical signal emitted by a photocathode when there is **no photon** hitting the photon detector.
- In **PMTs** depends on cathode material and area, temperature, age and exposition to daylight.
- In **SiPM** depends on spad size, temperature, bias voltage (kHz at room T).
- Key parameter in single photon applications.

Radiation hardness

- Damage caused by **ionizing radiation** or/and **neutrons**.
- It affect DCR, gain and QE.

Aging

- How the photon detector behaviour changes when operated at high counting rate during several years.
- Can affect gain, QE, and DCR.

Photon detectors family tree

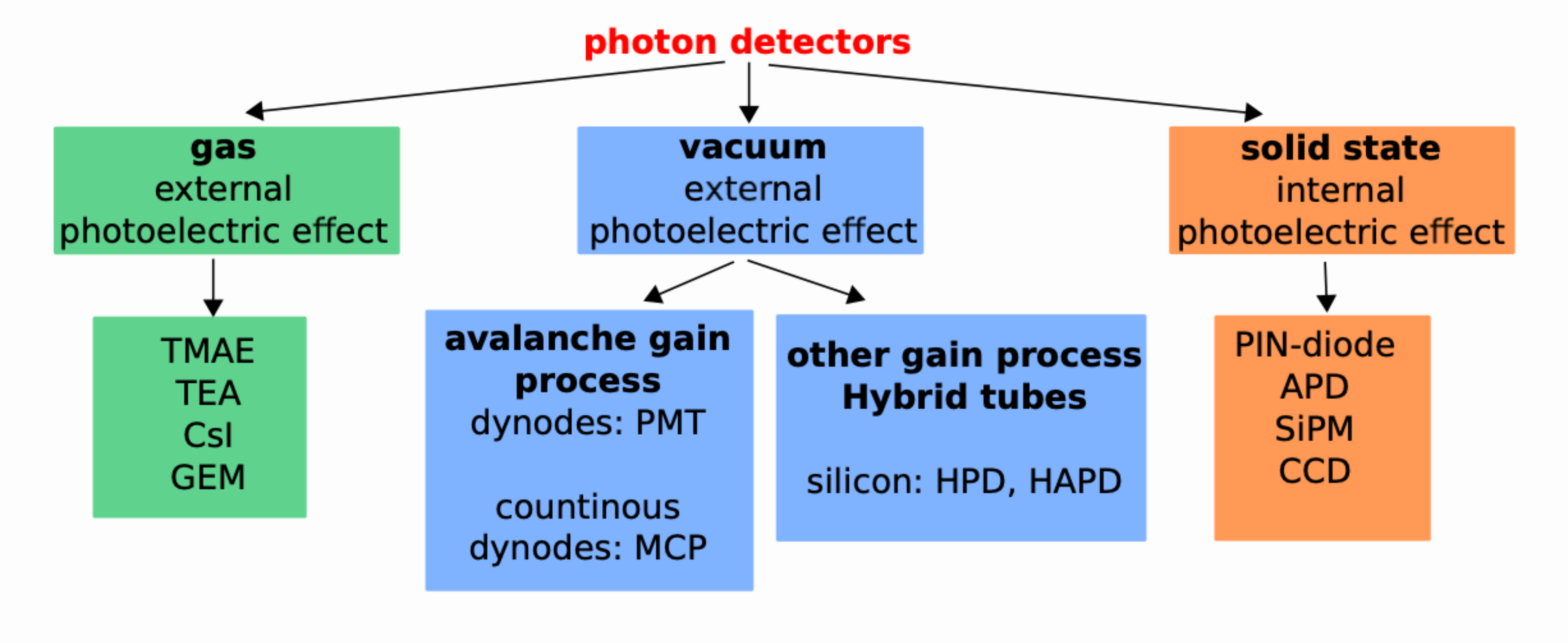
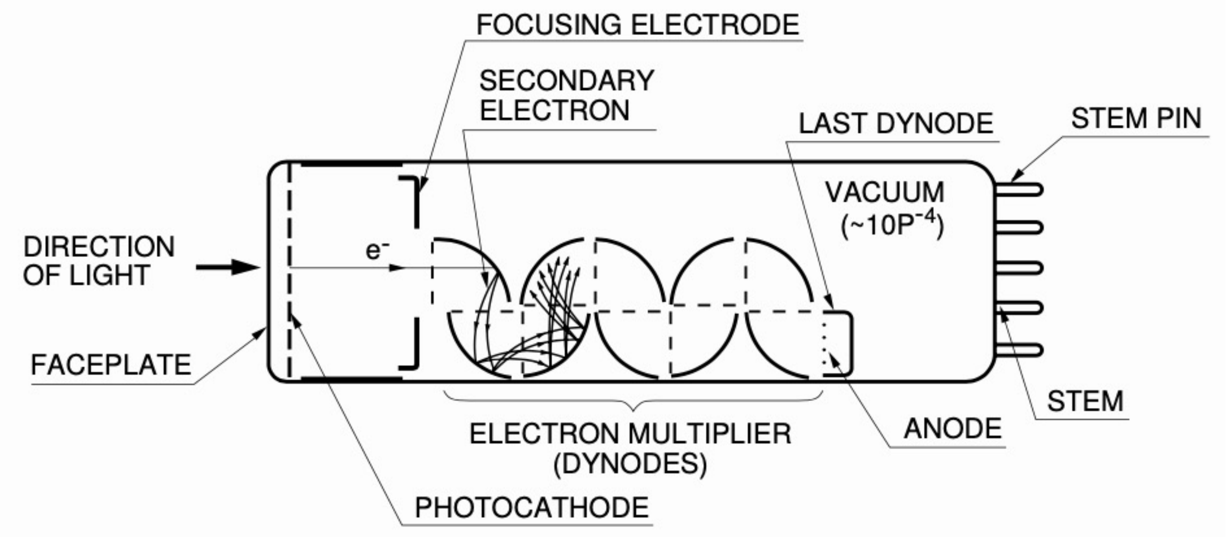


Photo-multiplier Tube (PMT)

- Photo electron emitted from the photocathode
- Secondary emission from N dynodes (8 to 14 with gain from 3 to 50).
- Voltage difference between dynodes with partition to accelerate electrons (bias in the order of kV).
- Sizeable output current (0.1-100mA)
- High photon detection efficiency.
- Sensitive to magnetic field.



