Radiation detection devices: core principles and diverse applications

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Outline

Introduction

Core Principles of Radiation Detection: *Types of Radiation, Interaction of Radiation with Matter*

Major Types of Detectors and Key properties: *Gas-Filled, Scintillators, Semiconductor, Efficiency, Energy – Spatial – Time resolution etc.*

Some Diverse Applications of Radiation Detectors:

- *Physics research experiments*
- *Nuclear related (waste management, energy production, safety...)*
- *Cultural heritage (artifact studies, archaelogical site inspections...)*
- *Safety and homeland security (illegal substances, explosives...)*

Closing remarks

A long way from...

first gold leaf electroscope built by Abraham Bennet in the 1700s

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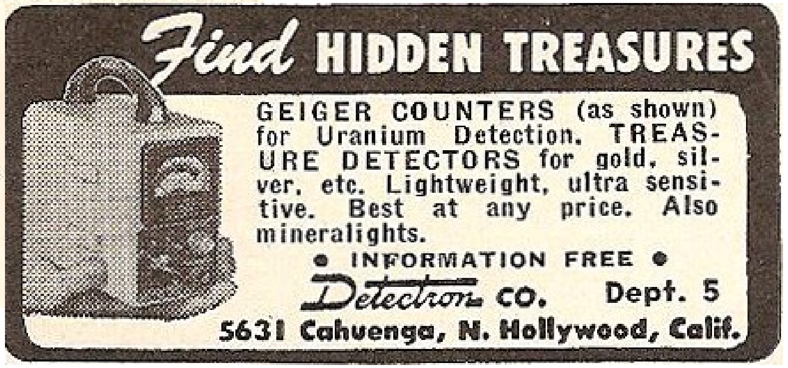

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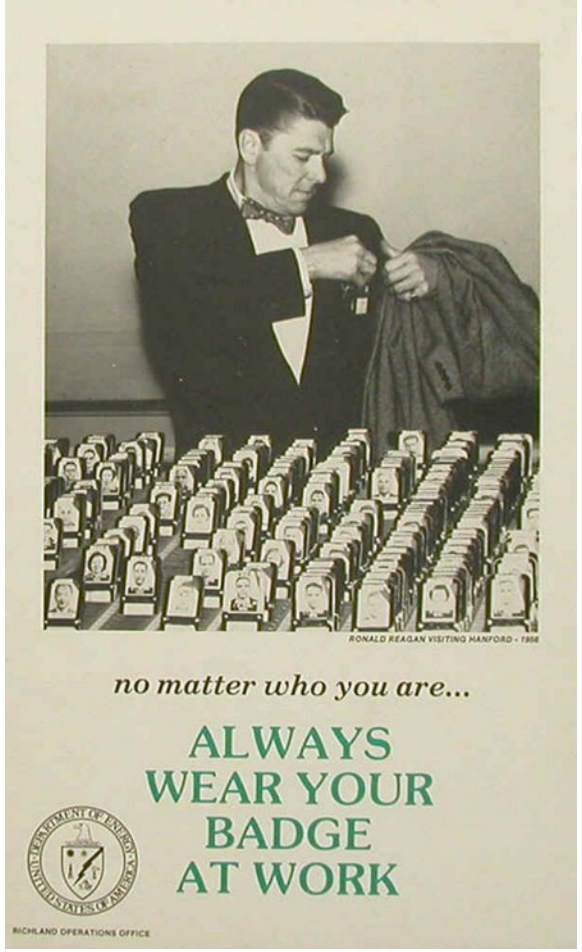
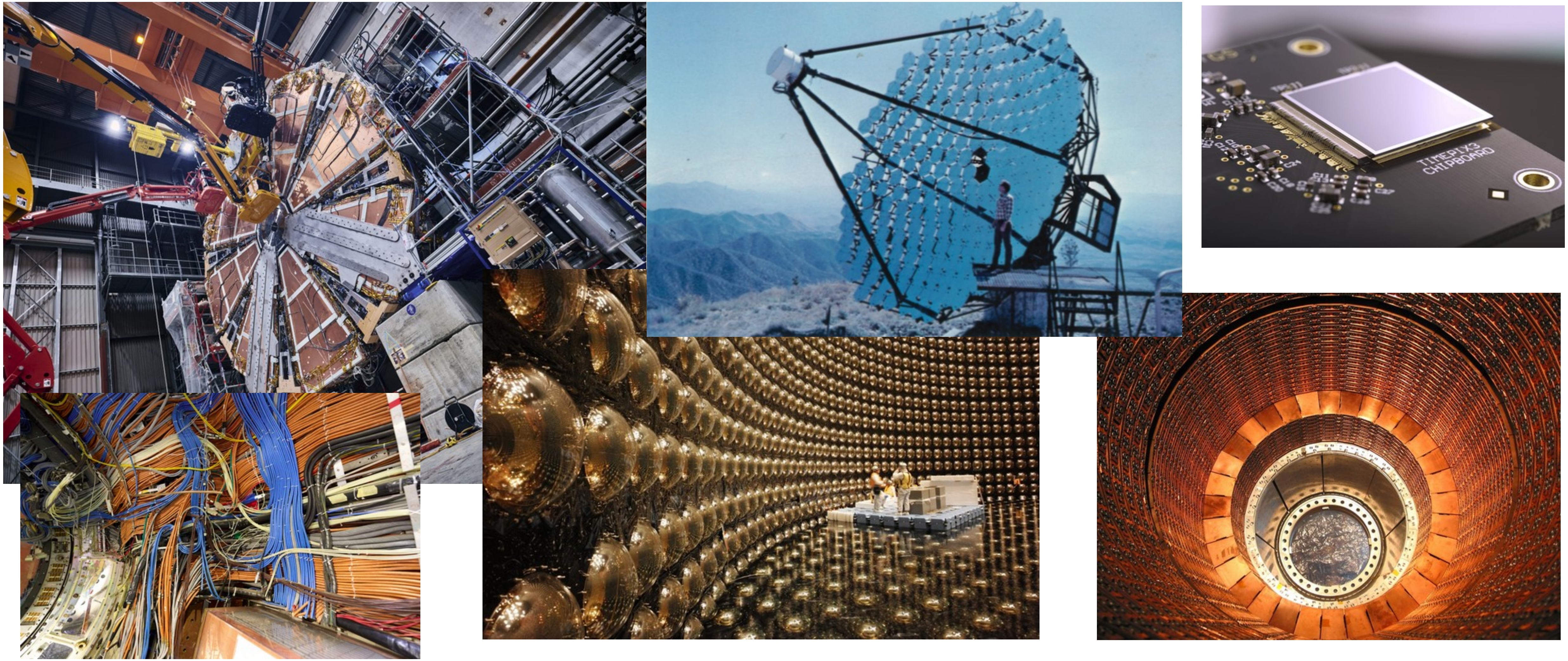
wrist band film badge



...to the most advanced



Radiation and Interaction with matter

Types of radiation

Ionizing Radiation:

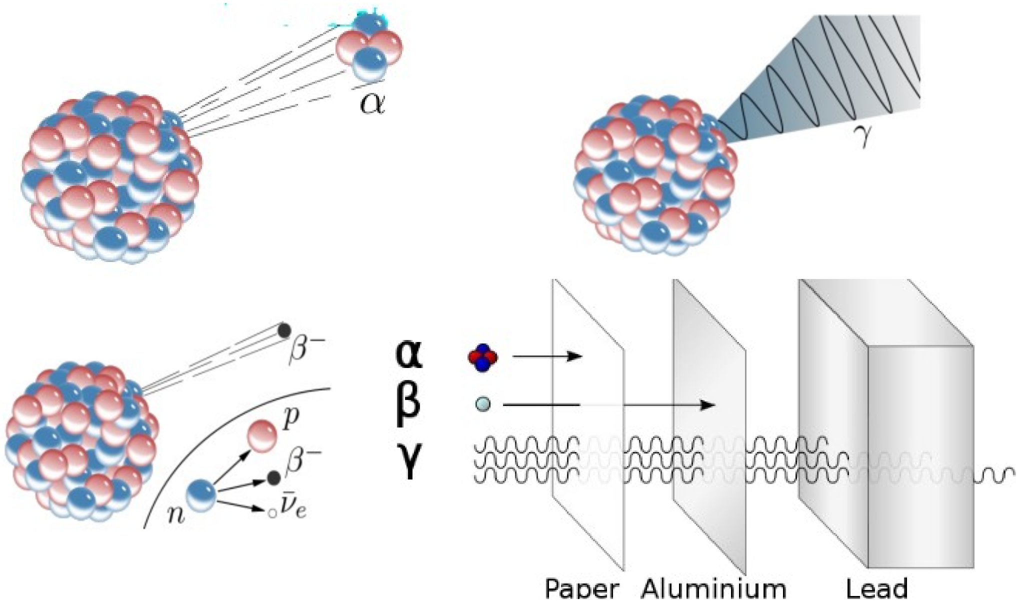
Alpha (α): Heavy, positively charged particles; low penetration (stopped by paper).

Beta (β): High-speed electrons or positrons; moderate penetration (stopped by plastic or a few mm of aluminum).

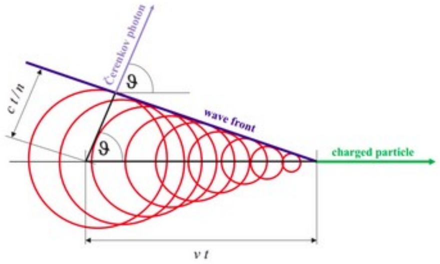
Gamma (γ) and X-rays: Electromagnetic radiation; highly penetrating (requires lead or thick concrete for shielding).

Neutrons: Uncharged, high penetration (requires hydrogen-rich materials like water or polyethylene).

Non-Ionizing Radiation: (e.g., microwaves, radio waves) does not ionize atoms but excites them.



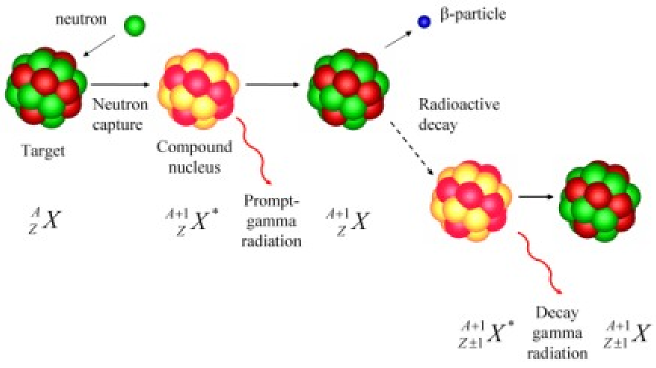
Different kinds of radiation travel different distances and have different abilities to penetrate



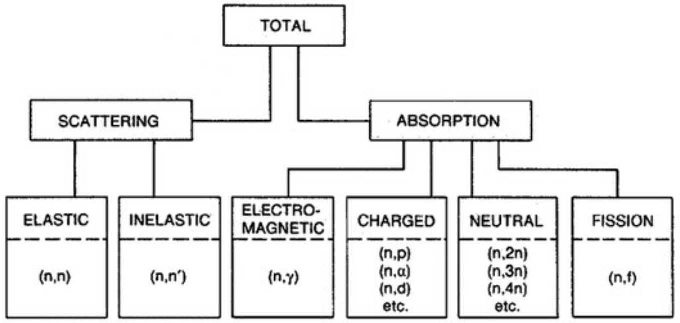
Other mechanisms to produce radiation: Cerenkov radiation, Transition radiation

Important for detection techniques

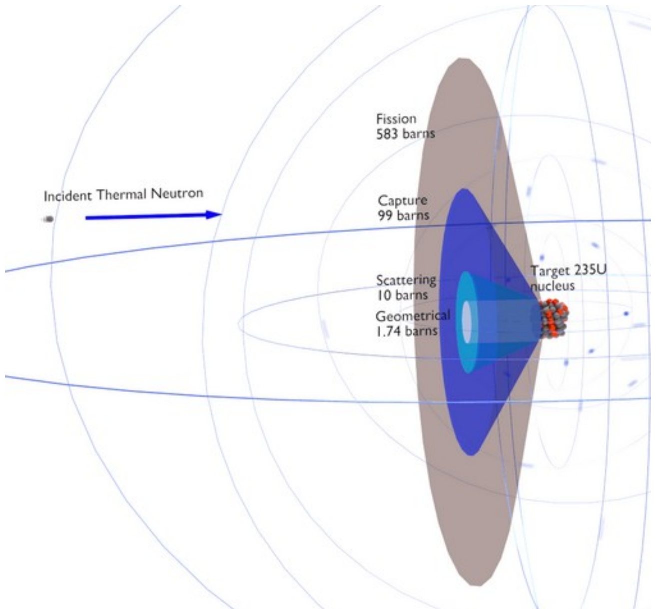
Neutrons: a special case (x – section reminder)



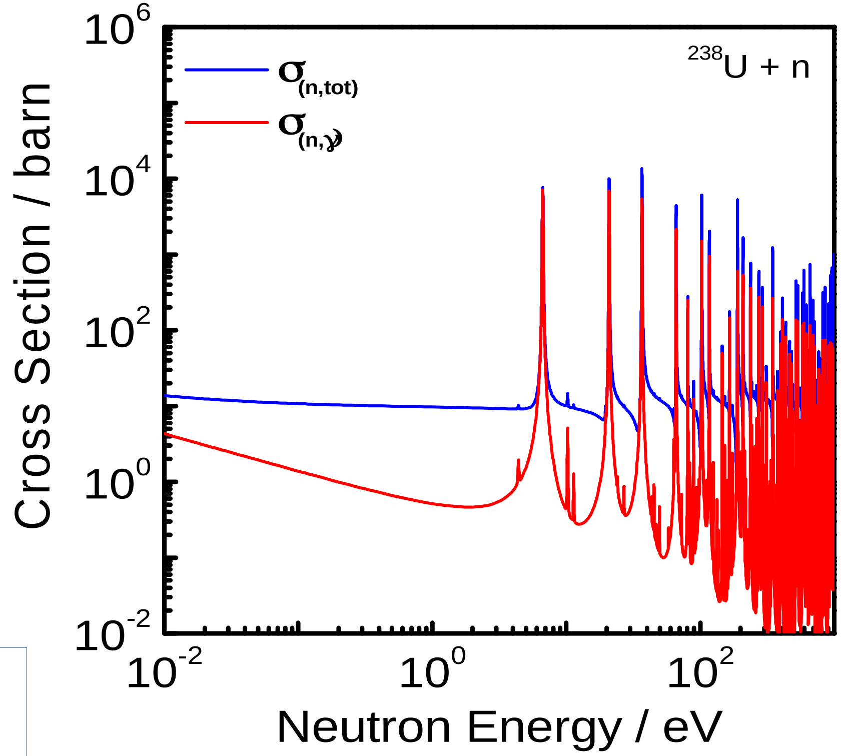
Neutron sources needed to apply specific techniques



The cross section depends strongly on the velocity of the neutron (E_n) and interacting nucleus



Typical way of n detection: use of converter material



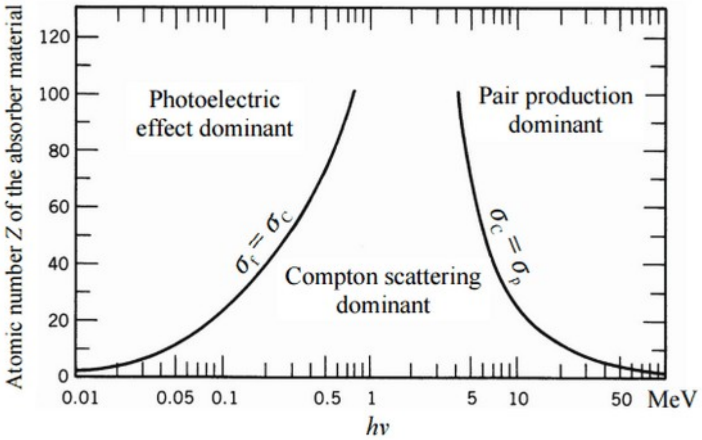
Interactions with matter

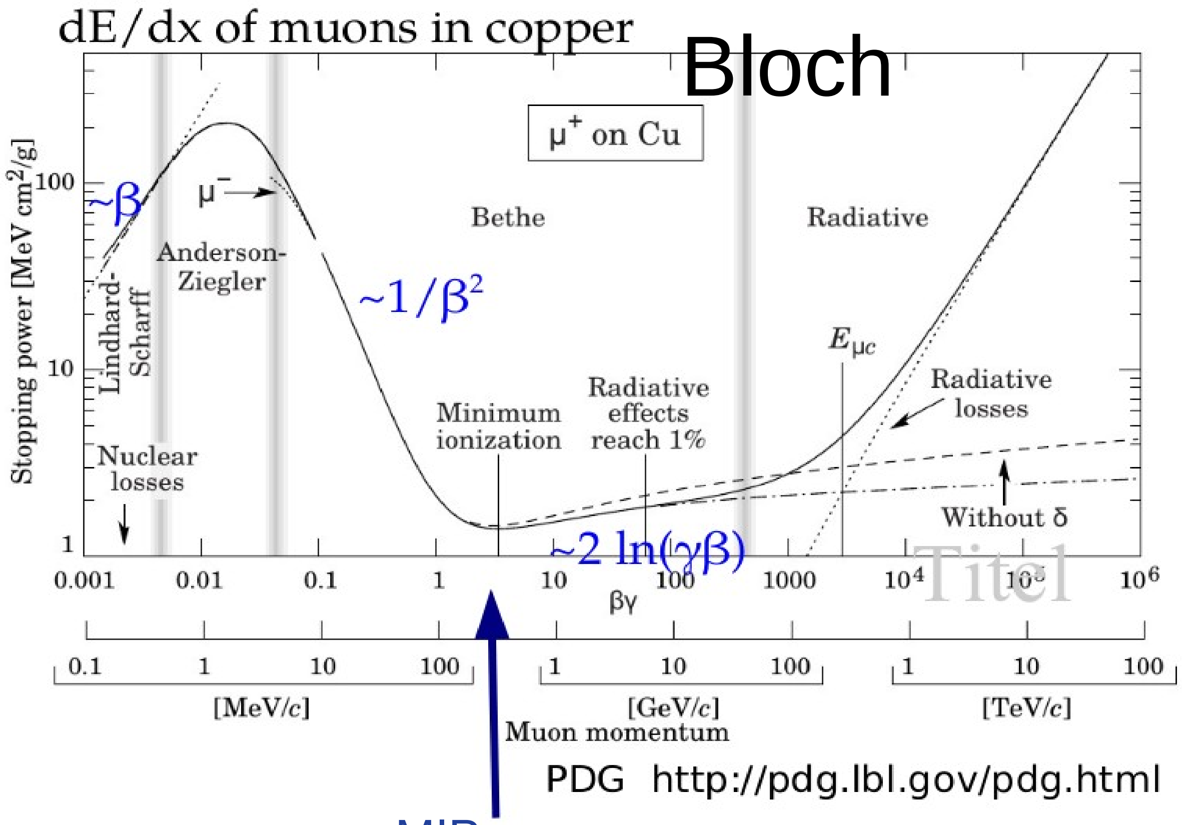
Main Goals: Detect and Identify!

Bethe – Bloch

Energy loss via Ionization, Bremsstrahlung, Multiple scattering.

Photons interacting with matter: Photoelectric Effect (PE), Compton Scattering (CS), Pair Production (PP).





PDG http://pdg.lbl.gov/pdg.html

MIP

Detection systems: basics

Universal concepts (reminder)

Regardless of the type of system (gaseous, scintillator, semiconductor)

Efficiency: What is detected compared to what actually reached the detector (intrinsic efficiency, geometric efficiency, overall efficiency)

Resolution: Energy, Spatial, Time

Energy Resolution: How well can the system measure the energy of the incoming radiation (usually expressed as a percentage or full width at half maximum, FWHM in energy units).

Spatial Resolution: The detector's ability to pinpoint the exact spot where radiation interacts.