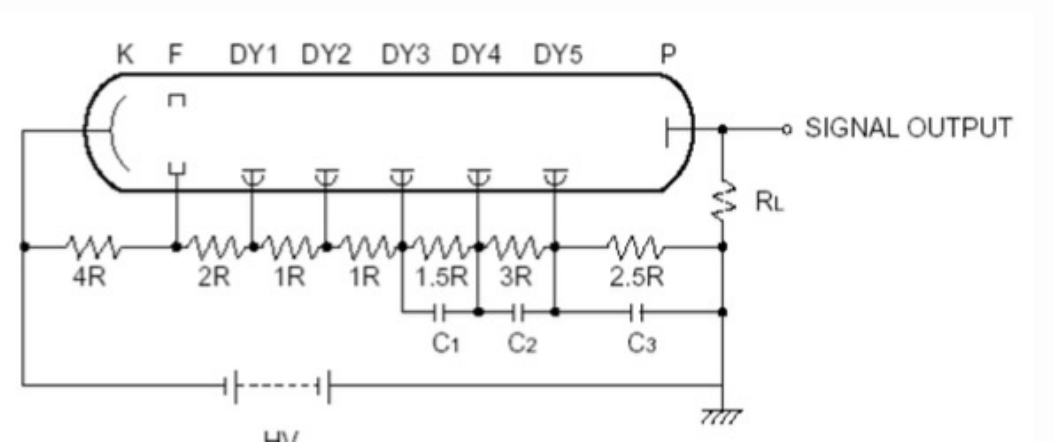
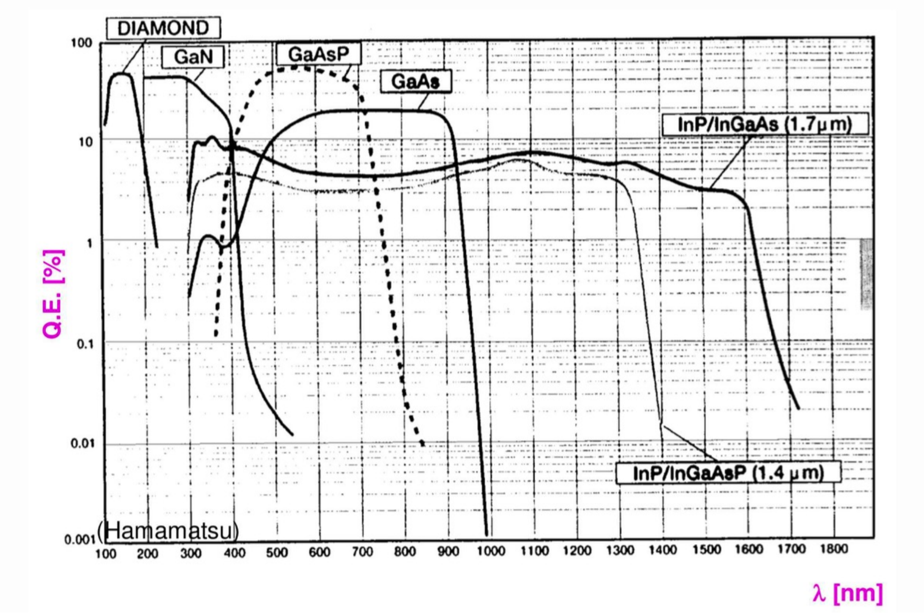


Photo-multiplier Tube (PMT)

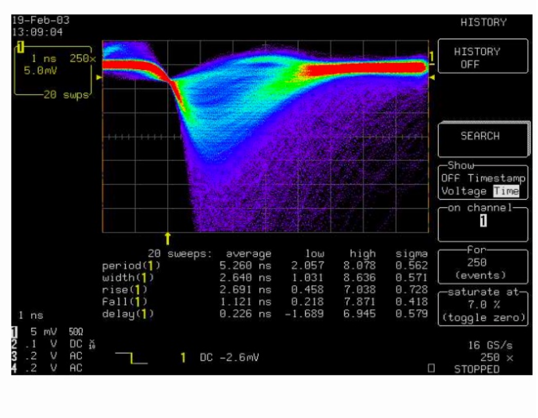
QE

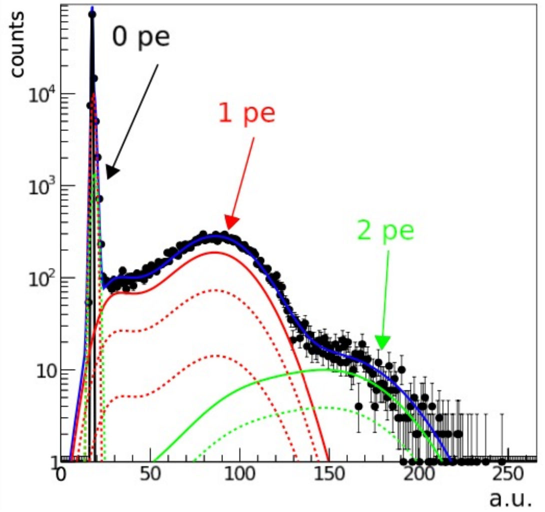
- Depends on the photocathode material and radiation wavelength.
- Main used in the blue-green spectrum, depending on the application.



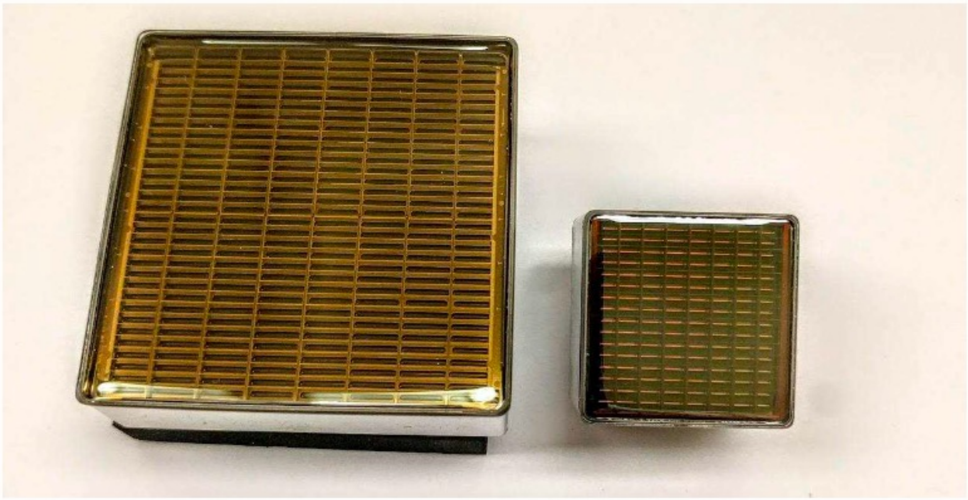
Gain fluctuation

- Gain in the order of 1Me.
- Gain fluctuation determined by the fluctuations of the number of secondary electrons emitted from the dynodes.
- Broaden amplitude spectrum.