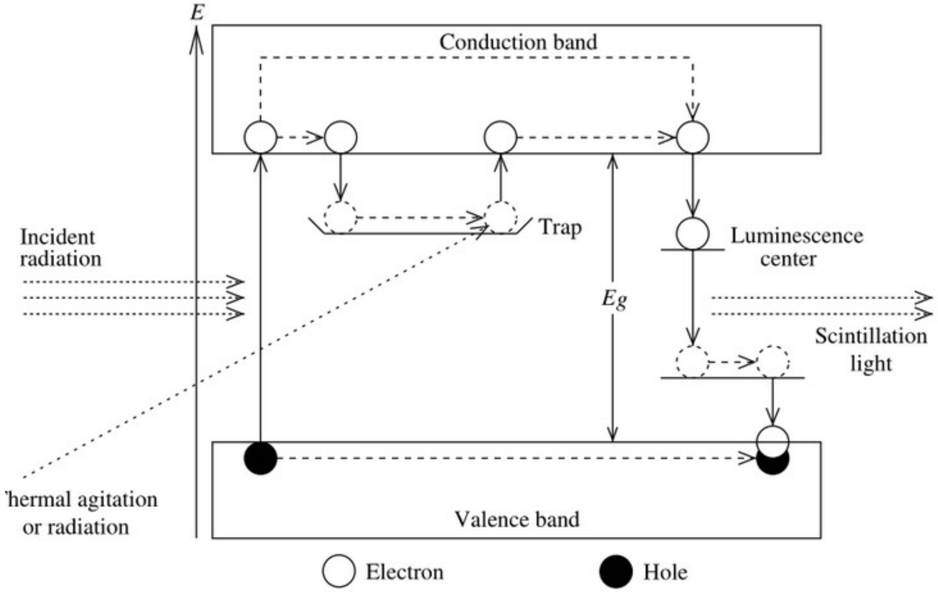
Time Resolution: The ability of the detector to distinguish between events that occur close together in time (determine the arrival of the particle – accuracy as a clock!).

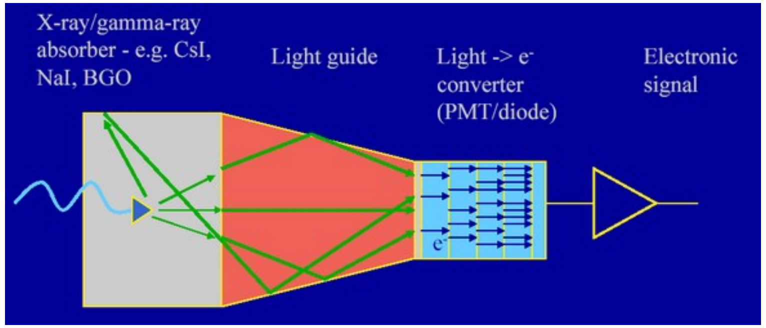
Background: unwanted events that is detected in addition to the radiation of interest

Scintillation detectors: basics

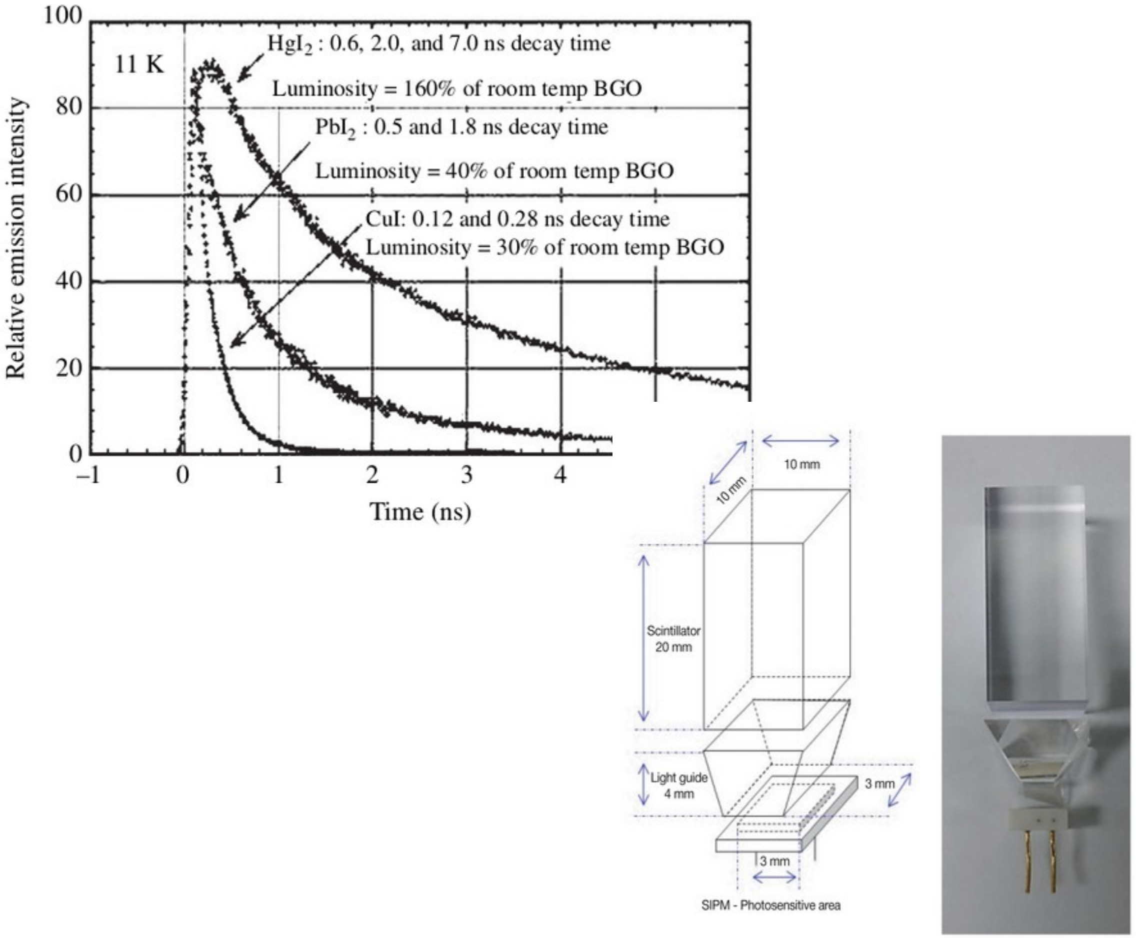
Creation of luminescence by interaction with ionizing radiation. Basic steps in scintillation detecting device:

- Incident radiation interaction with medium leads to emission of light (excitation – de-exitation process)
- Light is guided and collected by a photon sensitive devise (PMT or other photo-sensor)
- Electrons generated and multiplied create an electric signal
- Signal output corresponds to the light intensity and thus the deposited energy by the radiation in the medium





Scintillation detectors: properties I



Typical characteristics of scintillation devices:

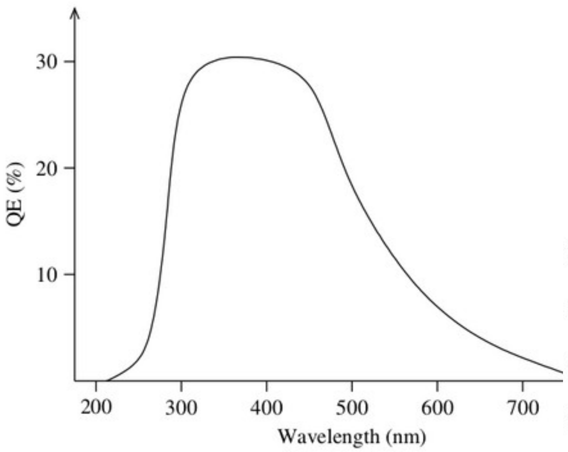
- Light yield: number of photons of specific λ produced per deposited energy (~ $2x10^4$ photons/MeV). Dependence on material, energy/type of radiation.
- Time profile: Duration of scintillation phenomenon is characteristic for each material (fast signal requires shorter time profile).
- Scintillation material should be as transparent to the wavelength of the scintillation photons.
- Light collection efficiency should be a high as possible.

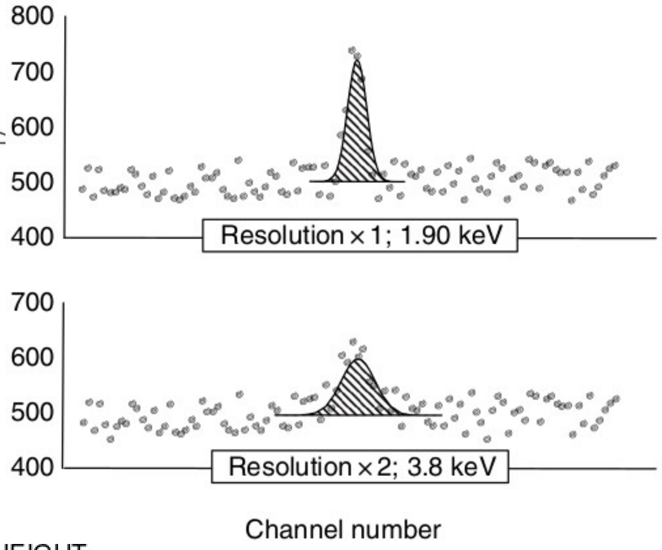
Chemical nature: Organic & Inorganic Scintillators
Physical state: Solid, Liquid, Gaseous

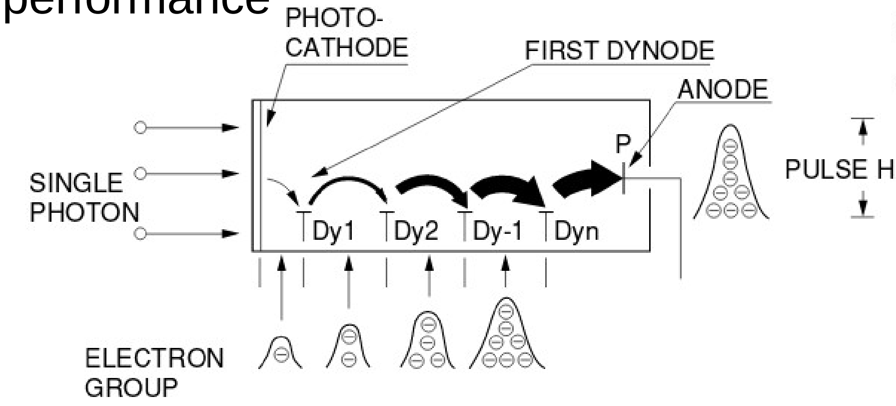
Scintillation detectors: properties II

Important properties of scintillation detection systems:

- Quantum efficiency: the rate of photons converted to electrons as a function of wavelength, Higher means more efficient system.
- Energy resolution:how well the system can distinguish different deposited energies by the incident radiation.
- Stability and Durability: how stable is the performance of the system in time.



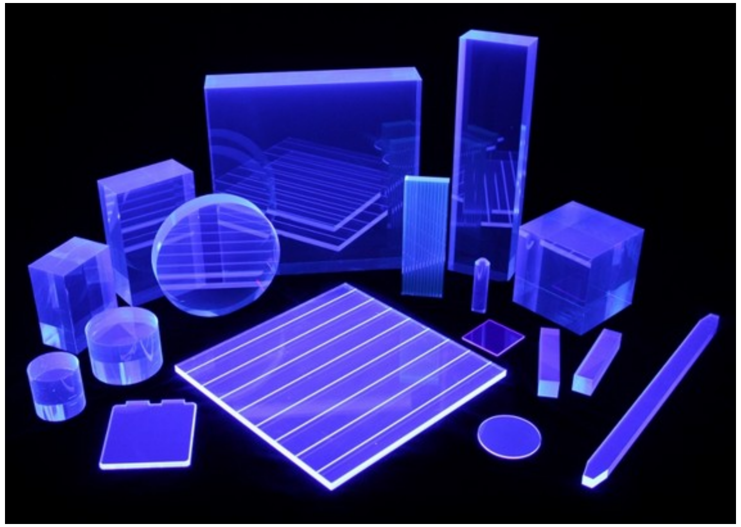


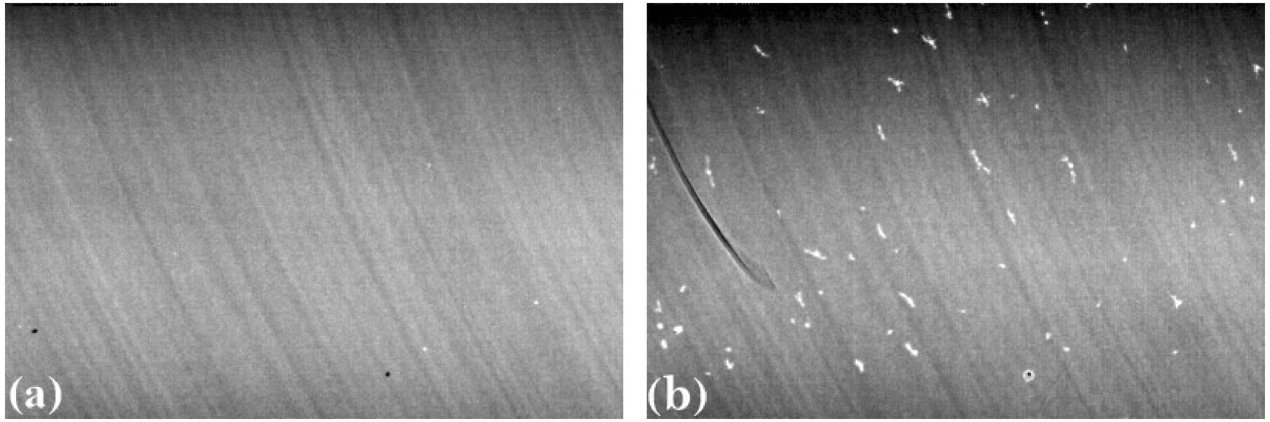


Scintillation detectors: radiation damage

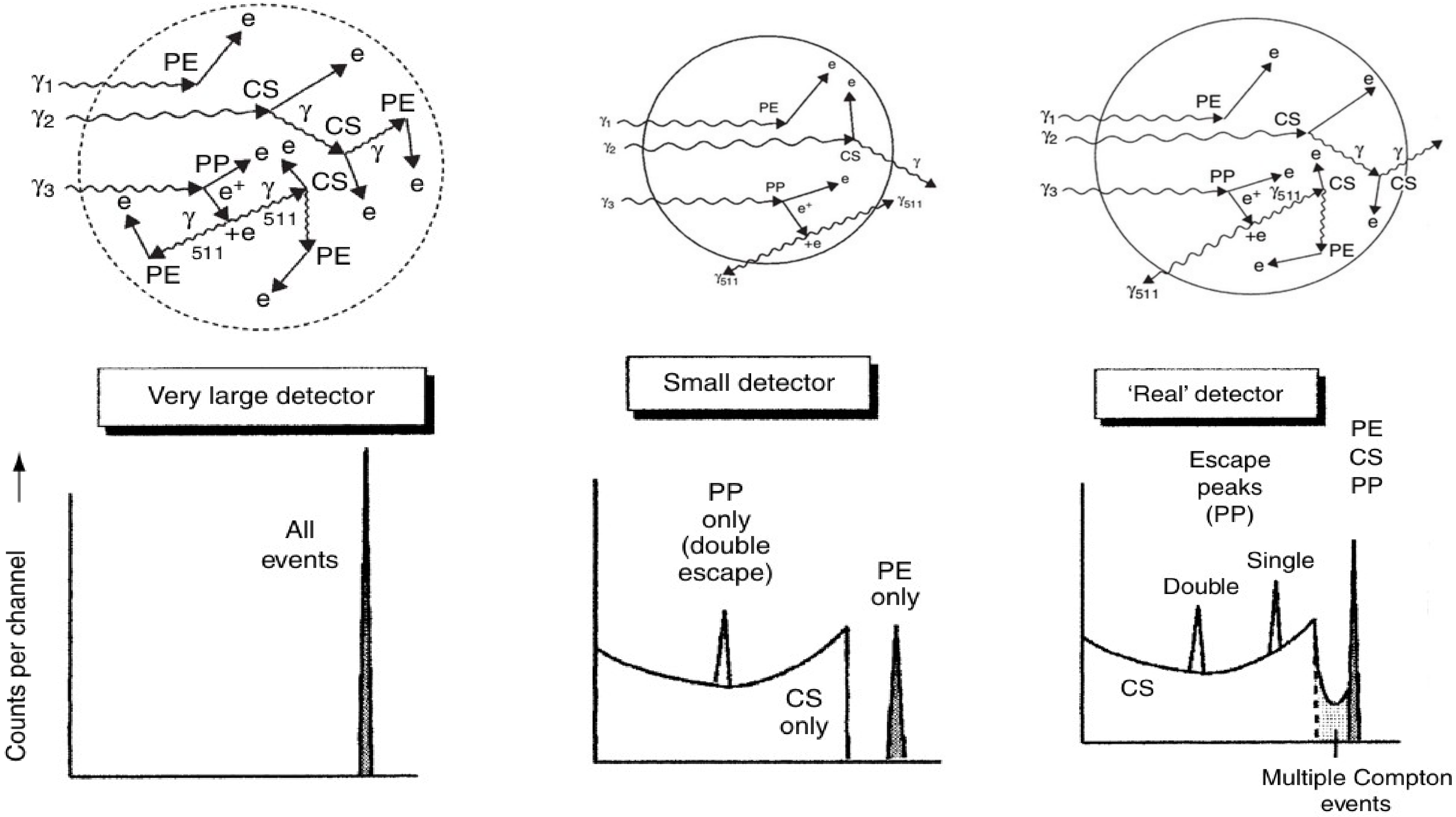
Scintillators can be prone to radiation damage potentially causing:

- Reduced light yield
- Decreased transparency
- Physical degradation of the scintillator material, reducing the overall efficiency





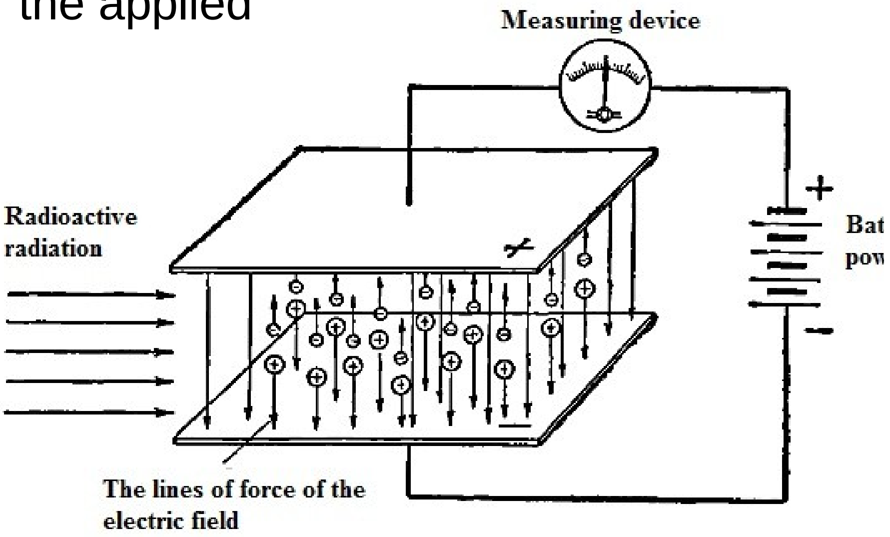
Scintillation detectors: gamma spectroscopy

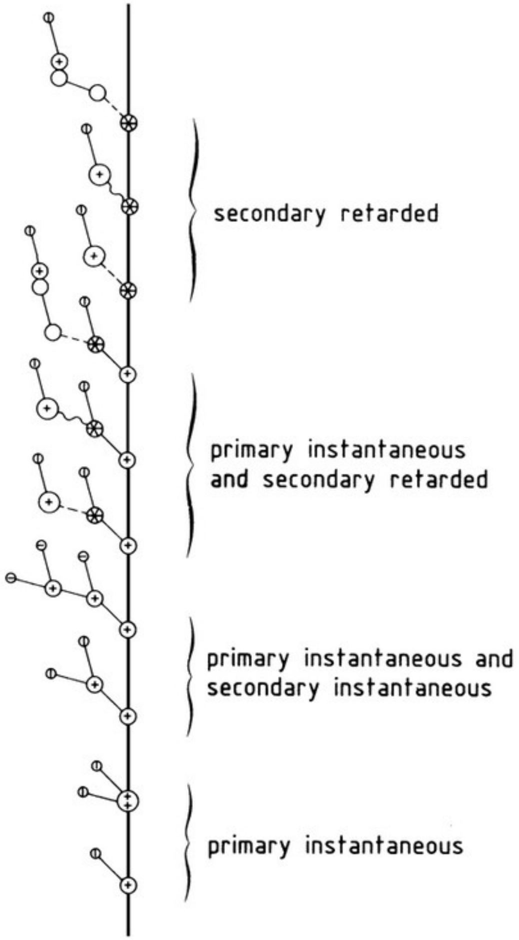


Gaseous detectors: basics

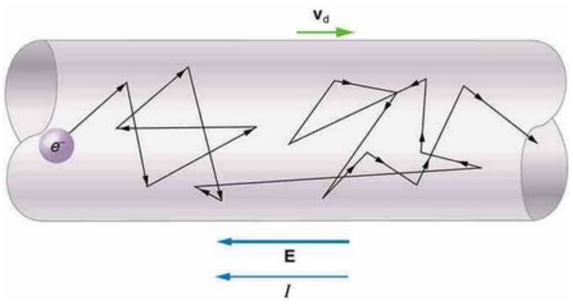
Charged produced via ionization of the medium. Basic steps in detecting device:

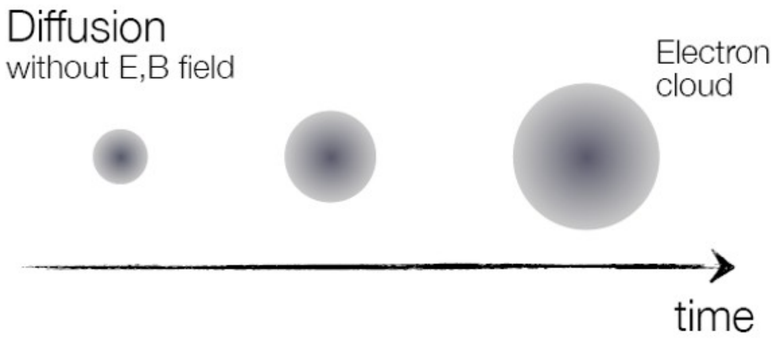
- Incoming radiation ionizes gas molecules, creating ion pairs
- Charge carriers drift under the influence of the applied electric field.
- Once charges move, signal is induced.