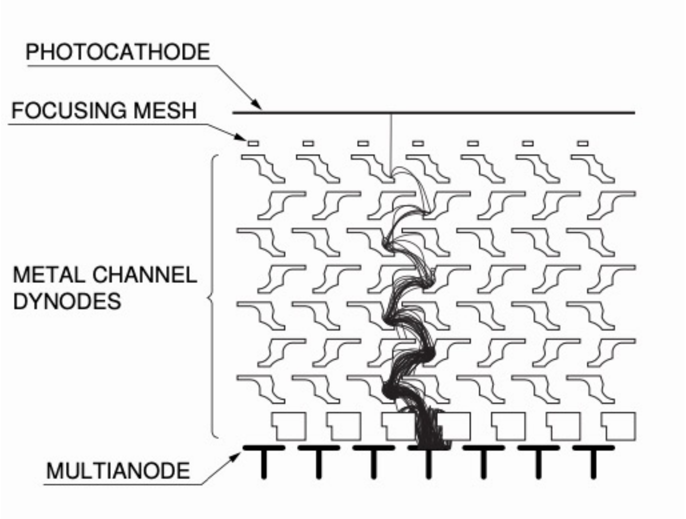




Multi-anode photo-multiplier tube (MAMPT)

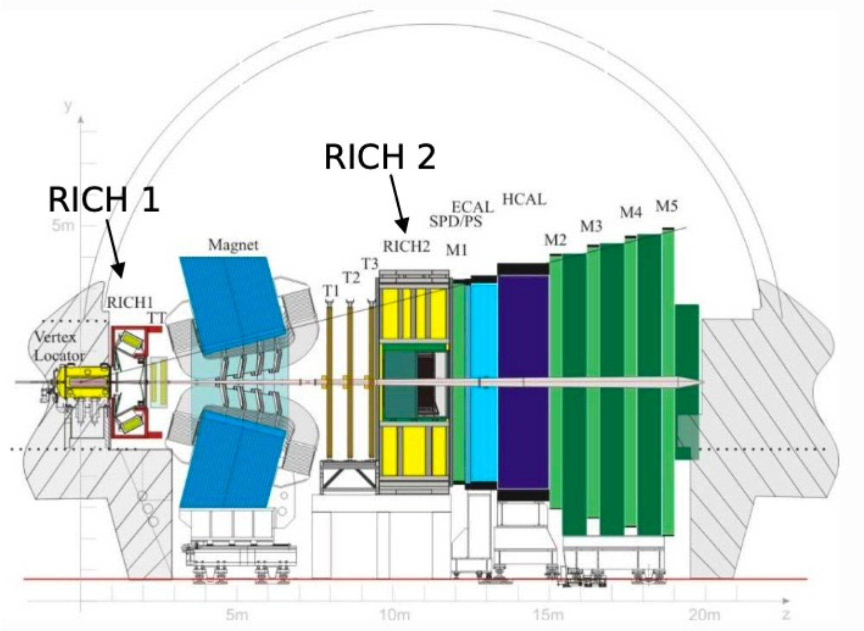


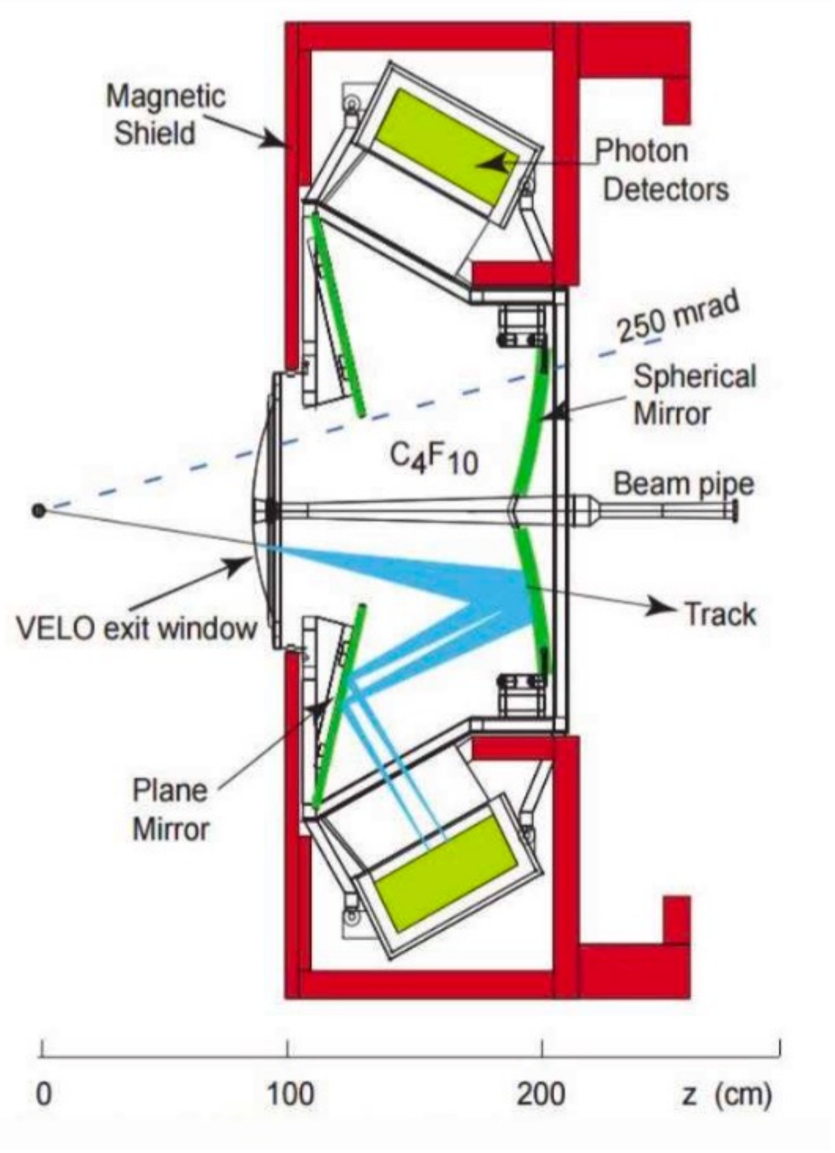
- Position sensitive PMTs (up to 64 dynodes in 1inch tube).
- Good PDE (active area ~80%, QE up to 45%).
- Low cross-talk (<2%) and low dark count rate.
- Gain ~ 10^6Me at 900V (gain fluctuation).
- Relatively good time resolution (TTS ~ 150ps).
- Metallic packaging (kovar): resilient to magnetic field.