Gaseous detectors: properties I

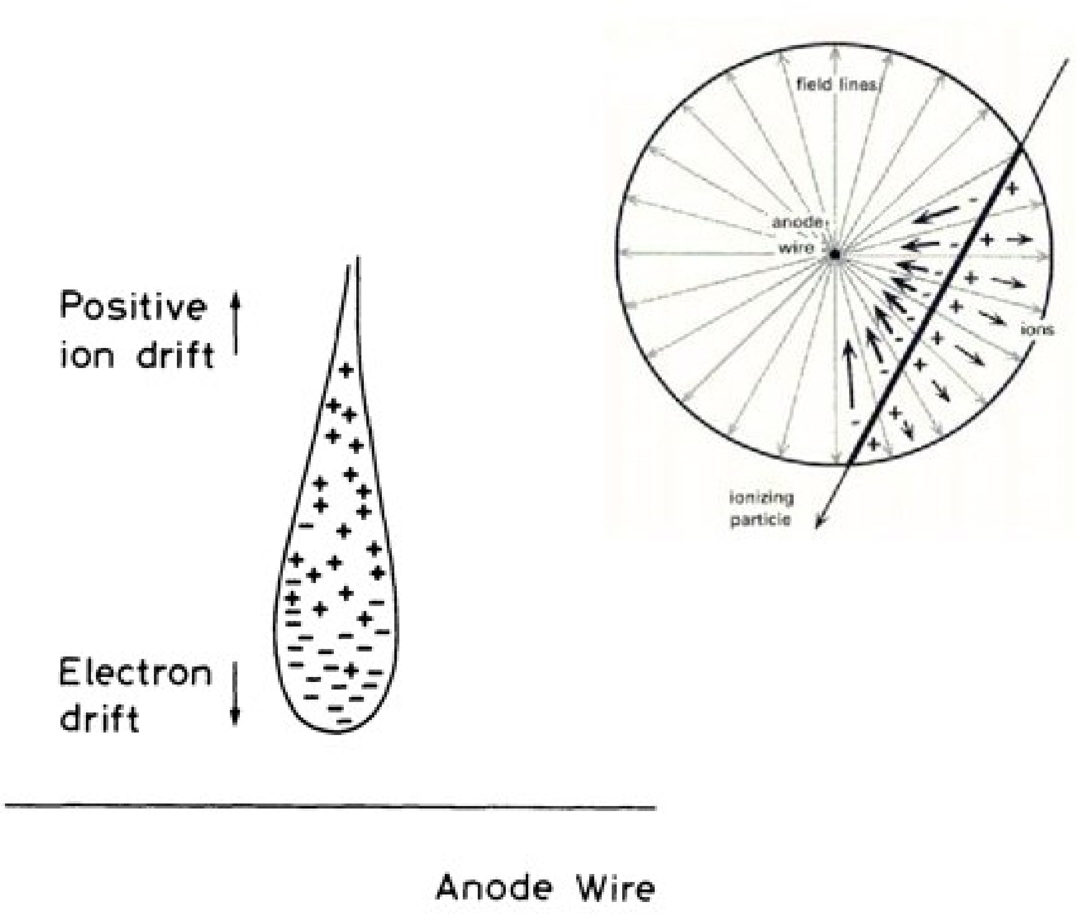




Key properties of gas-filled devices:

- Drift velocity: macroscopic observable, the average speed of charge carriers drifting though the gas volume. (E-field only and E – B field cases).
- Diffusion: Positive ions or free electrons created within the gas have some tendency to diffuse away from regions of high density due to the random thermal motion. A point-like collection of free electrons will spread about the original point into a Gaussian spatial distribution whose width will increase with time.
- Diffusion depends mainly on gas pressure, temperature and mean free path of the charge carriers

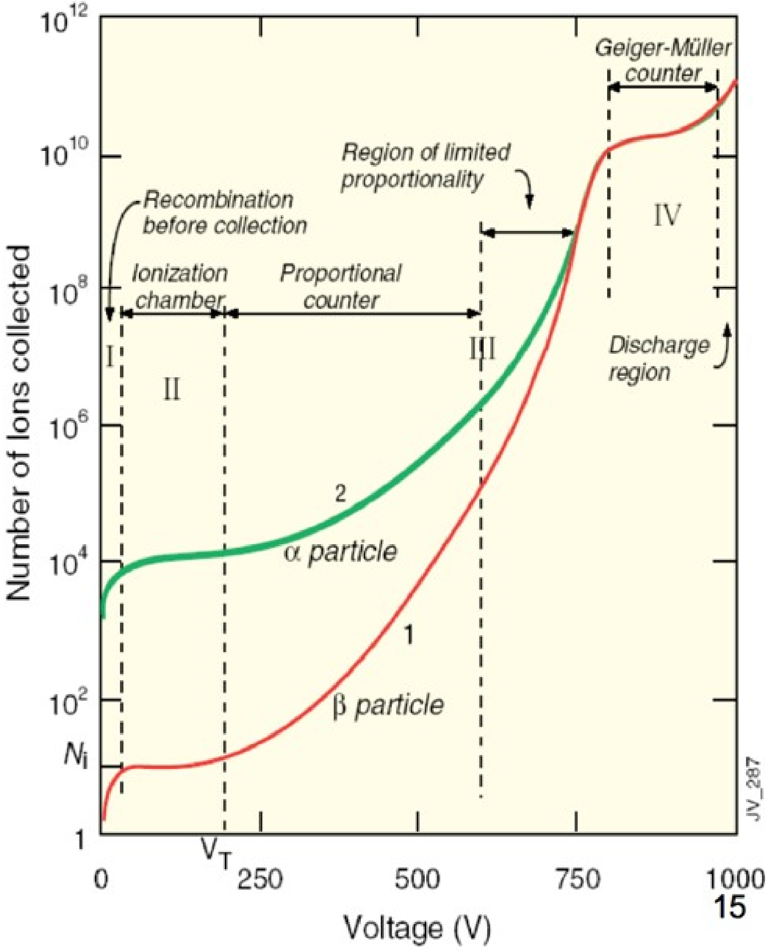
Gaseous detectors: properties II



Key properties of gas-filled devices:

- Multiplication: the number of ions created per path length defines the 1st Townsend coefficient
- Gas gain G: defined as the ratio between the number of electrons reaching the anode over the initial number of electrons at the point where multiplication is starting.
- Amplification depends strongly on the geometry of the detection system (parallel plates vs cylindrical geometry).

Gaseous detectors: properties III



Ionization mode:

Full charge collection

No multiplication – gain = 1

Proportional mode:

Multiplication of ionization

Signal proportional to ionization

Measurement of dE/dx

Secondary avalanches need quenching

Gain ~ 10^4 – 10^5

Limited proportional mode (saturated, streamer):

Strong photoemission

Strong quenches or pulsed HV

Gain ~ 10^{10}

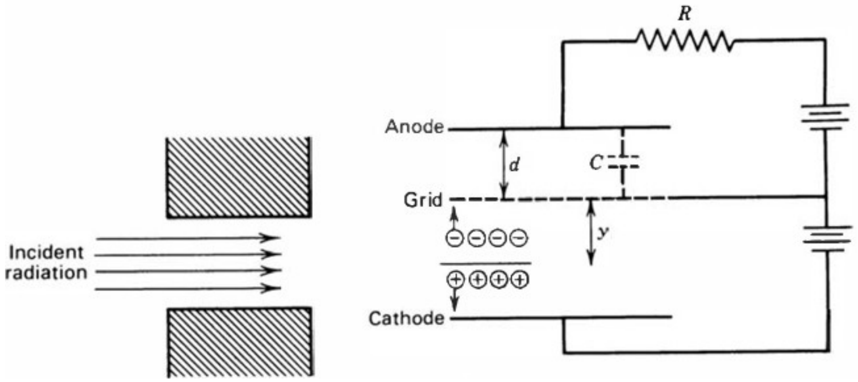
Geiger mode:

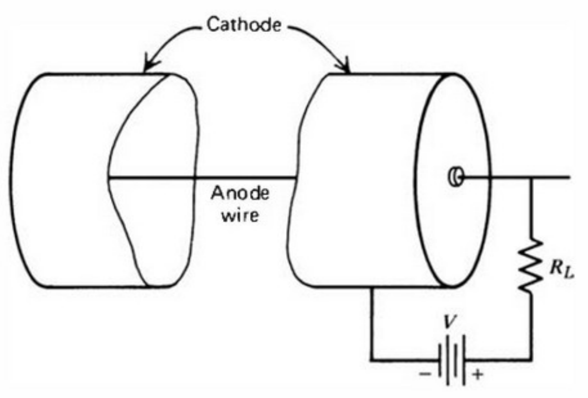
Massive photoemission

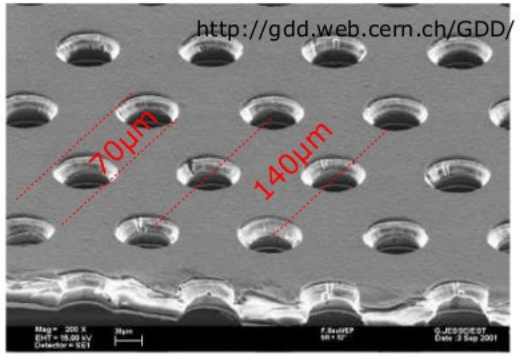
Full length of anode wire affected

Discharge stopped by HV cut

Gaseous detectors: types







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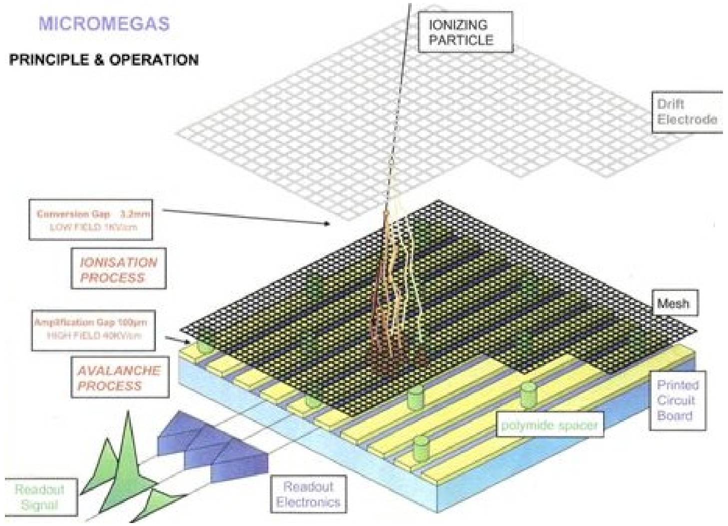
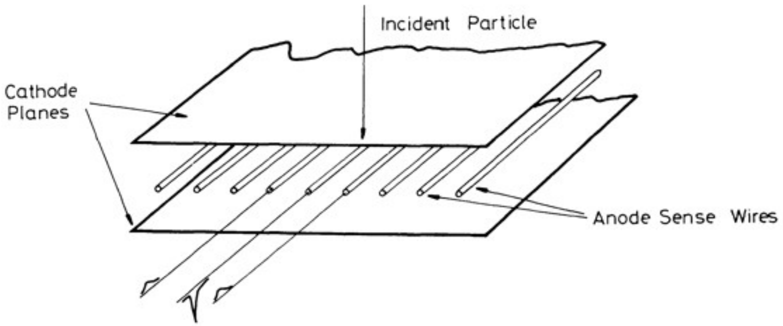
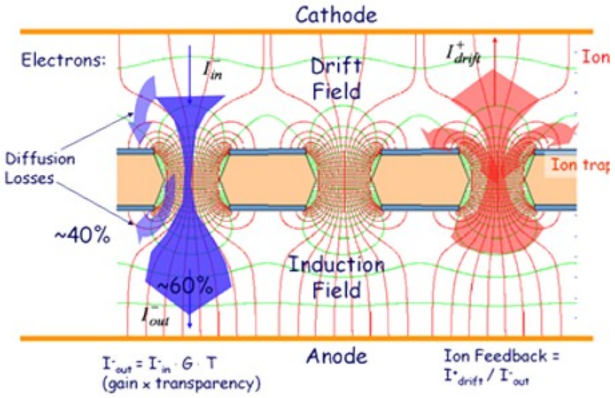


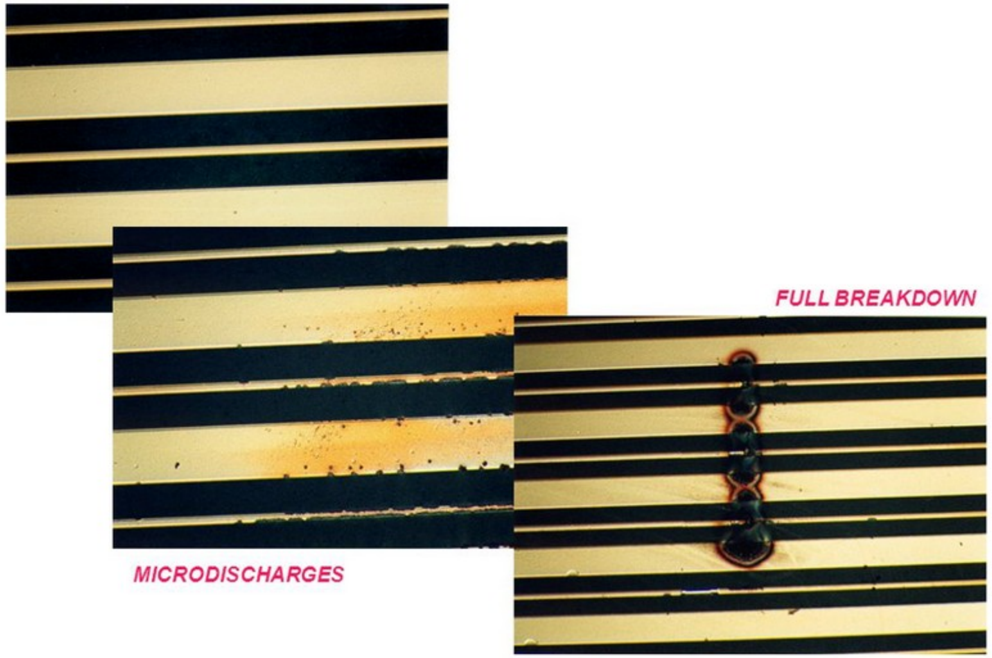




http://www.infn.it/csn5/joomla/GEMINI/

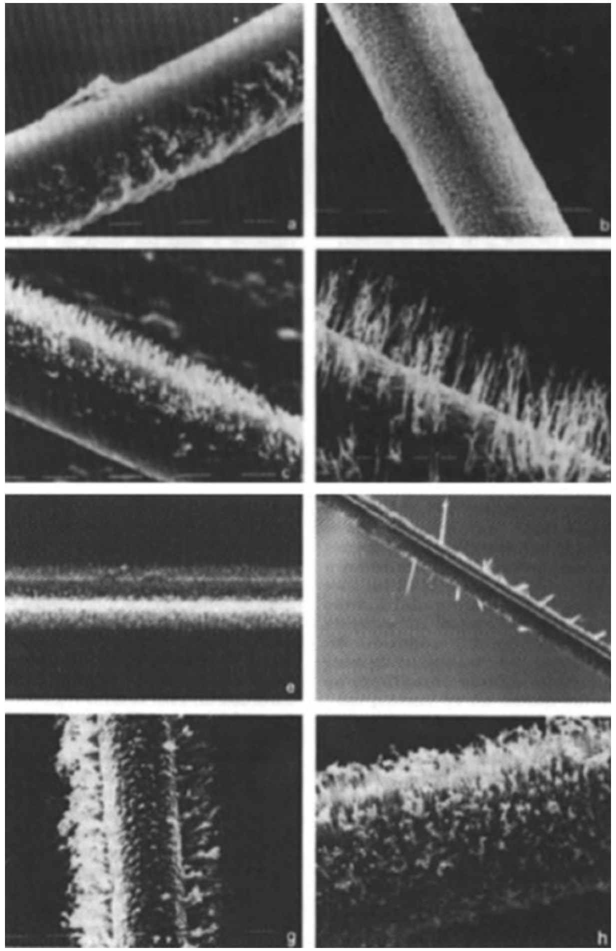
Gas Electron Multiplier (GEM)

Gaseous detectors: radiation damage (and others)



Ageing can occur:

- Mechanical stress can alter the electrostatic properties.
- Gain degradation due to long term used (accumulation of large numbers of avalanches), leading the reduced energy resolution.
- Polluting molecules producing deposits on wires

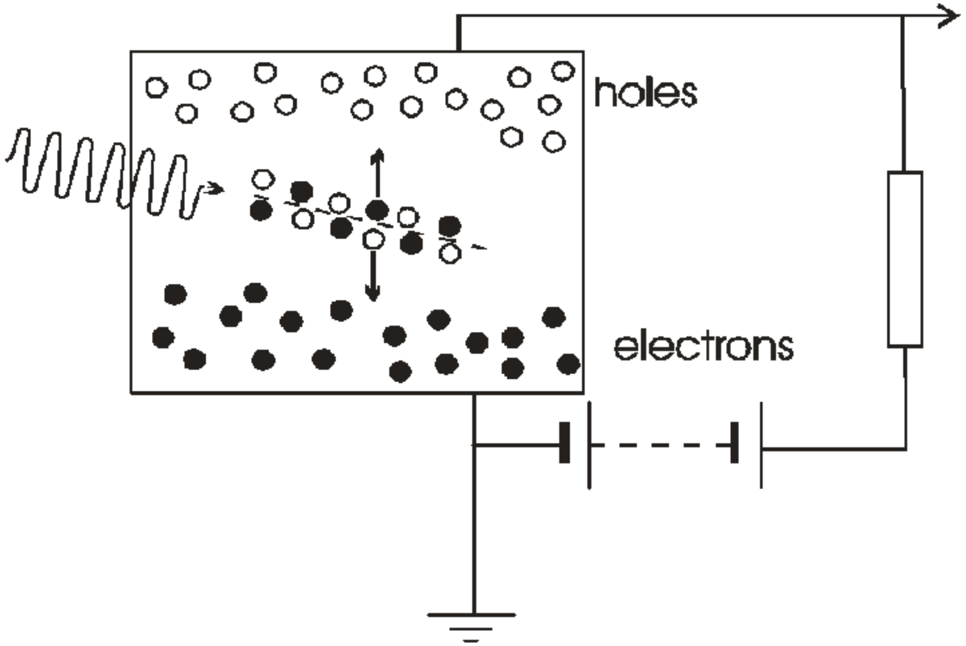


F.Sauli courses IEEE-NSS 2002

Semiconductor detectors: basics

Operation similar to an ionization chamber. Basic steps in detecting device:

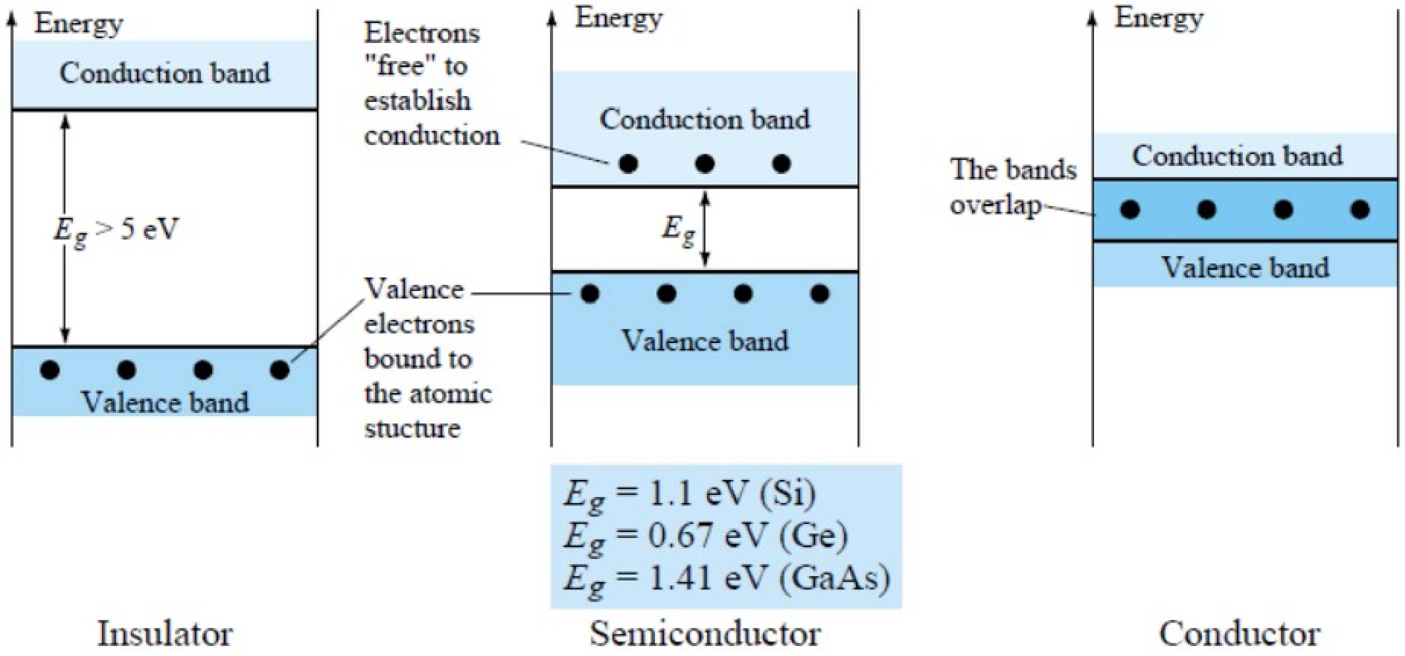
- Radiation interacts with the medium creating electron – hole pairs (instead of e – ion pair in gas).
- Applying electric field, leads to collection of charges.
- Many applications (gamma spectroscopy, tracking and vertexing, PID).
- Low temperature requirements and radiation damage issues.



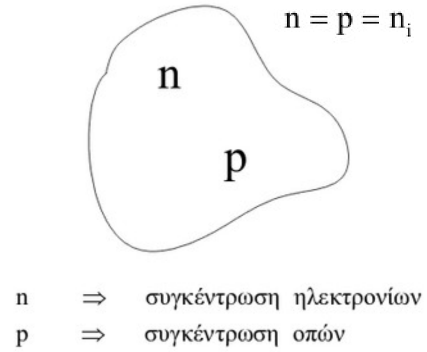
Semiconductors: properties

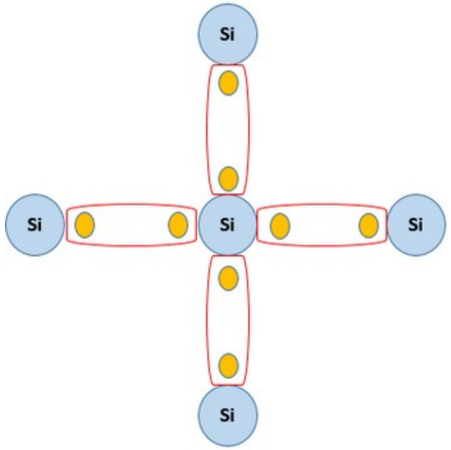
Charge carriers produced via ionization of the medium. Basic steps in detecting device:

- Eg ~ 1 eV for semiconductors, many electron
- High density leading to high stopping power
- Creation of large number of e/h pairs (direct impact on energy resolution capabilities)



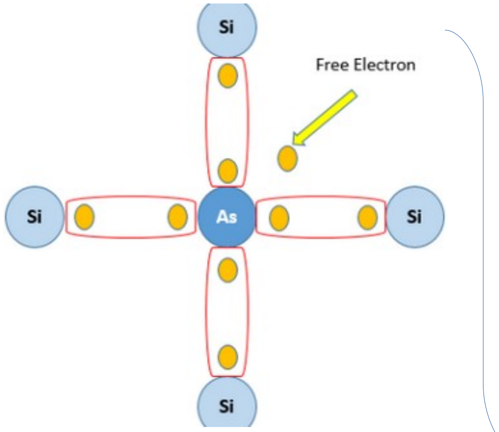
Semiconductors: types

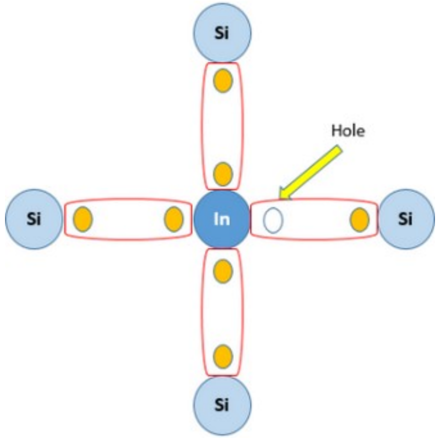




pure

N-type





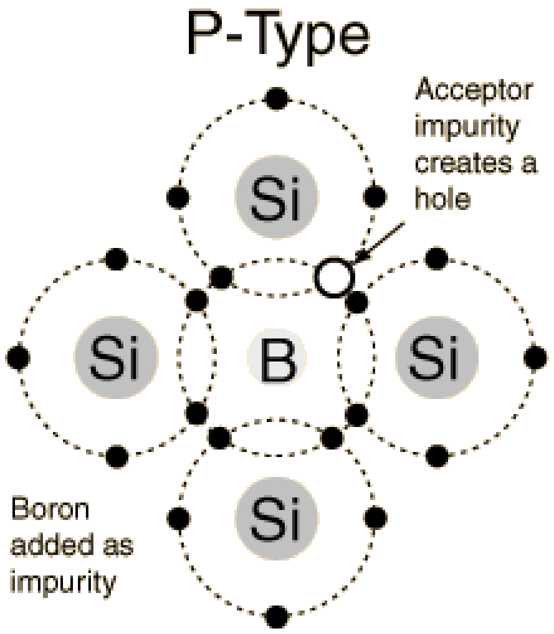
P-type

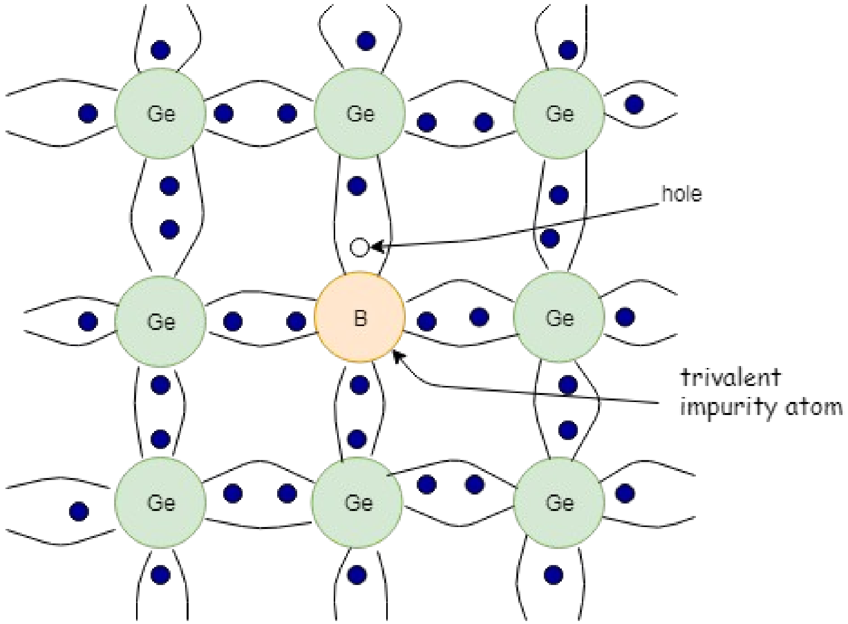
doped

Semiconductors: pure (intrinsic) vs doped

- Pure: balance between negative/positive (no intentional impurities) e.g. Si and Ge
- Doped (n-type): a dopant is introduced with more valence electron than the semiconductor material
- Doped (p-type): a dopant is introduced with less valence electron than the semiconductor material
- Doped semiconductors are essential in creating electronic components

Semiconductors: B in Si and Ge

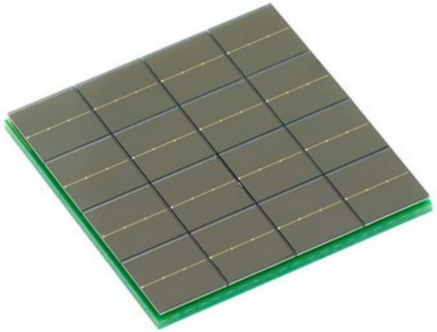




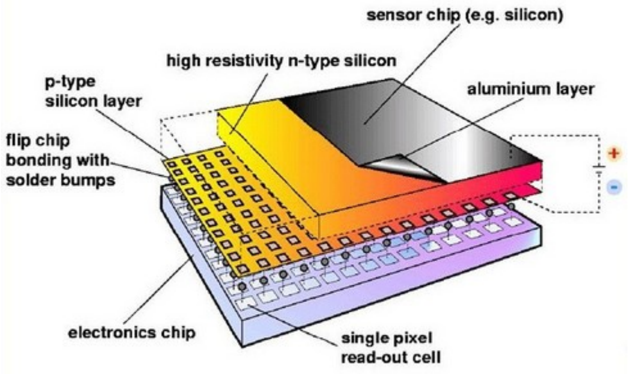
Semiconductor detectors: types

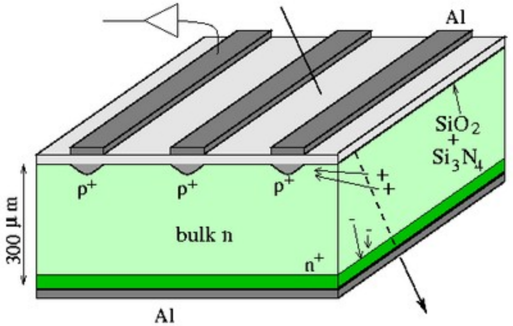
Many types for multiple applications:

- Silicon (Si), Germanium (Ge), Cadmium Zinc Telluride (CZT)
- Silicon Drift Chambers
- Photodiodes, Avalanche Photo Diodes (APD)
- Silicon Photomultipliers (SiPM)
- ...



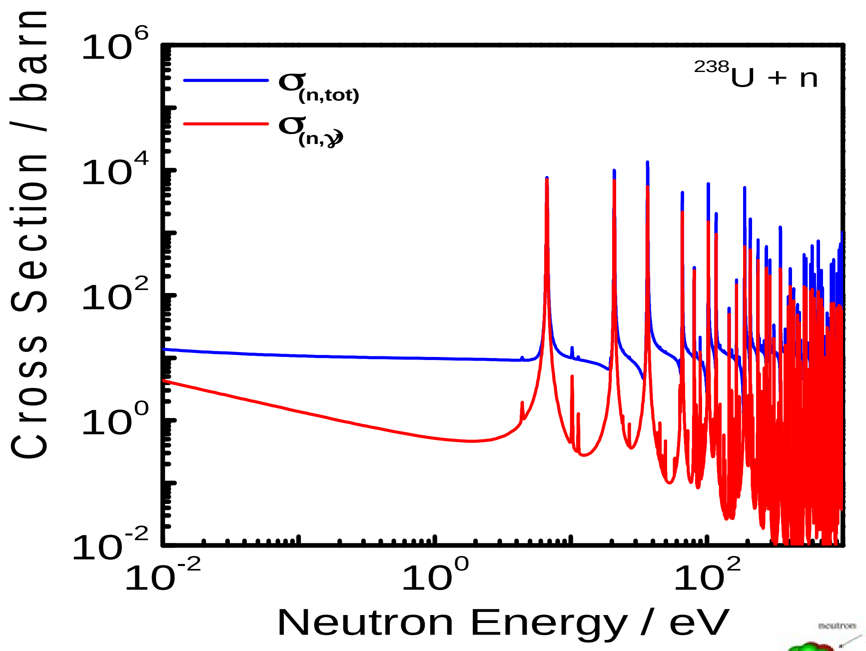
Various types, geometries, applications..



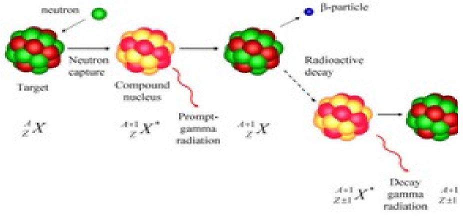


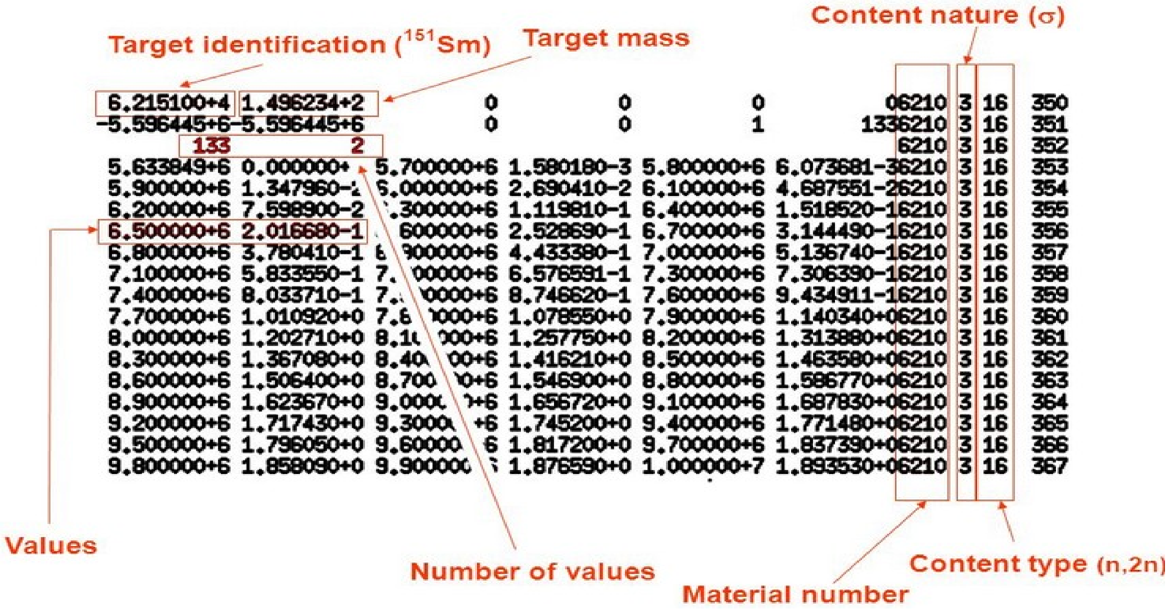
Applications: neutron related

Nuclear Reaction Data



- Energy dependent x-section
- Angular and energy distributions for products
- Neutron resonance parameters
- Neutron multiplicities
- Decay schemes
- Uncertainties