MAPMT application in LHCb RICH detector

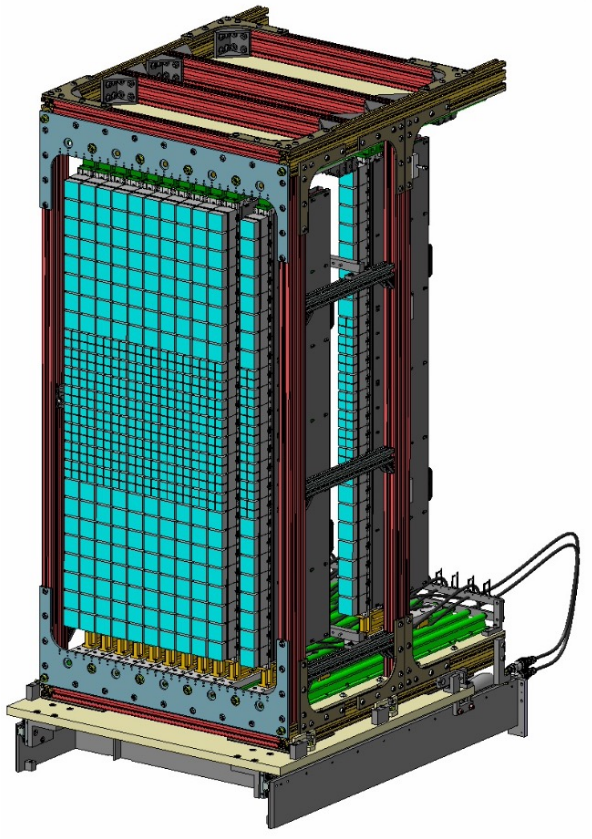
- LHCb experiment at CERN built to study b- and c-hadrons physics.
- Two Ring Imaging Cherenkov Detectors installed: π/K/p separation 2.6-100 GeV/c.
- Cherenkov cones generated by charged particles passing through gas radiator are imaged as rings on photon detector plane.