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 9.200000+6 1.717430+0 9.3000   +6 1.745200+0 9.400000+6 1.771480+06210 3 16  365
 9.500000+6 1.796050+0 9.60000   6 1.817200+0 9.700000+6 1.837390+06210 3 16  366
 9.800000+6 1.858090+0 9.900000    1.876590+0 1.000000+7 1.893530+06210 3 16  367
```

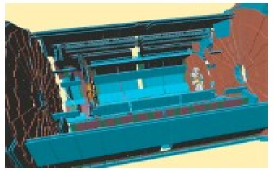
Focus mainly on neutron induced reactions.
Limited (but expanding) coverage of charged-particles, photons, etc.

Motivation: Who needs Neutron Data?

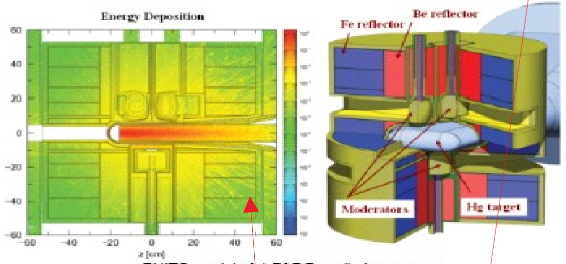
Physics basic research
- experiments design
- testing theory models
- experimental data analysis

Astrophysics

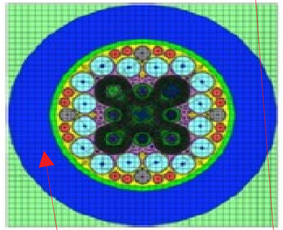
Energy production
- reactors R&D
- radiation shielding
- operation safety
- waste disposal

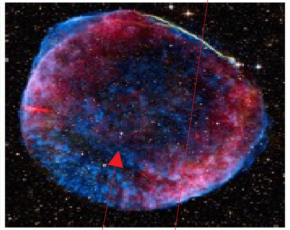

ATLAS detector muon system, simulated in GEANT4


"Neutron carwash" radiation detector



PHITS model of J-PARC spallation source


SCALE model of INL Advanced Test Reactor


Supernovae are the site of r-process nucleosynthesis

ENDF B-VII.1


NNDC Brookhaven

Homeland security
- detection of nuclear materials
- illicit trafficking
- criticality calculations
- devices R&D

Nuclear Medicine
- radiotherapy
- dose calculations
- radioisotope production
- diagnostics

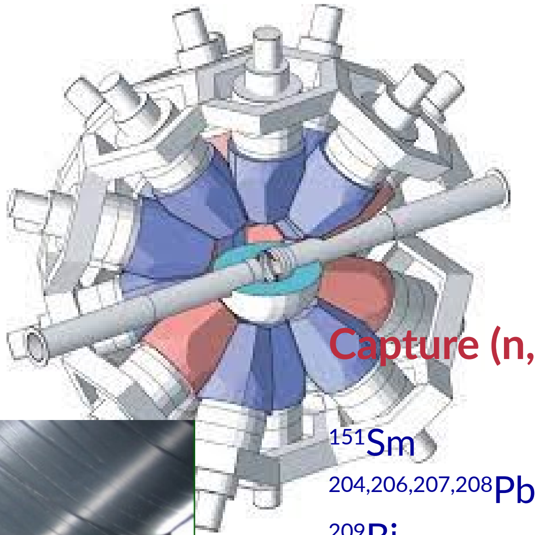
n_TOF: Total Absorption Calorimeter (TAC)

40 pentagonal + hexagonal BaF_2

4π geometry (95%)

Alu mounting structure (2 hemispheres)

Neutron absorber (similar properties to ^{6}LiH)



Capture (n,γ)

^{151}Sm

^{204,206,207,208}Pb

^{209}Bi

^{232}Th

^{24,25,26}Mg

^{90,91,92,94,96}Zr

^{93}Zr

^{139}La

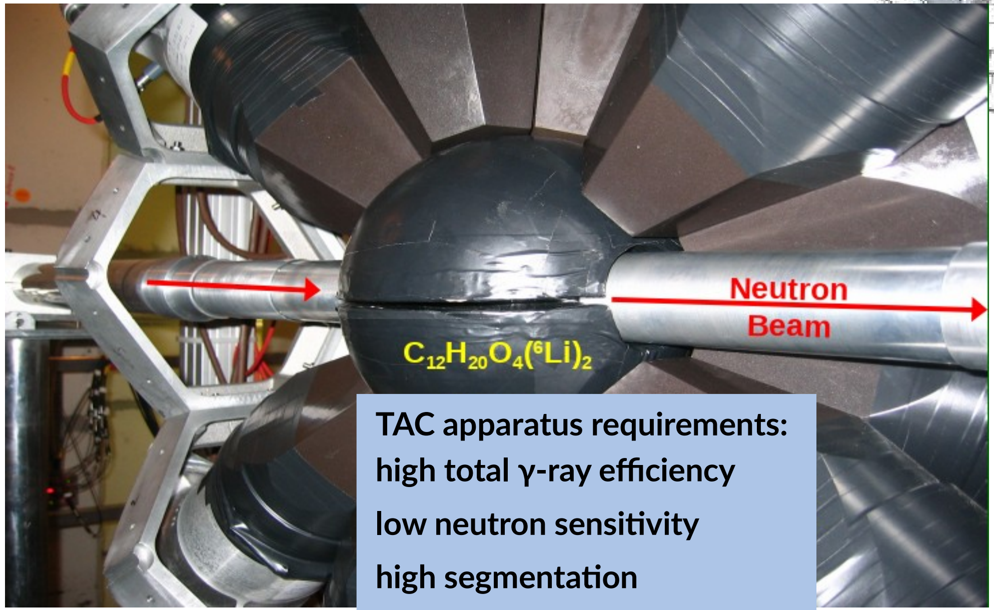
^{186,187,188}Os

^{197}Au

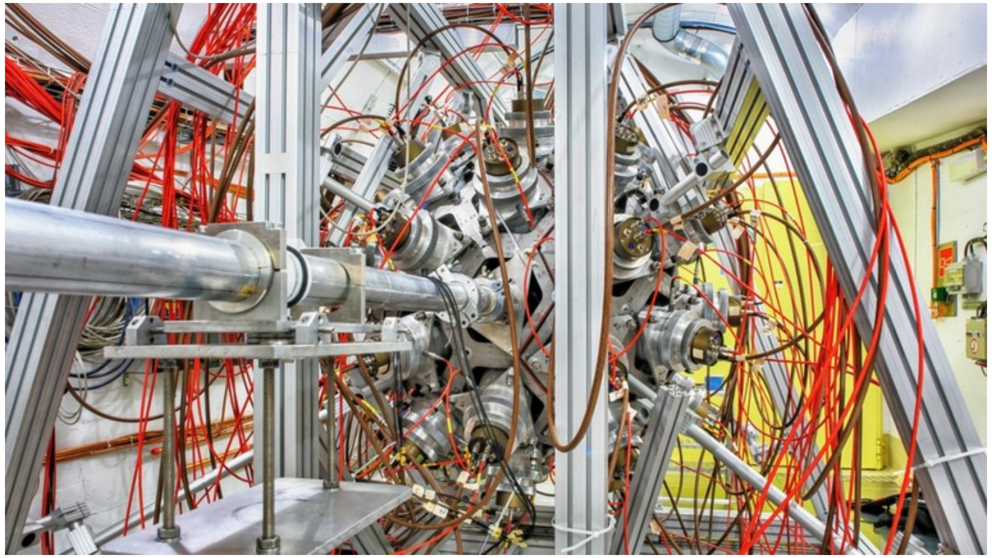
^{233,234}U

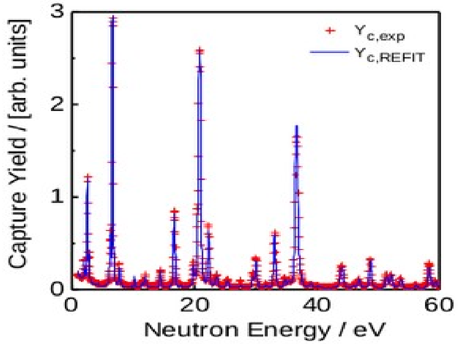
^{237}Np, ^{240}Pu

^{243}Am



TAC apparatus requirements:
- high total γ-ray efficiency
- low neutron sensitivity
- high segmentation
- good energy resolution
- fast time response

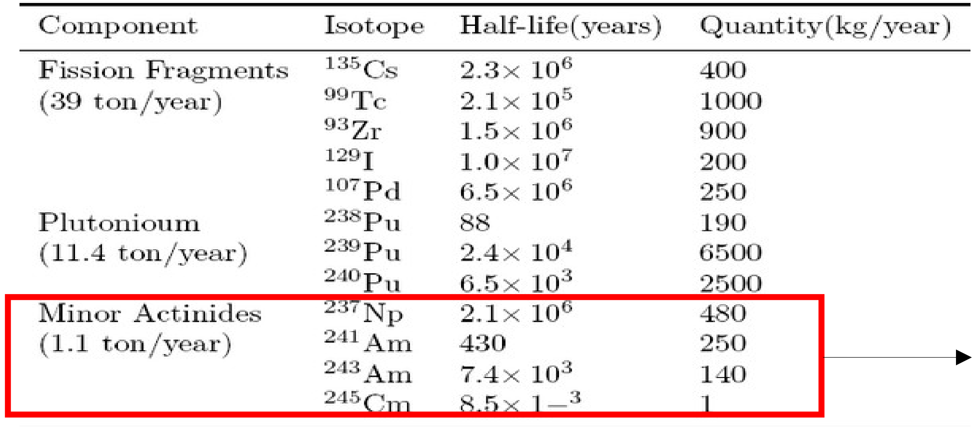




Radiative neutron capture cross section of ^{238}U:
- Important quantity for the development prospects of nuclear reactors
- Nuclear data uncertainties have an impact on the design and fuel cycle performance of innovative nuclear systems
- Inconsistencies in literature data

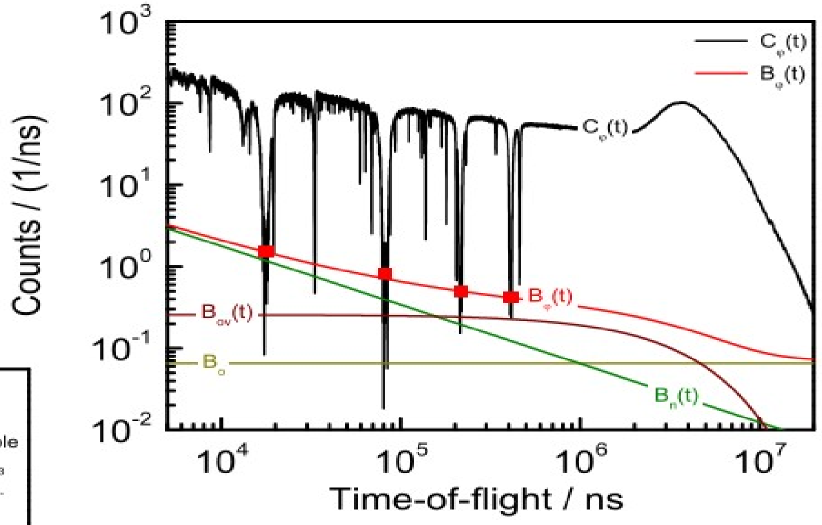
Goal: produce cross section for the URR with improved uncertainty

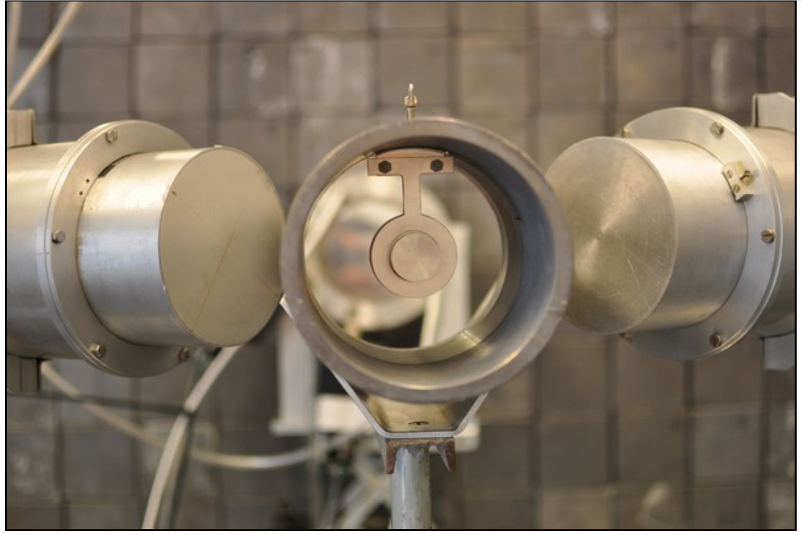
^{241}Am(n,γ) at GELINA (JRC - Geel)



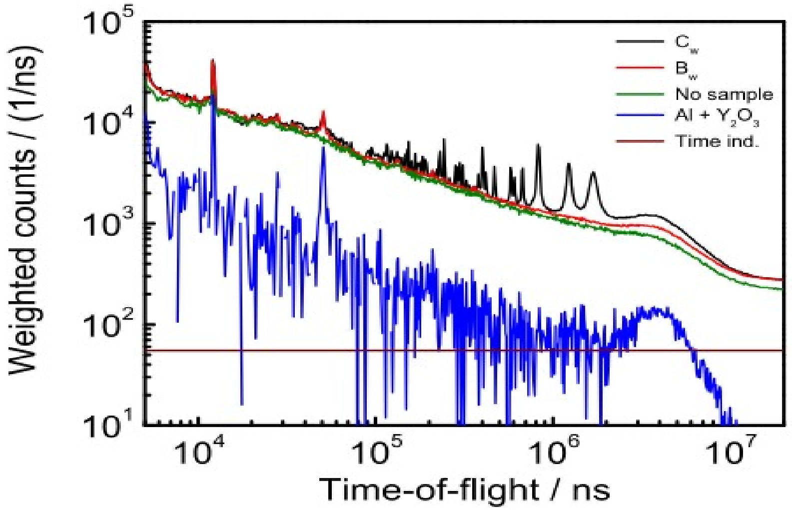
Component	Isotope	Half-life(years)	Quantity(kg/year)
Fission Fragments (39 ton/year)	^{135}Cs	2.3×10^6	400
	^{99}Tc	2.1×10^5	1000
	^{93}Zr	1.5×10^6	900
	^{129}I	1.0×10^7	200
	^{107}Pd	6.5×10^6	250
Plutonioum (11.4 ton/year)	^{238}Pu	88	190
	^{239}Pu	2.4×10^4	6500
	^{240}Pu	6.5×10^3	2500
Minor Actinides (1.1 ton/year)	^{237}Np	2.1×10^6	480
	^{241}Am	430	250
	^{243}Am	7.4×10^3	140
	^{245}Cm	$8.5\times 1{-}^3$	1

Long term radiotoxicity and high volume makes geo-disposal not an optimum solution



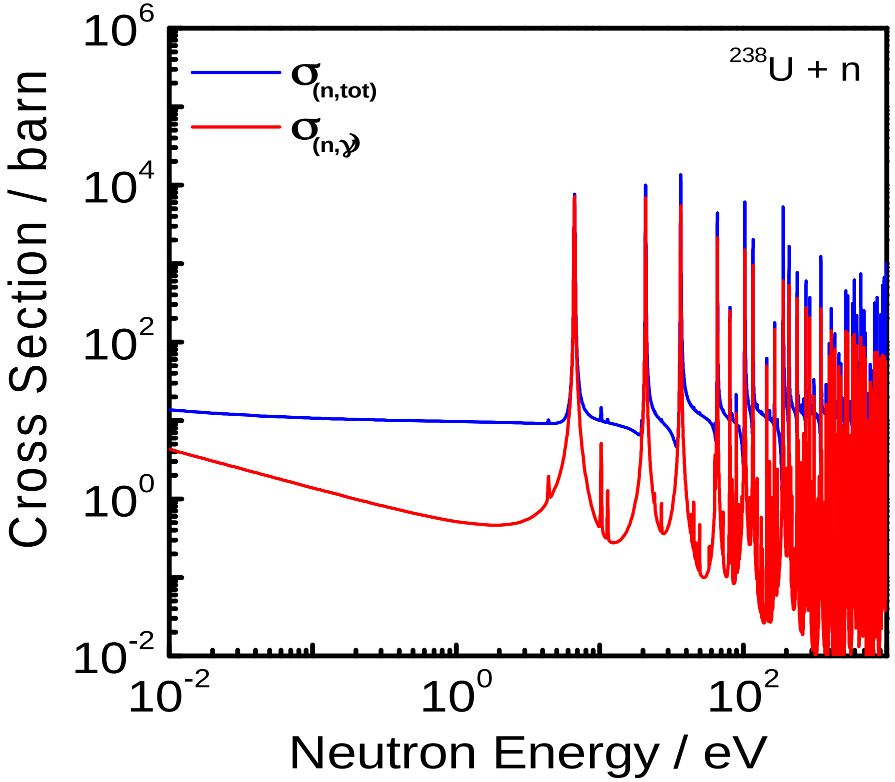


Pair of Scintillation Detectors



- Demanding measurement
- Required careful and time consuming data analysis

Neutron Resonance Analysis



Resonances appear at energies, which are specific for each nuclide

- Resonances can be used for:
  - Nuclide identification and quantification
  - Elemental (& isotopic) composition