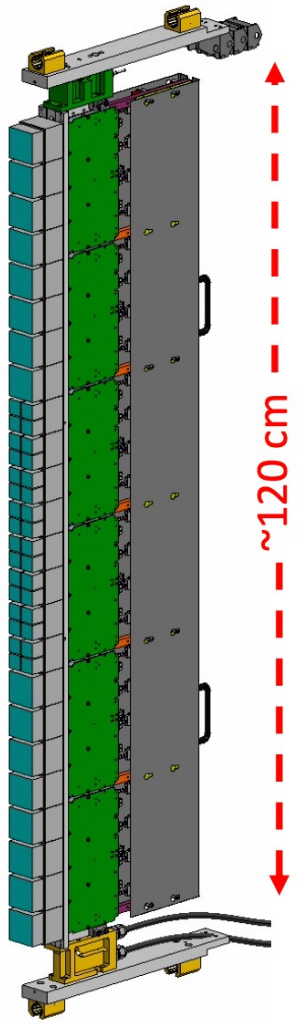




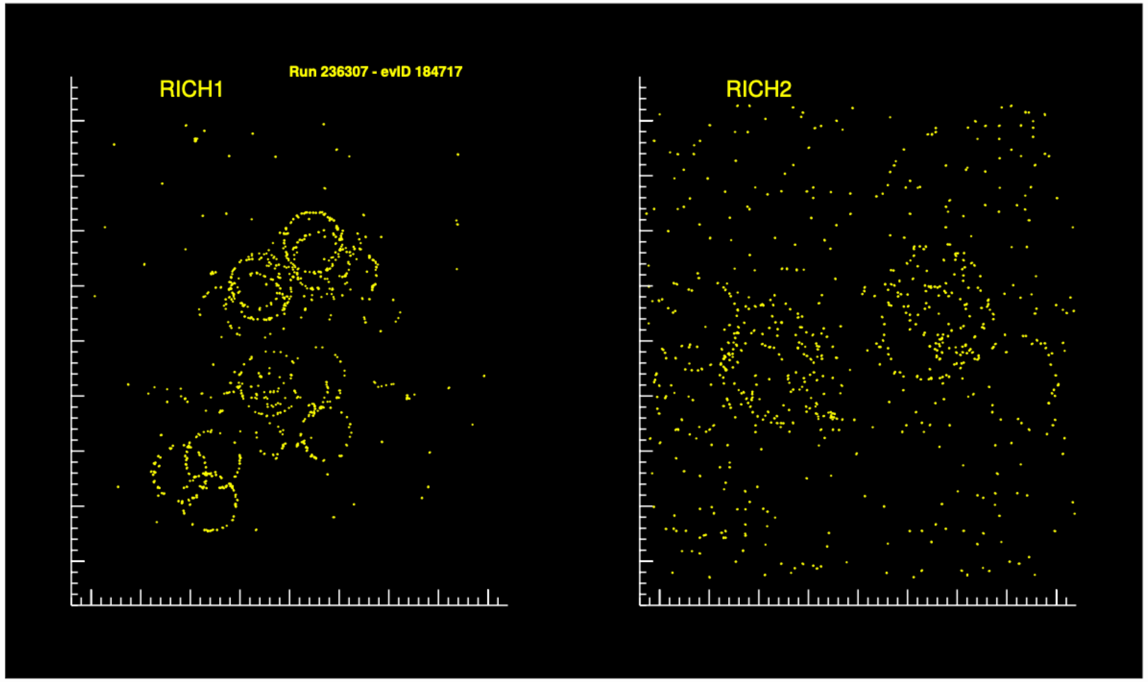
MAPMT application in LHCb RICH detector

MAPMT employed in RICH 2

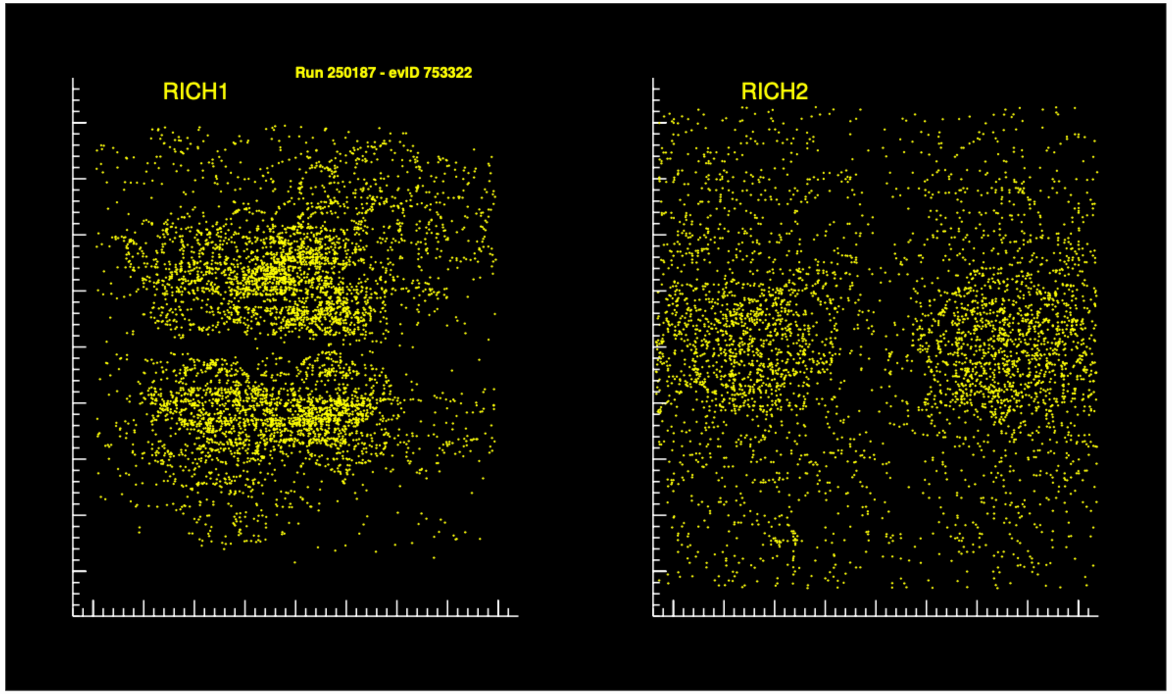




MAPMT application in LHCb RICH detector



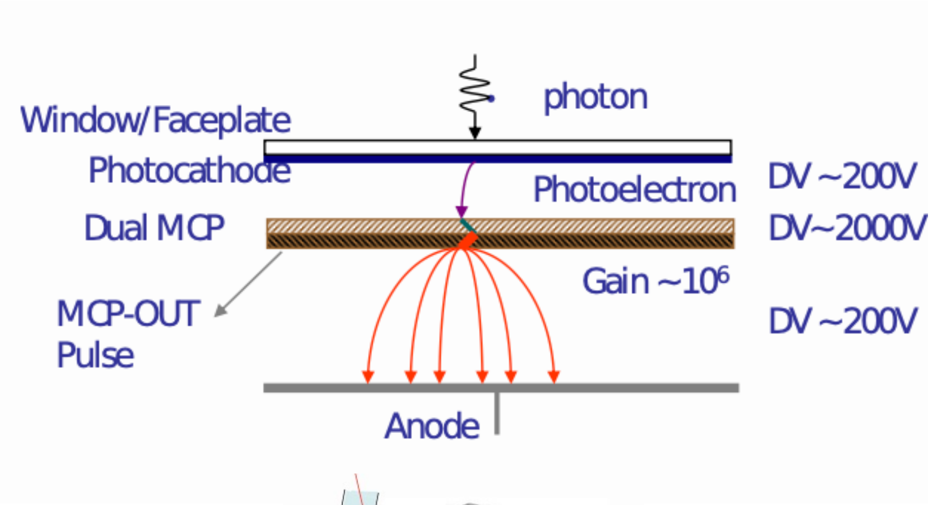
Characteristic ring shape signals.

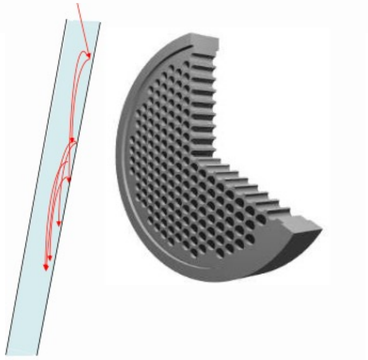


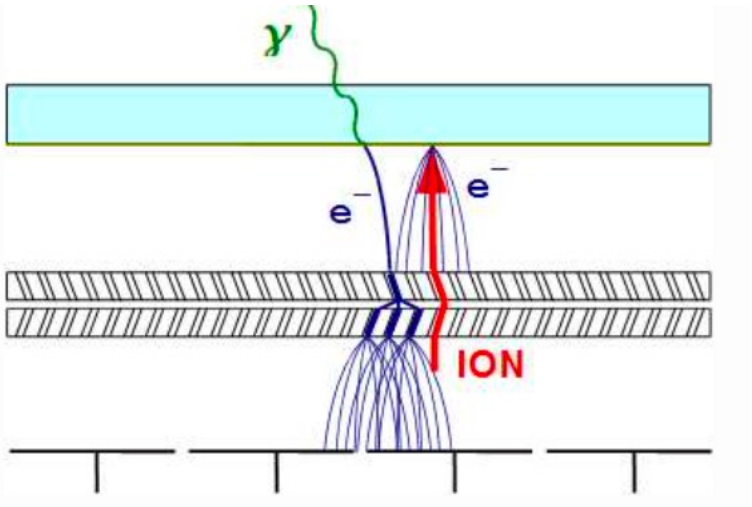
The importance of low noise and position sensitive photon detectors.