- NRCA & NRTA
  - No sample preparation needed
  - Non - destructive
  - Negligible residual activation

Cultural Heritage: studies

Resonances appear at energies, which are specific for each nuclide

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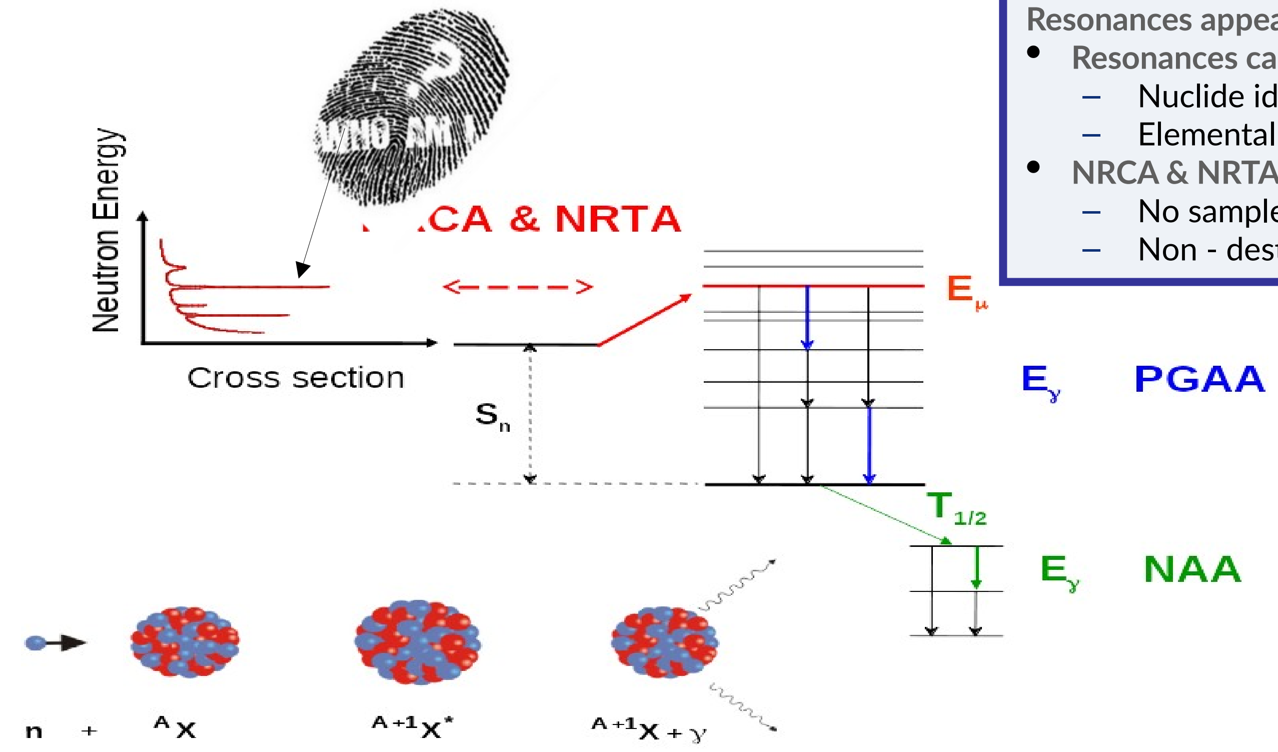
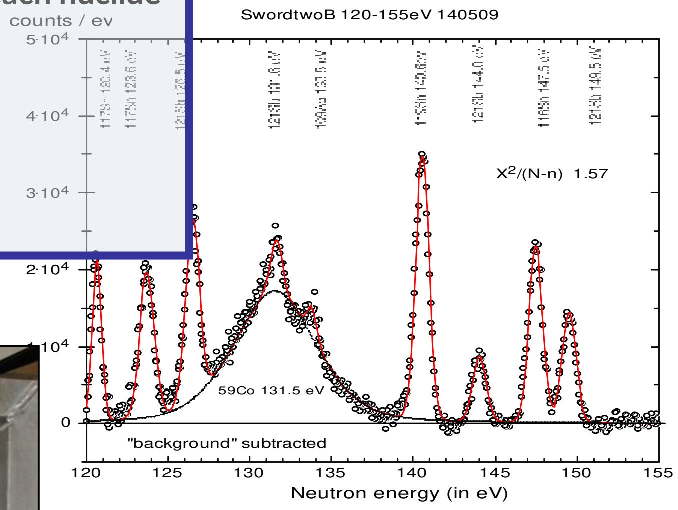
  - Nuclide identification and quantification
  - Elemental (& isotopic) composition
- NRCA & NRTA
  - No sample preparation needed
  - Non - destructive





http://ancient-charm.neutron-eu.net/ach

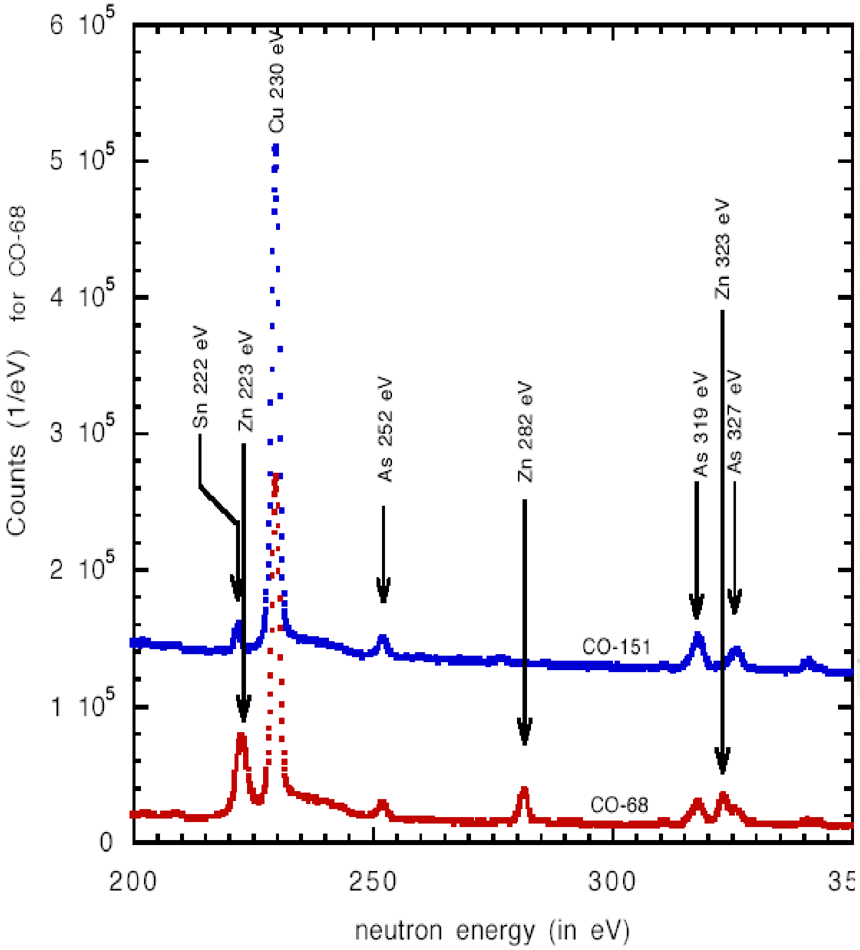
Tin – bronzes containing Sb, As and Ag

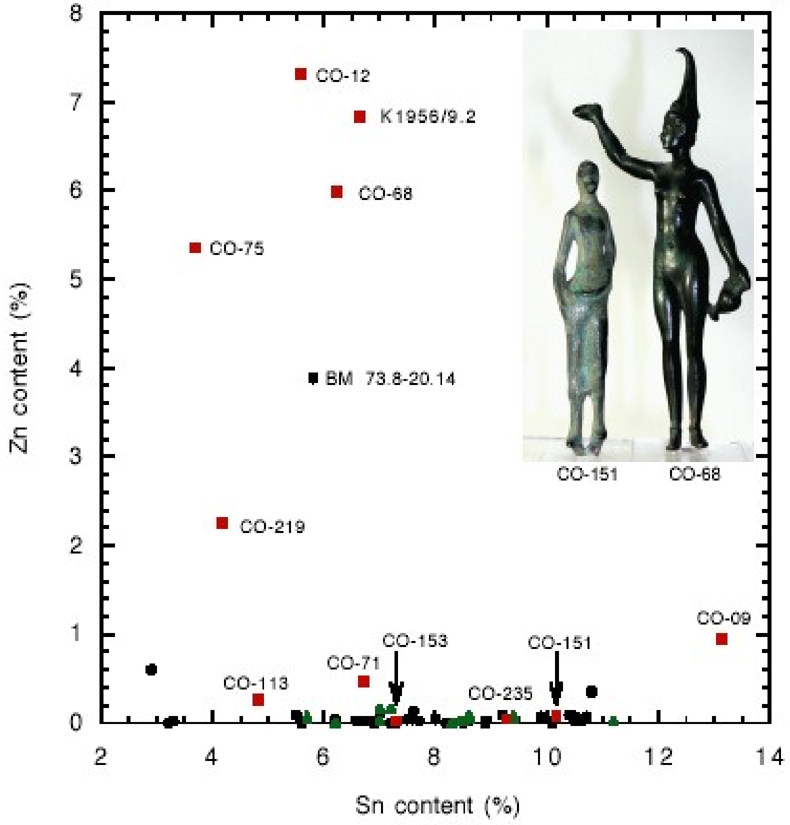
Presence of In and/or Co (not in all cases nor along all spots)

Postma and Schillebeeckx, JRNC 265, 297 (2005)
Postma, Schillebeeckx and Halbertsma, Archaeometry 46, 365 (2004)

Cultural Heritage: authenticity control

H. Postma, P. Schillebeeckx and R.B. Halbertsma, Archaeome

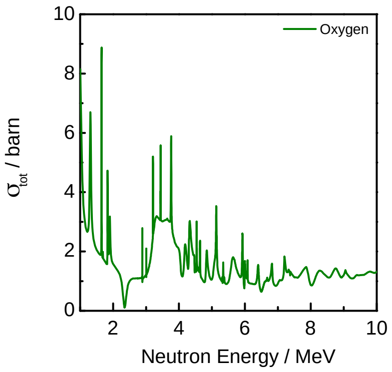


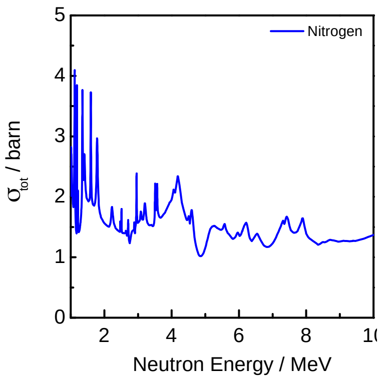


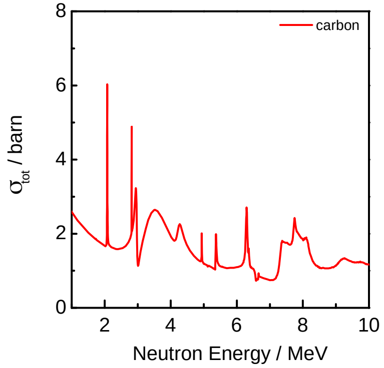
Two statuettes from National Museum of Antiquities in Leiden (NL).

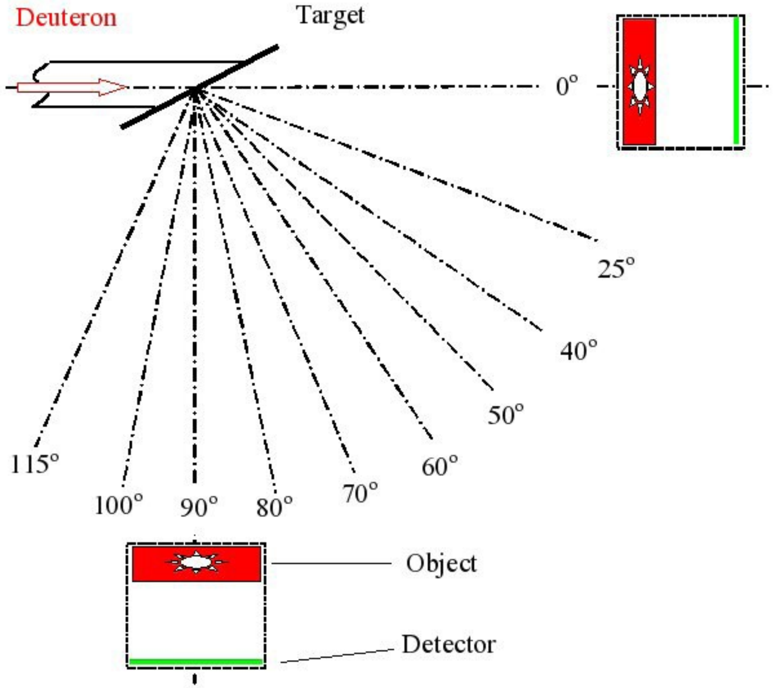
Security: detection of explosives and illegal substances

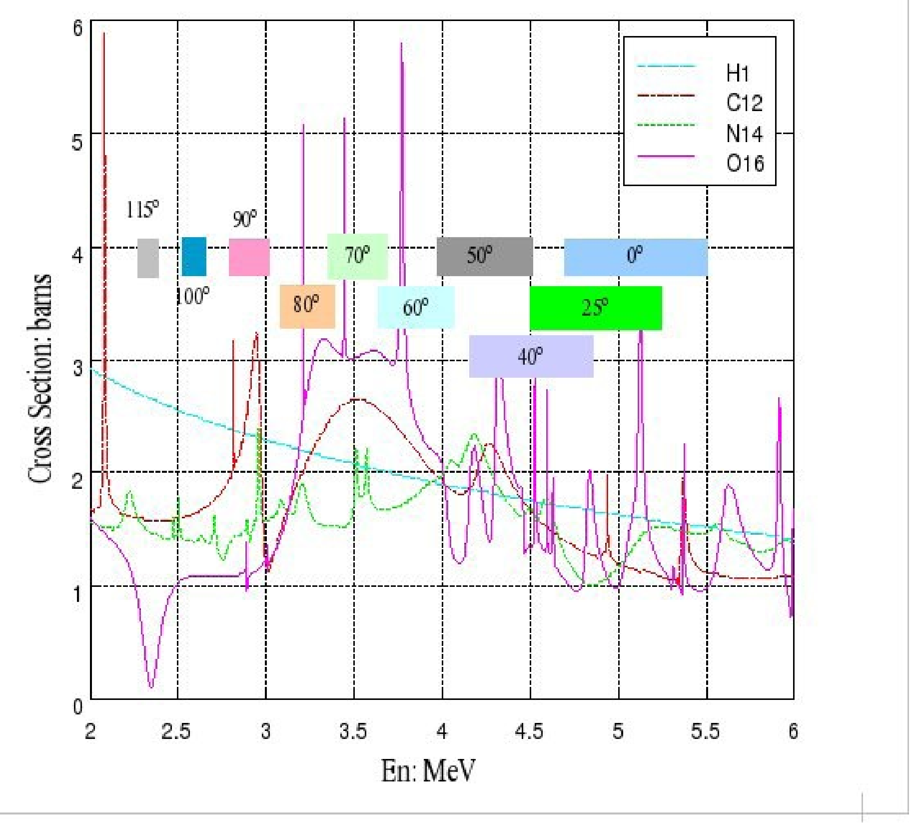
Neutron source: d(d,n)^{3}He at E_d = 2.5 MeV
Detector: plastic scintillator viewed by a CCD camera







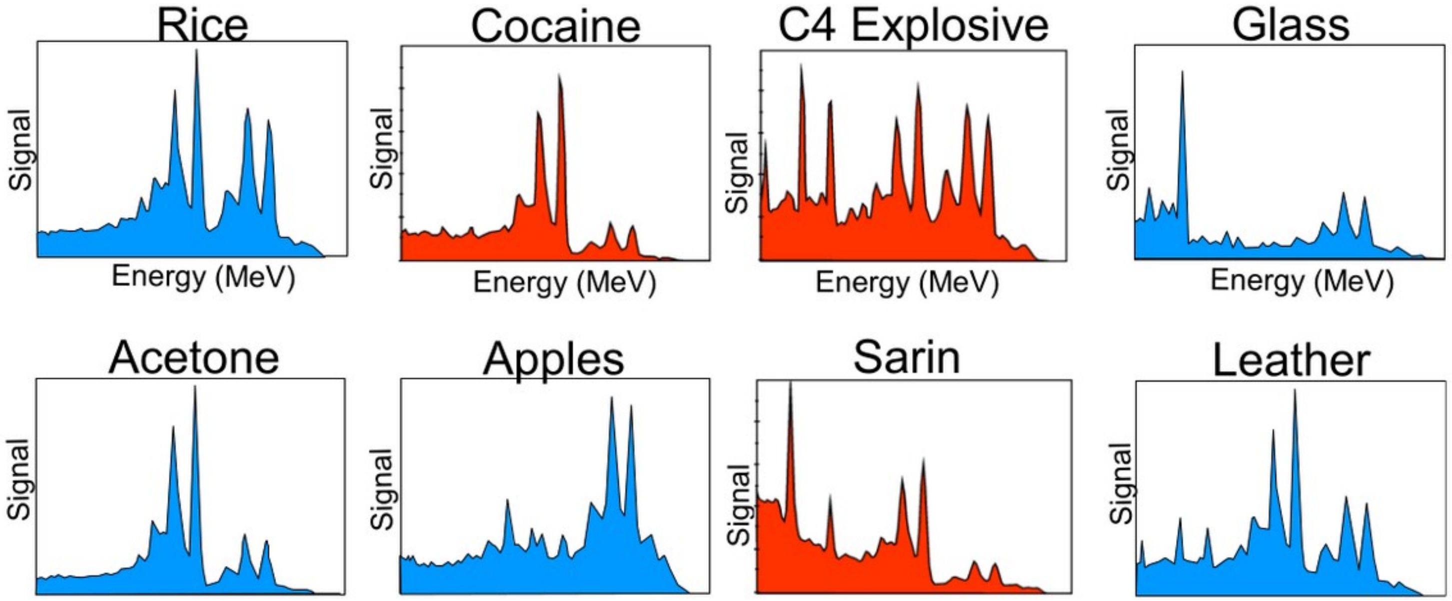




G. Chen and R.C. Lanza, IEEE Transactions on Nuclear Science, 49 (2002) 1919 – 1924

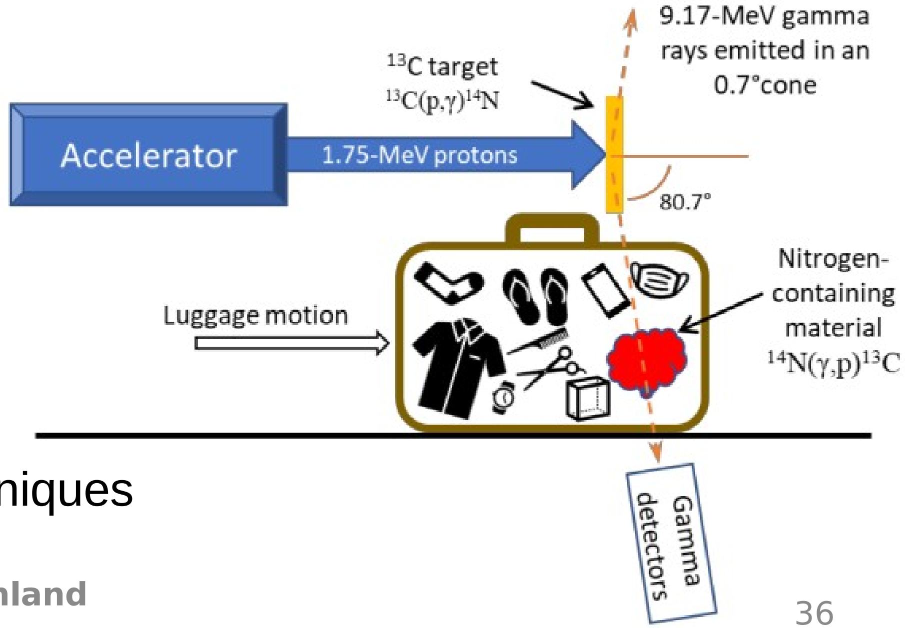
Security: detection of C, O and N

LLNL-BOOK-819857 IM-1029000



Inelastic gamma rays from C4 show prominent peaks of N, C and O, in different proportions compared to other materials.

Spectra of gamma rays resulting from inelastic scattering of neutrons from selected materials



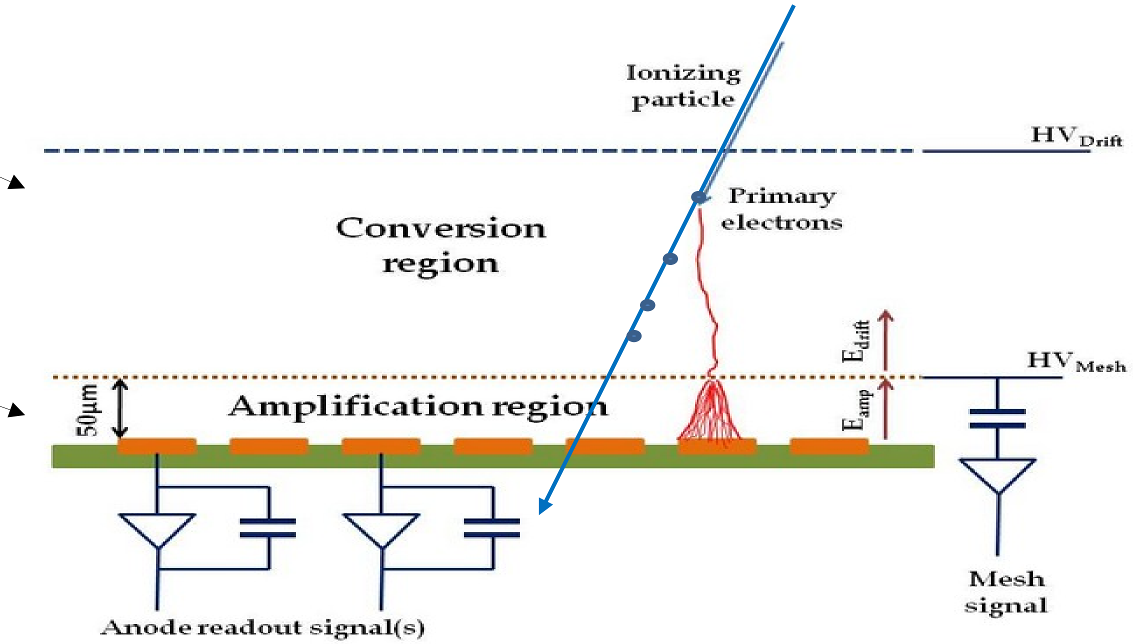
Nuclear Resonance Absorption techniques

MM basics

Typical Micromegas: Principle of Operation

Drift gap/Conversion region
Ionizing particles create electrons, which drift towards readout plane.

Amplification region
Avalanches/amplification, charge movement induces signals.



Characteristic advantages of the technology:

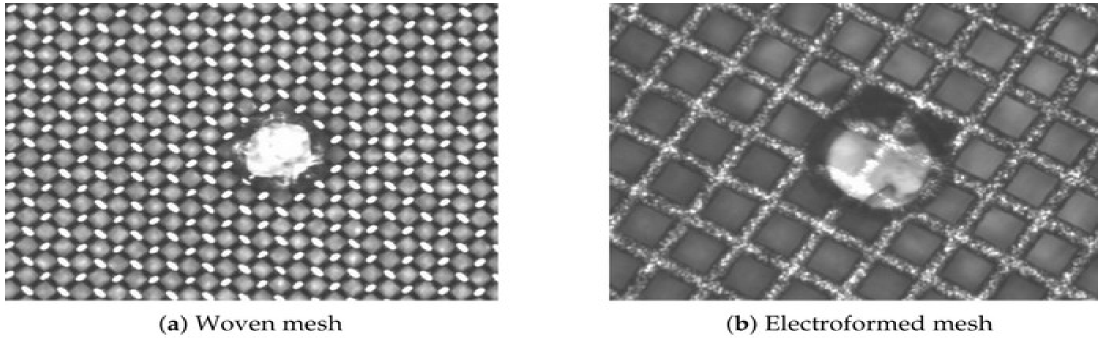
Simplicity, Granularity, Homogeneity, Scalability, High rate capabilities, Radiation hardness, Low cost

Y. Giomataris, P. Rebourgeard, J. Robert, G. Charpak, MICROMEGAS: A high granularity position sensitive gaseous detector for high particle flux environments, Nucl. Instrum. Meth. A 376 (1996) 29–35

MM Fabrication techniques: mesh

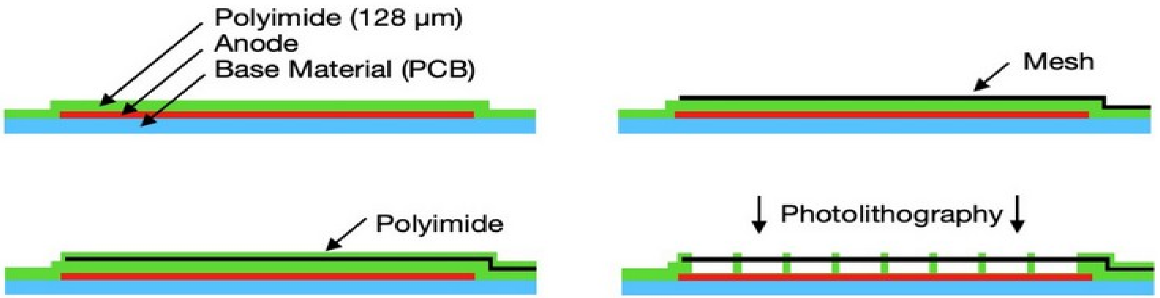
Micromegas detectors are built using different types of meshes depending on the fabrication technique/application

- flat meshes made of thin metallic sheets (4–10 μm), holes produced by micro-machining processes (electroforming, chemical etching etc.)
- mesh made of mechanically woven stainless-steel wires (18 μm up to 30μm typical wire thickness)


(a) Woven mesh

(b) Electroformed mesh

“Bulk” technology a big step for the industrialization/production of large scale MM

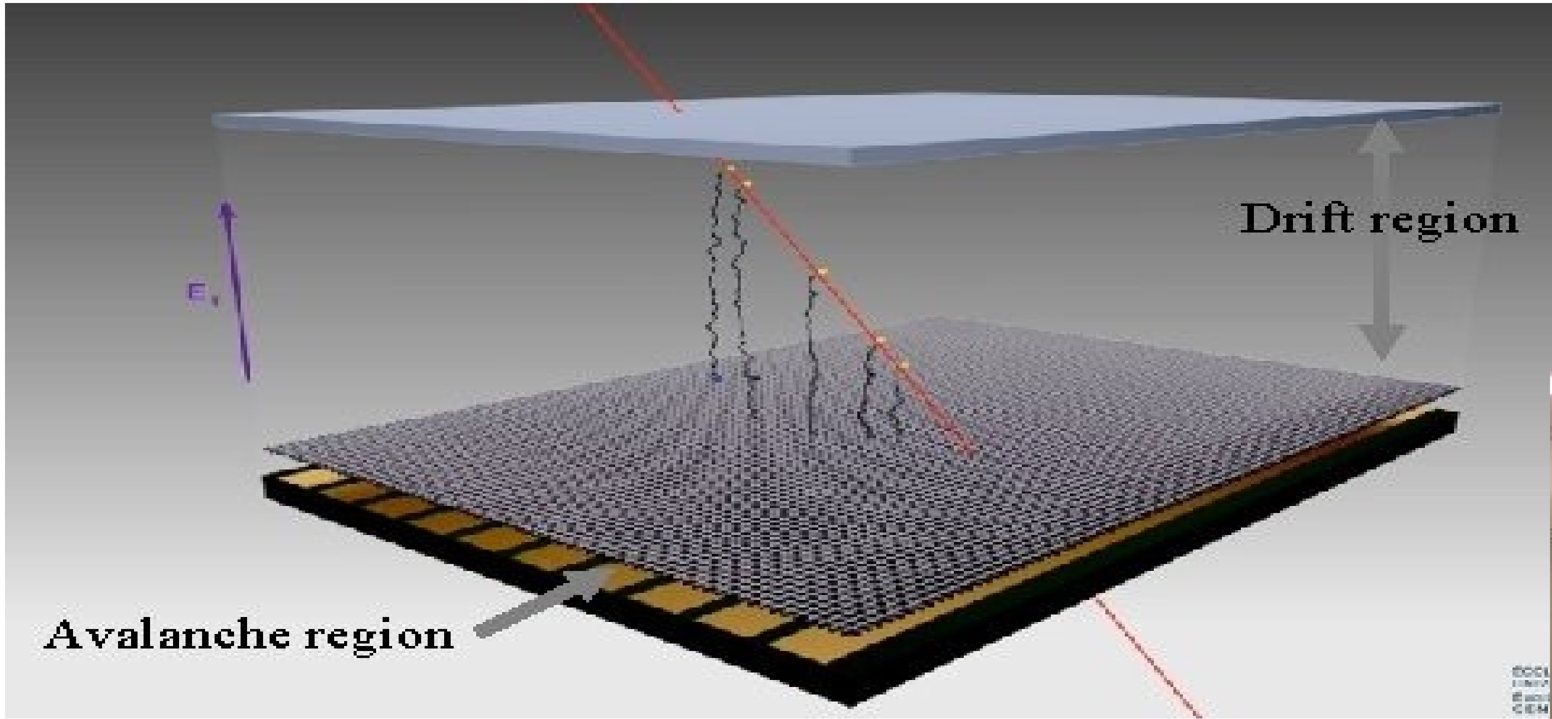


Principle: embedded metallic woven mesh on a Printed Circuit Board

- in Microbulk MM, mesh, pillars and read-out are constructed in a single structure
- bulk technology is applied to the majority of today’s MM

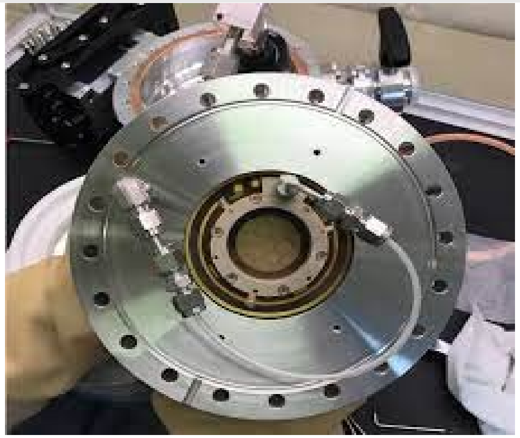