Micro Channel Plate PMT (MCP-PMT)

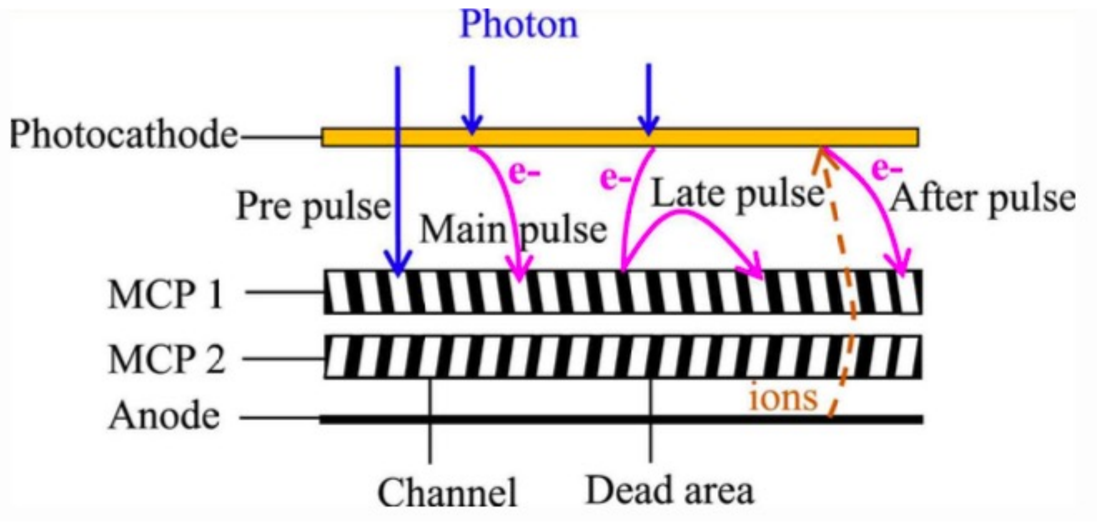
- Like PMT, but **continuous dynode structure** based on lead-glass disk with aligned pores, instead of dynodes structure.
- Gain ~$10^{6\text{-}7}$ **Me** single photon.
- Can be position sensitive with segmented anode.
- Small thickness leads to **excellent intrinsic time resolution**.
- Low sensitivity to magnetic field.
- They **age quite fast**. Back propagation of ions from the anode. Al foil between MCPs block is a trade-off solution.



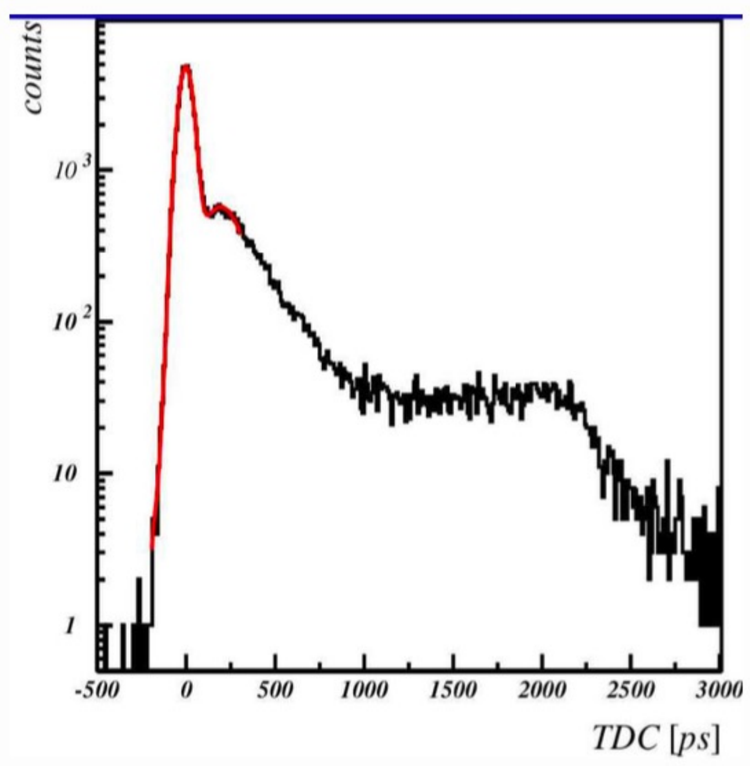




MCP-PMT timing properties



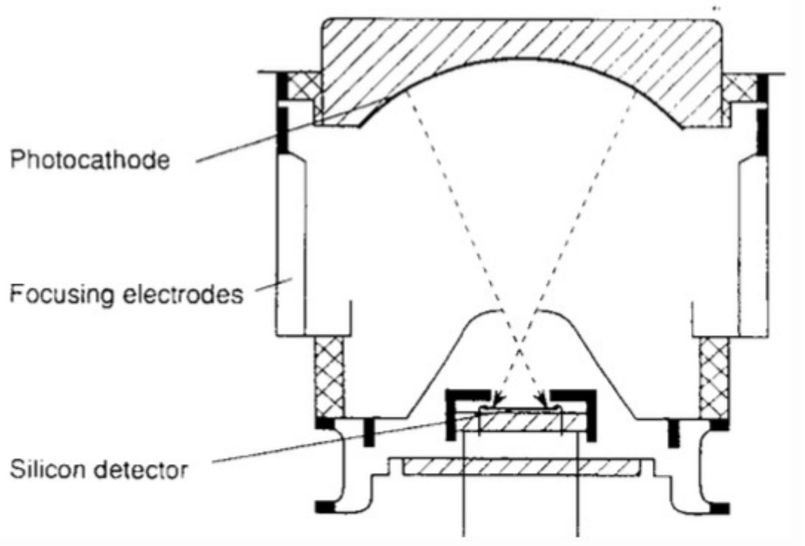
- Pre-pulse: no photon conversion in photocathode, SE in micro-channel, lower amplitude.
- Main pulse: photon conversion in photocathode, SE in micro-channel, nominal amplitude.
- Late pulse: after photoelectron backscattering and re-entry in micro-channel, ~nominal amplitude.
- After pulse (Ion Feed-Back): ionisation effects → Degradation of gain and quantum efficiency

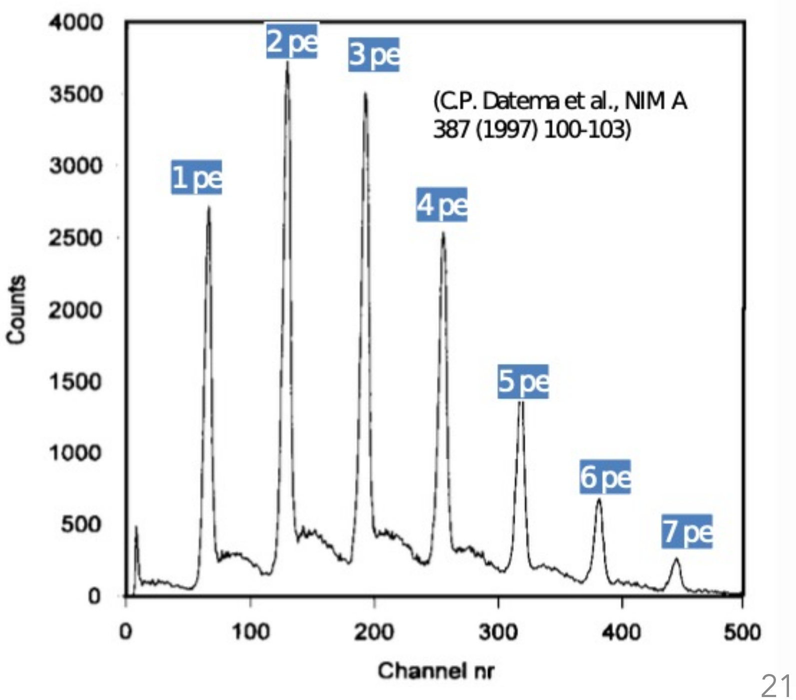


Single photon time distribution peaked at **~40ps**.

Hybrid photon detectors (HPD)

- Combination of **vacuum** and **solid-state** technology.
- **Gain**: single pe$^-$ highly accelerated (~20kV) creates e-h pairs in the solid-state detector anode (~5000e signal, Wsi = 3.6 eV).
- **Negligible gain fluctuation**, excellent E resolution.
- Great granularity (depends on silicon chip).
- **High voltage** needed (heating).
- Sensitive to magnetic field.
- **Low noise electronics** needed to detect small signal.
- Complicated manufacturing.





Solid state photon detector

p-i(n)-n photodiode biased in reverse direction, with thin p layer because visible light is absorbed quickly by Si.

Photodiode (PD):

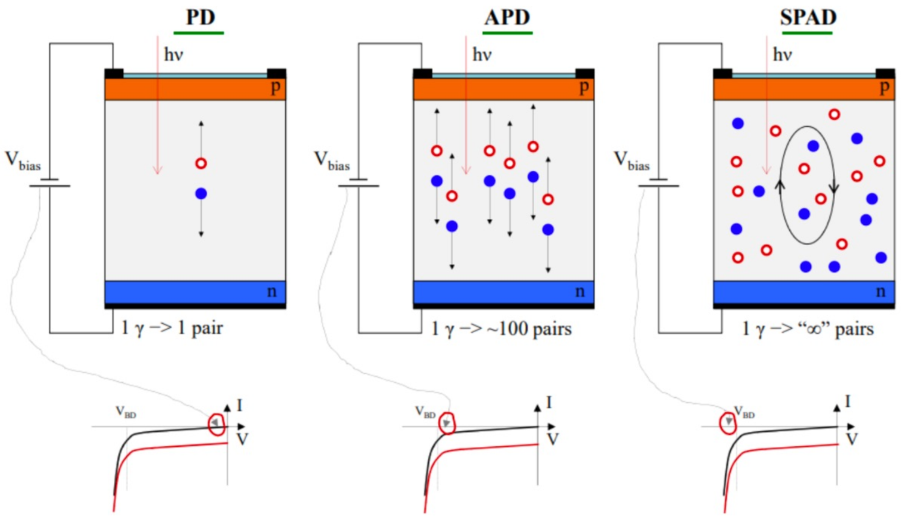
- Few volts in reverse bias 0V < Vbias < Vapd.
- Unitary gain.

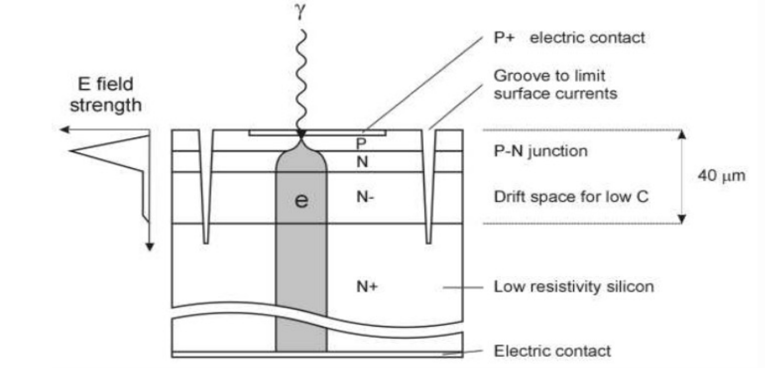
Avalanche PD (APD):

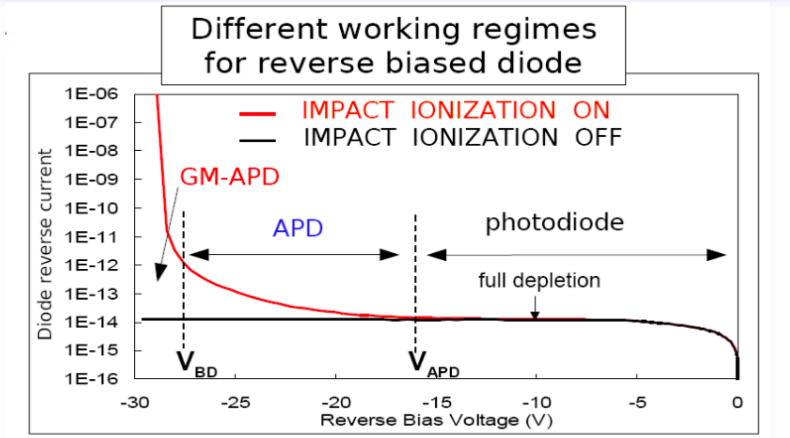
- Vapd < Vbias < Vbd
- photons create electron-hole pairs in the thin p-layer on top of the device and the electrons induce avalanche amplification in the high field at the p-n junction.
- Linear mode, gain 50-500, high gain fluctuation.