Micromegas in a bulk. Nucl. Instrum. Methods 2006, 560, 405–408

Micromegas: various applications

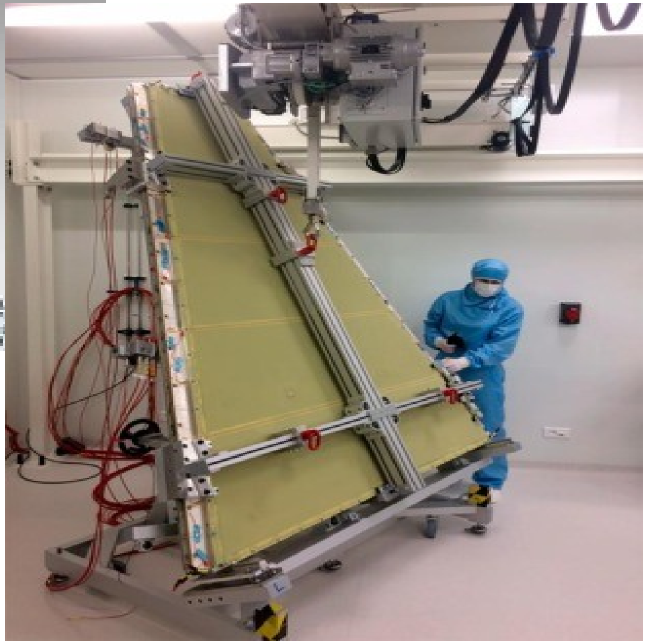


MM used in numerous experiments:

- particle physics (LHC/ATLAS)
- dark matter (CAST)
- neutrinos (T2K)
- astrophysics
- neutron TOF experiments (n_TOF)
- …



PICOSEC Micromegas for precise timing



LM1 Micromegas for ATLAS
New Small Wheel @ CEA – Saclay

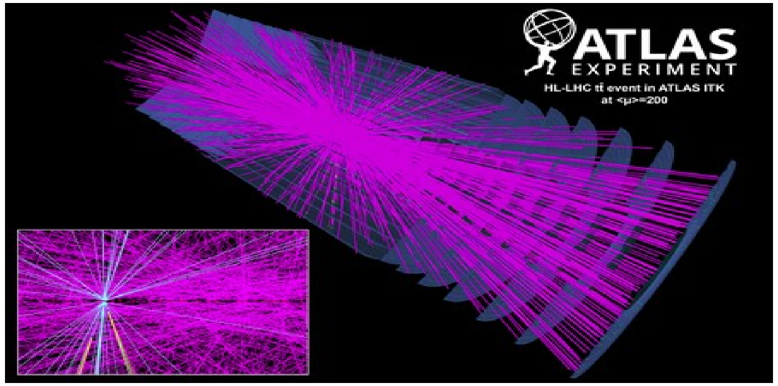
Applications: Timing

Aim for ~ 20 ps timing in particle tracking

High Luminosity consequences:

High pile-up (up-to 200 events/BC) with large number of tracks

Harsher radiation environment



Requirements:

- Large surface coverage.
- Multi-pad readout for tracking.
- Resistance to aging effects.

Demand for precise timing detectors for physics (Time of Flight, Particle Identification)

Rising needs related to medical and industrial application

PID techniques: Alternatives to RICH methods,
J. Va'vra, NIMA 876, 185 – 193, 2017
https://doi.org/10.1016/j.nima.2017.02.075

Available technology:

Solid state detectors

- Avalanche PhotoDiodes: (σ_t ~ 20 ps)
- Low Gain Avalanche Diodes (σ_t ~ 30 ps)

➔ *Radiation hardness ?*
➔ *Cost*

Gaseous detectors

- Resistive Plate Chambers (RPCs, σ_t ~ 30 ps)
  High rate limitation
- Micro-Pattern Gaseous Detectors (σ_t ~ 1 ns)

Improve Micromegas performance by **~ 2 orders of magnitude**

1st step: proof of concept

Next steps: increase area, position-sensitive, radiation hardness

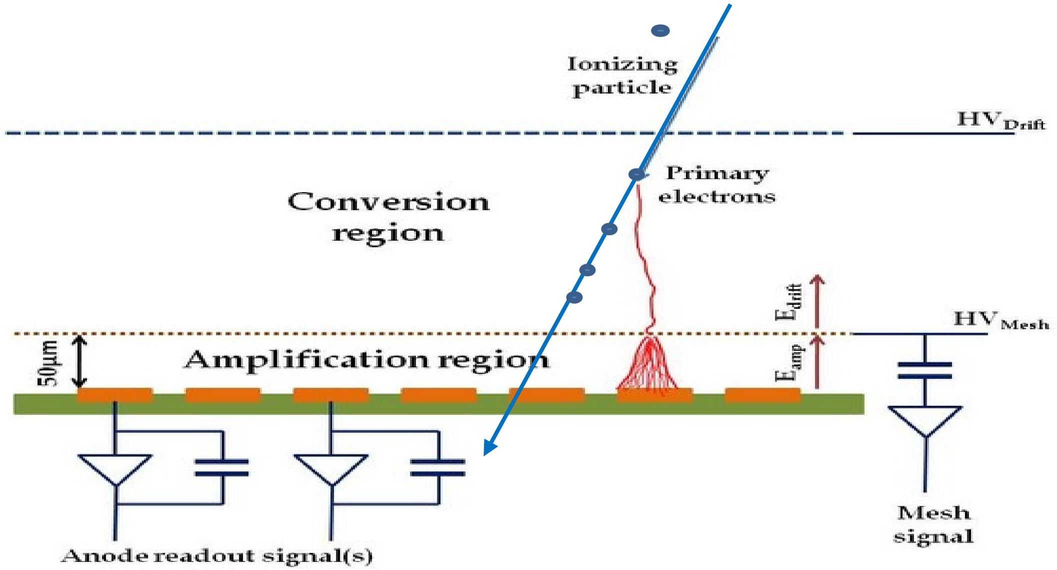
A typical Micromegas

Drift gap/Conversion region
Ionizing particles create electrons, which drift towards readout plane.

Amplification region
Avalanches/amplification, charge movement induces signals.

Characteristic advantages of the technology:

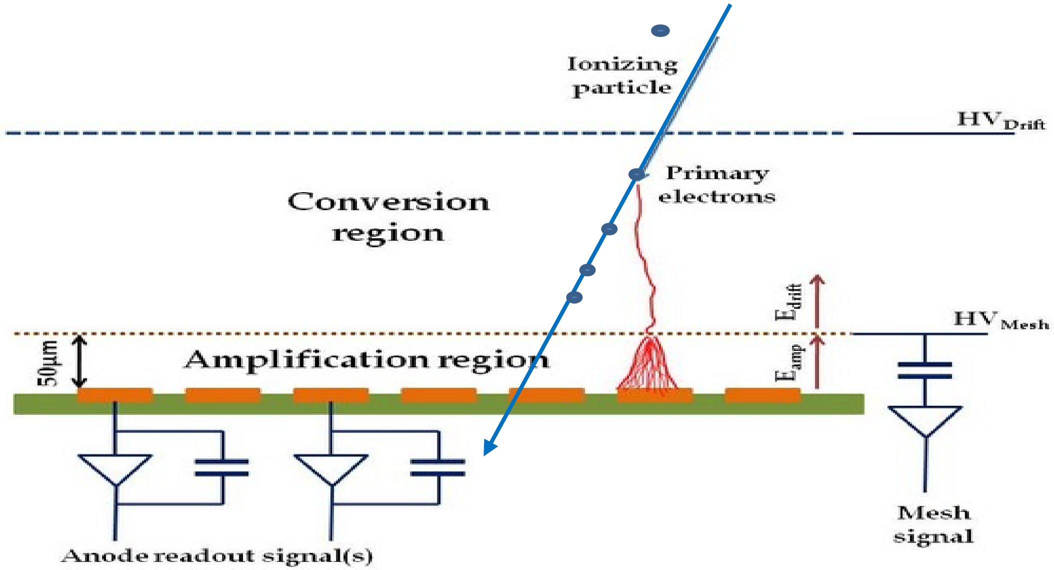
Simplicity, Granularity, Homogeneity, Scalability, High rate capabilities, Radiation hardness, Low cost



A typical Micromegas: limitations

Drift gap/Conversion region
Ionizing particles create electrons, which drift towards readout plane.

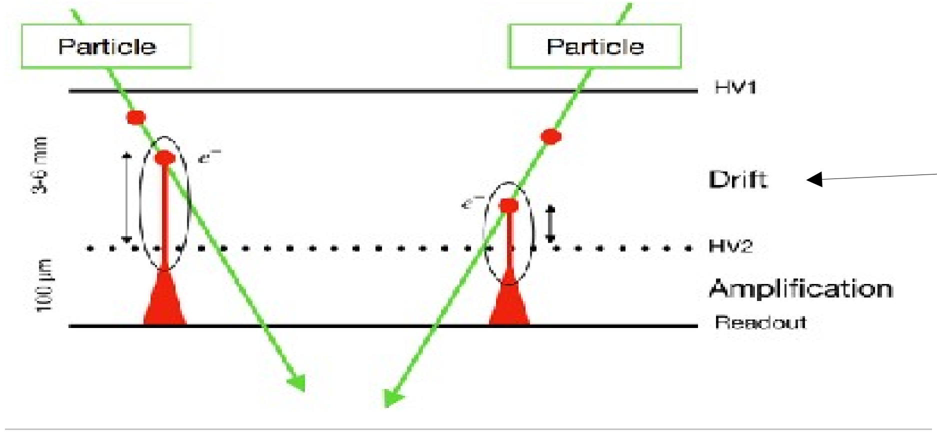
Amplification region
Avalanches/amplification, charge movement induces signals.



Characteristic advantages of the technology:

Simplicity, Granularity, Homogeneity, Scalability, High rate capabilities, Radiation hardness, Low cost

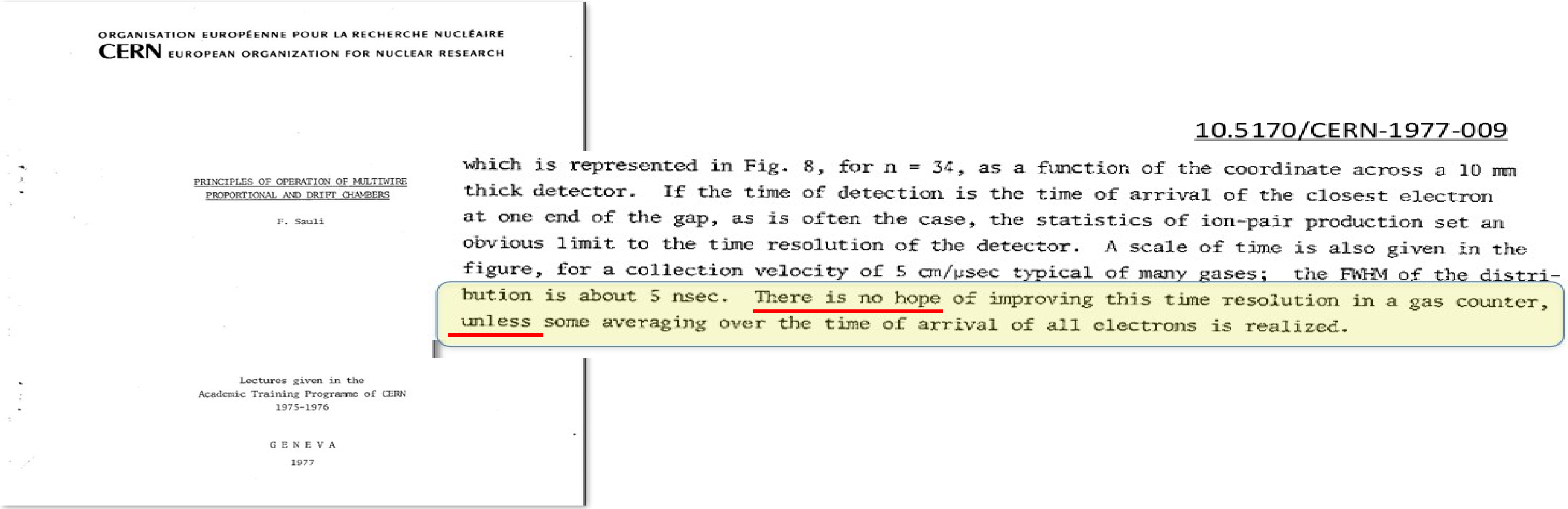
Timing properties/Limitations



- Ionizations occur in different positions along the particle’s trajectory → ~ ns time jitter for a 3-6 mm conversion region
- Diffusion effects

Limitations: reminder

The Physics of Ionization offers the means for precise spatial measurements (high spatial resolution) but inhibits precise timing measurements



ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PRINCIPLES OF OPERATION OF MULTIWIRE
PROPORTIONAL AND DRIFT CHAMBERS

F. Sauli

Lectures given in the
Academic Training Programme of CERN
1975-1976

GENEVA
1977

10.5170/CERN-1977-009

which is represented in Fig. 8, for n = 34, as a function of the coordinate across a 10 mm thick detector. If the time of detection is the time of arrival of the closest electron at one end of the gap, as is often the case, the statistics of ion-pair production set an obvious limit to the time resolution of the detector. A scale of time is also given in the figure, for a collection velocity of 5 cm/μsec typical of many gases; the FWHM of the distribution is about 5 nsec. There is no hope of improving this time resolution in a gas counter, unless some averaging over the time of arrival of all electrons is realized.