Single photon APD:

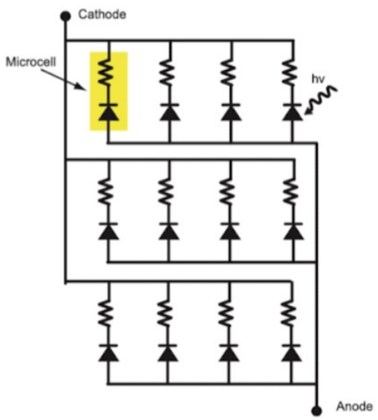
- Vbias > Vbd
- Geiger mode, self-sustained avalanche.
- Quenching circuit needed.

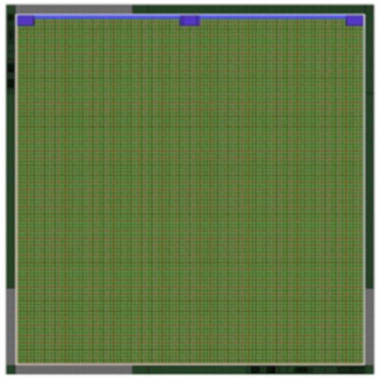




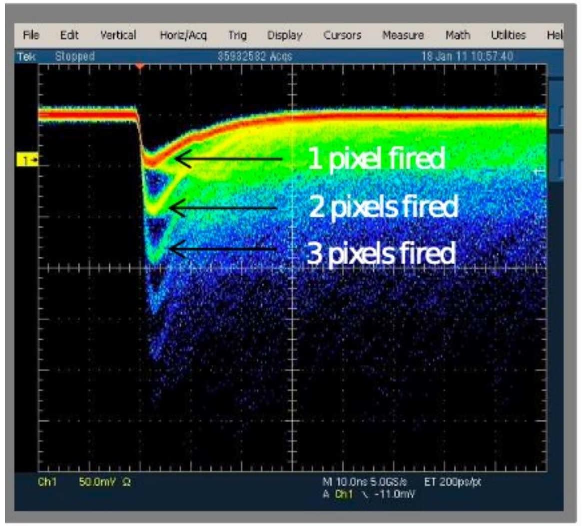


Silicon Photo-Multiplier (SiPM)





- Matrix of N pixels connected in parallel on a common Si substrate.
- Pixel: SPAD + **quenching resistor** (dimensions of 10-100μm).
  → dimensions affect several characteristics.
- Output current proportional to the number of fired pixels.
- **High QE** (~90%) of silicon in green/red. Several type sensitive on the blue range too.
- **Fill factor~40%.**
- **Good timing,** can reach down to **tens of ps**.
- Trenches between pixels to reduce **cross-talk** (photons from avalanche).
- High **dark count rate** (~10kHz at room temperature).
- High **radiation** environment induces defect in the silicon leading to high dark count rate and after-pulsing → **Annealing.**



Silicon Photo-Multiplier (SiPM)

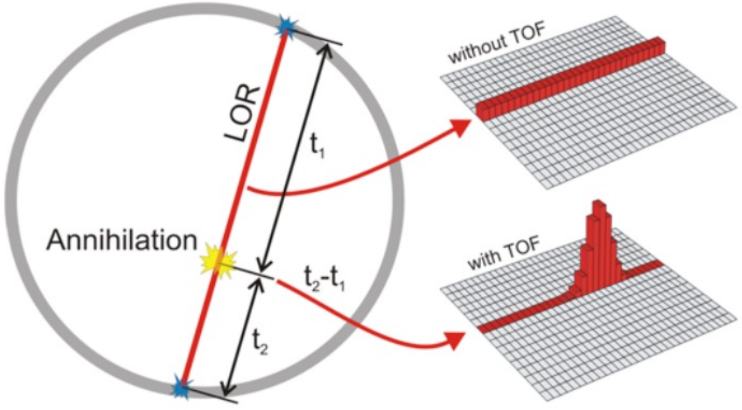
Advantages:

- High gain: 105 – 106 with low voltage (<100V).
- Low power consumption.
- Fast timing: ~ 50 – 100ps for single photons.
- Insensitive to magnetic field.
- High photon detection efficiency ~50%.
- Very compact, versatile geometry.

Disadvantages:

- High dark count rate at room temperature: 100kHz - 1MHz.
- High dependence on temperature.
- Optical cross talk.
- Sensitive to radiation damage: DCR can reach 100MHz after irradiation → need to operate at very low temperature.

SiPM application in TOF-PET



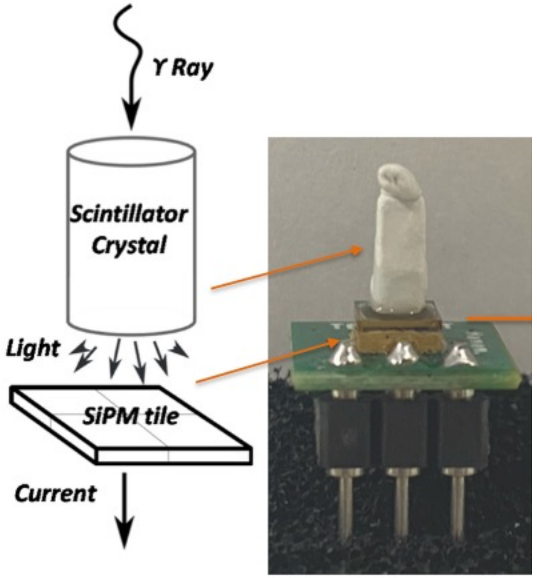
- **Positron Emission Tomography** systems exploit the emission of the anti-parallel 511keV γ-rays to generates several Lines Of Response (LORs), which allow to reconstruct the position of the annihilation events.

- **Time-of-Flight** information leads to higher resolution.

- **SiPMs** are used coupled with fast scintillators (LSO, BGO, …) to obtain resolutions in the order of 100ps.

- SiPM also allow **compactness and granularity**.

- No sensitive to magnetic field → possible coupling with MRI



Conclusions

- **Many types** of photon detectors developed over the years.
- **Sizes** from 1x1 mm to 20inch diameter.
- Single channel or position sensitive.
- Single photon operation or multi-photons.
- Each **application** can need different device adapted to wavelength, speed, magnetic field conditions, etc…
- Just **few examples** shown in these slides.
- **Constant R&D** ongoing to develop new technologies.