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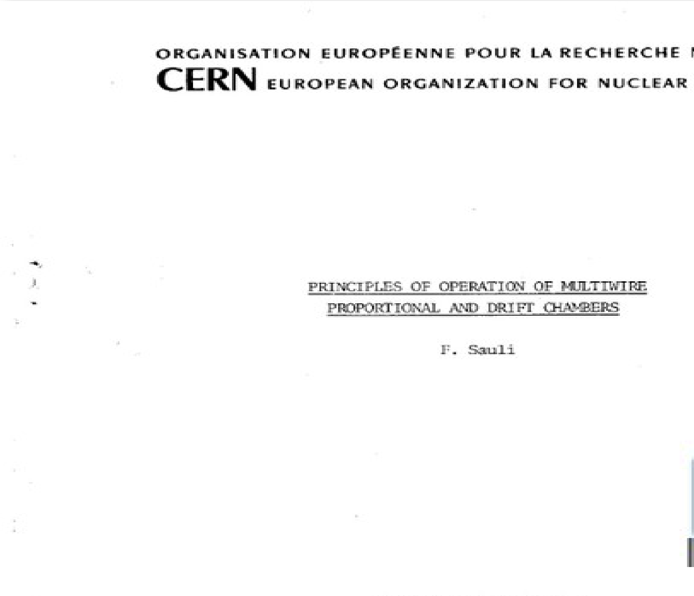

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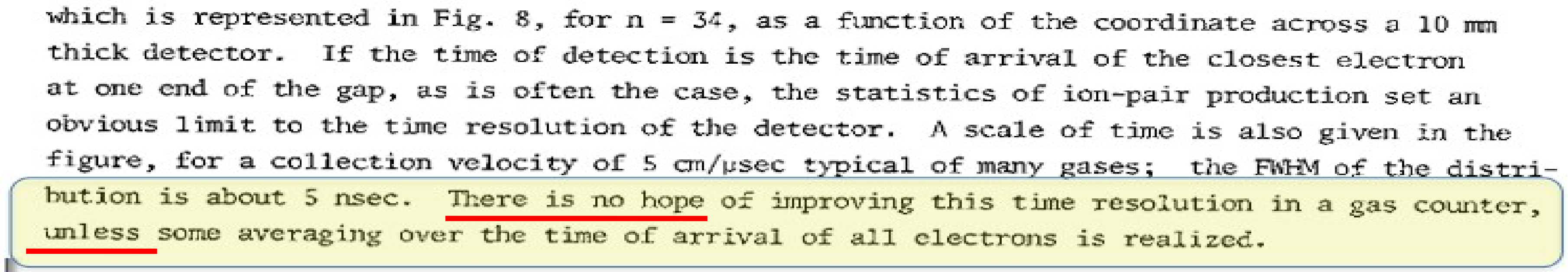

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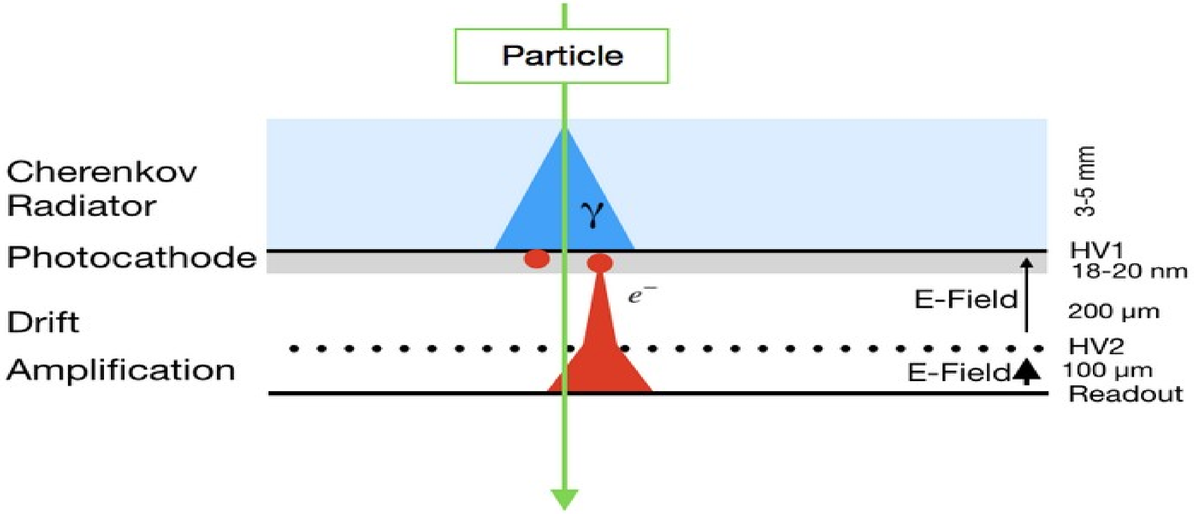
In order to use gaseous detectors for precise (ps) timing of charged particles we should turn other Physics phenomena against the stochastic Nature of ionization

- Cherenkov radiation → provide prompt photons
- Photoelectric effect → convert photons to prompt electrons

The PICOSEC concept



Small drift gap (~200 μm) + High E-field:

- ✓ Pre-amplification possible
- ✓ Limited direct ionization
- ✓ Reduced diffusion impact

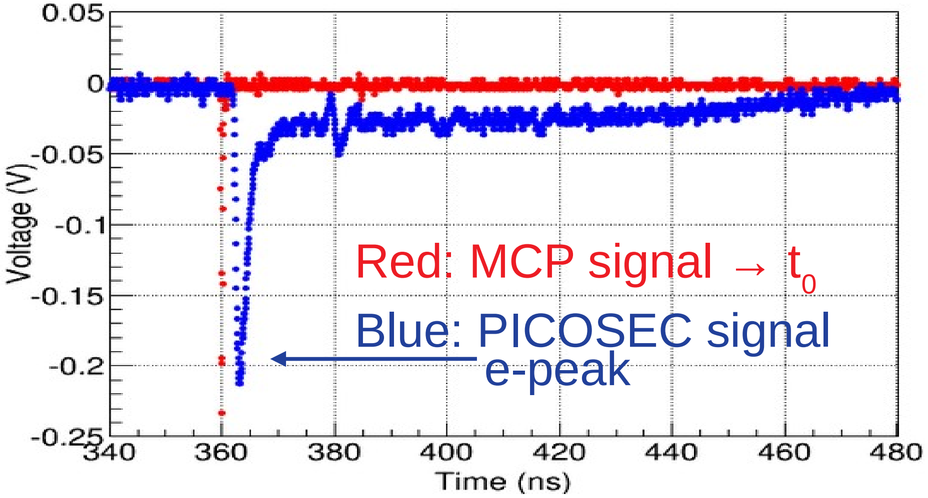
Cherenkov radiator/Photocathode:

- ✓ Photo-electrons emerging the photocathode simultaneously (fixed distance from the mesh)
- ✓ produce sufficient number of photo-electrons

Cherenkov radiator + Photocathode

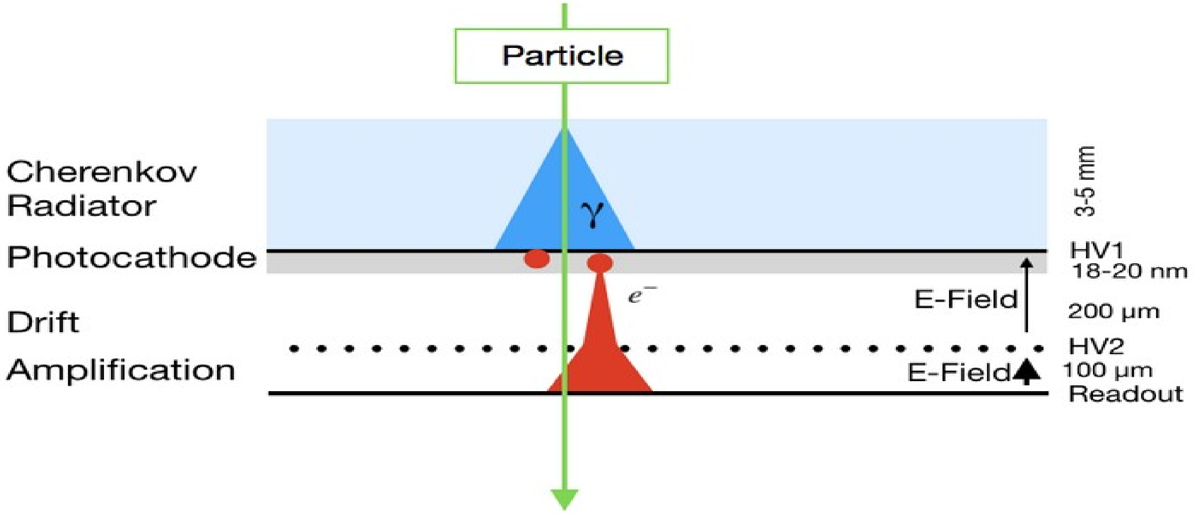
- ✓ Particle produce Cherenkov light
- ✓ Photo-electrons emerge from photocathode
- ✓ Electrons amplified by a two-stage Micromegas

Signal components: Fast <1ns (electron peak) &
Slow ~100ns (Ion-tail)



Result: improved timing resolution

The PICOSEC concept



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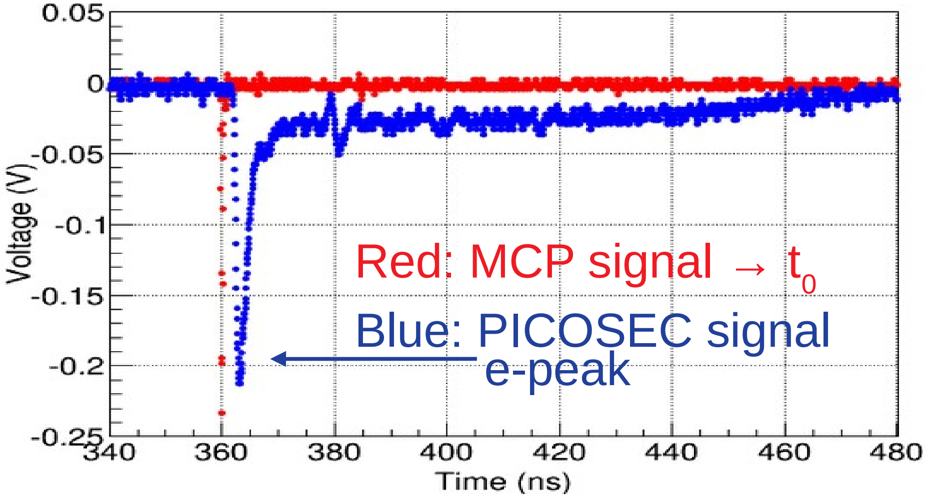
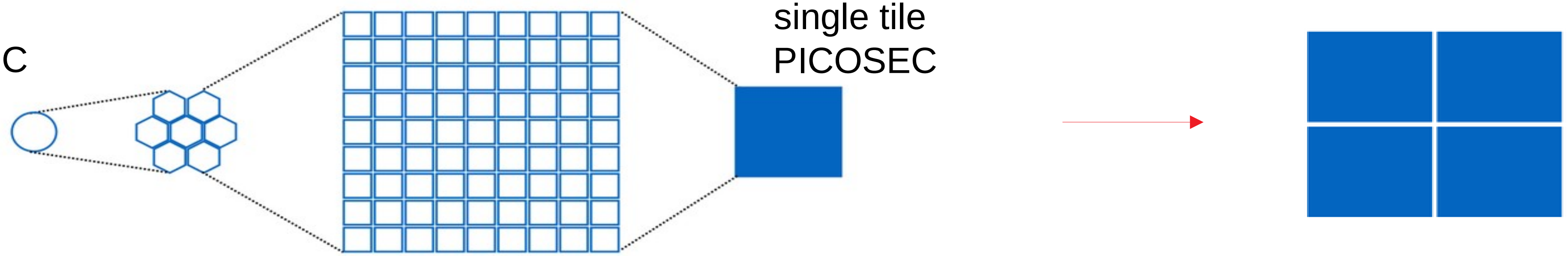


More info: High Precision Timing with the PICOSEC Micromegas Detector, Particle Physics Seminar, Universität Bonn – Physikalisches Institut 17 June 2021

Towards large area coverage: modular design



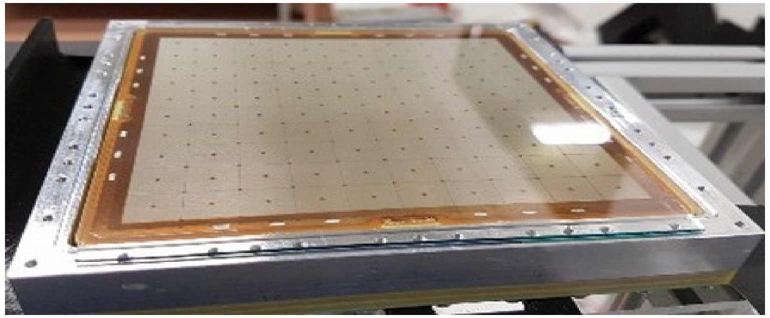
single cell PICOSEC

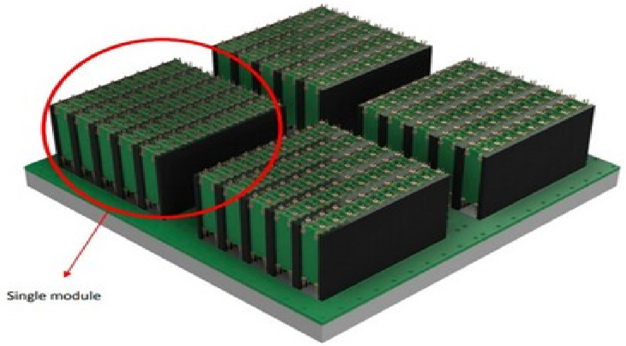
single tile PICOSEC

multipad PICOSEC

segmented PICOSEC detector

tile window pattern PICOSEC



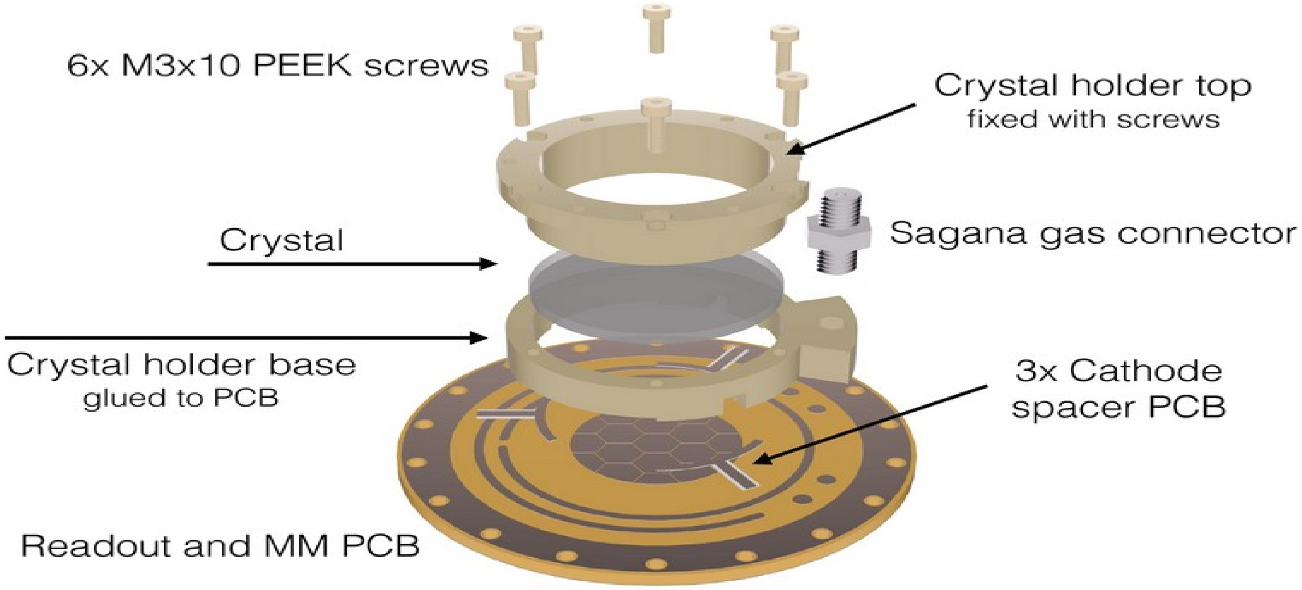


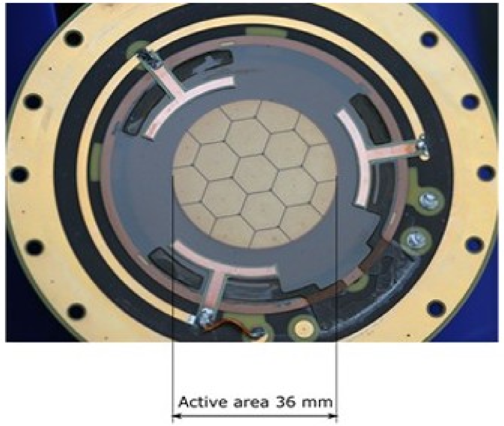
Schematics/photos not to scale

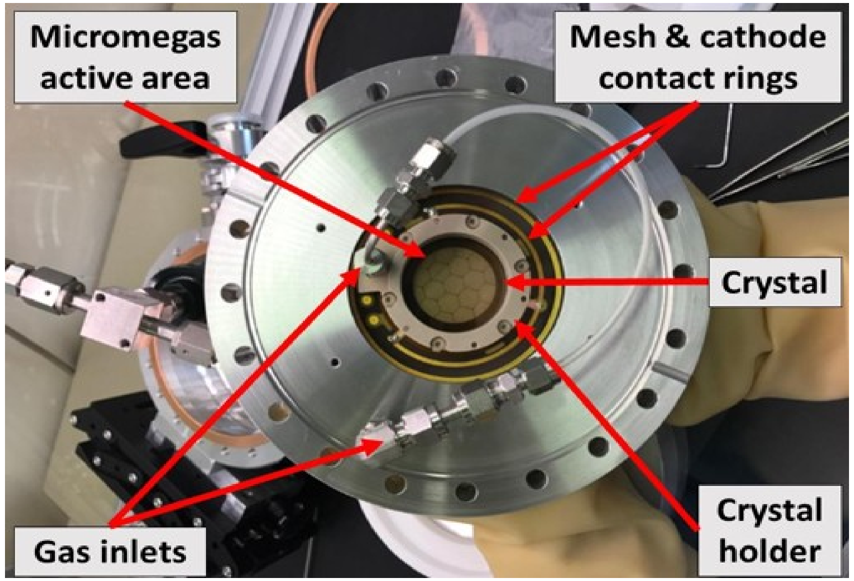
S. Aune et al., Timing performance of a multi-pad PICOSEC-Micromegas detector prototype, https://doi.org/10.1016/j.nima.2021.165076

Scaling up: engineering issues

The first multipad PICOSEC





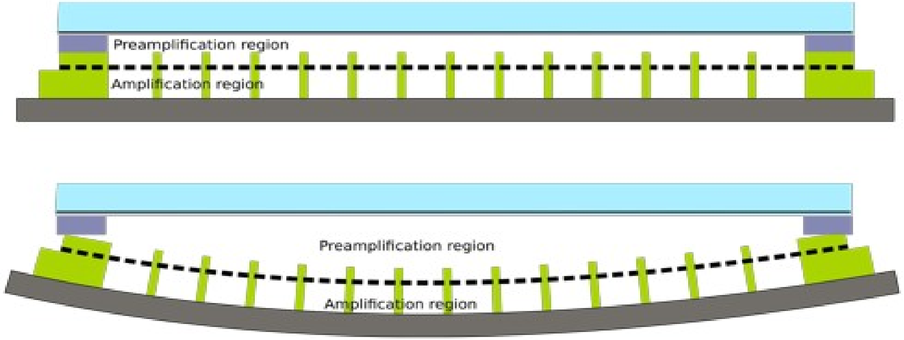


Similar detector configuration as for single pad:

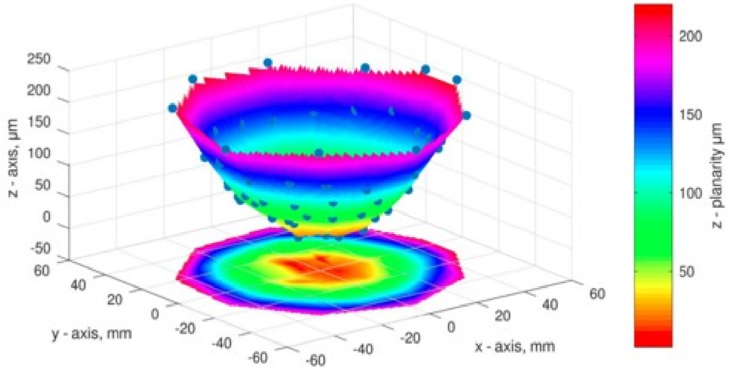
- MgF_2 radiator 3 mm thick,
- 18 nm CsI on 5 mm Cr
- Bulk MicroMegas
- “COMPASS gas”
- 200 μm drift gap

Optimum operation point: **V_{drift}/V_{anode}: -475V/+275V**

First multipad PICOSEC: unforeseen deformation

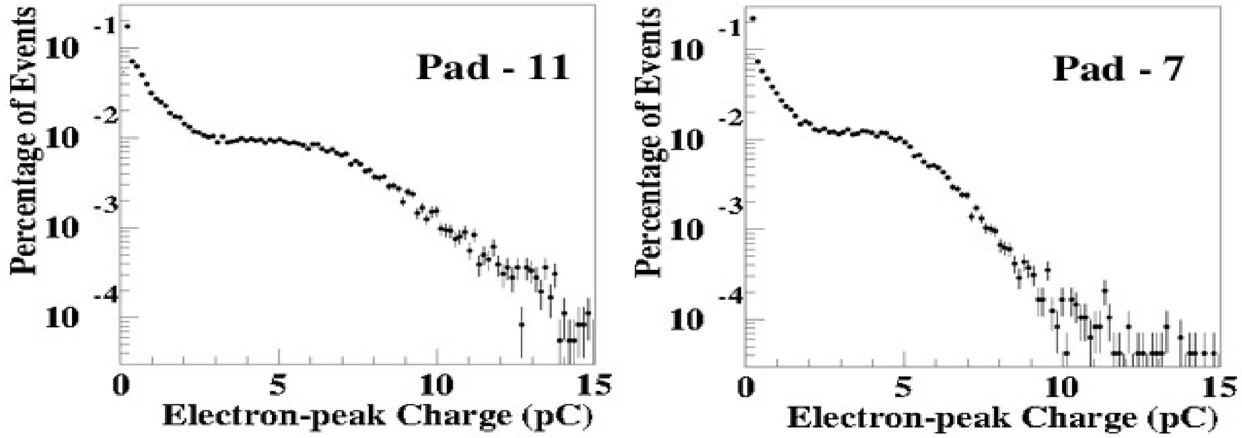


A. Utrobicic



ZEISS O-INSPECT 863 – CERN Metrology service

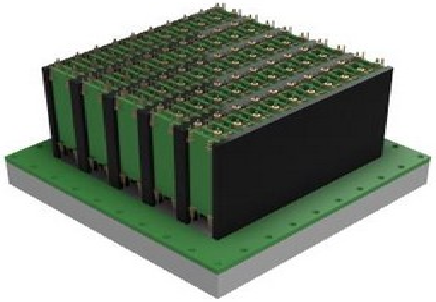
evident lower gain



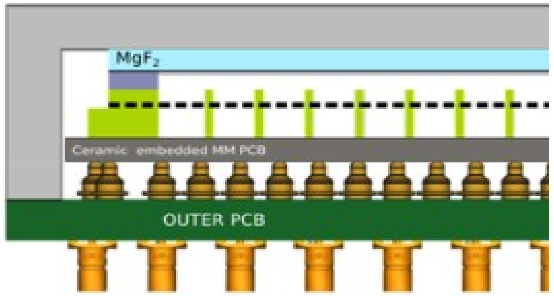
- Timing performance revealed anode deformation (confirmed later by an optical device measurement)
- Drift gap non uniformity → spatial variation of the detector gain
- Direct impact on the timing performance between pads
- Corrections applied, restored a uniform timing response over all detector active area

Timing performance of a multi-pad PICOSEC-Micromegas detector prototype, NIM A 933 – 2021

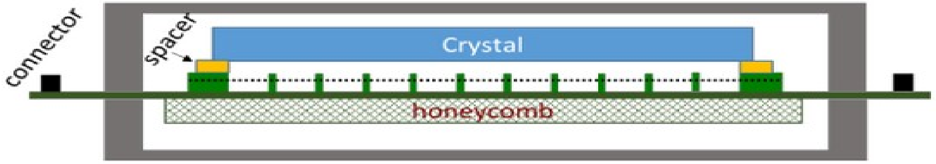
Alternative method for a flat(er) anode



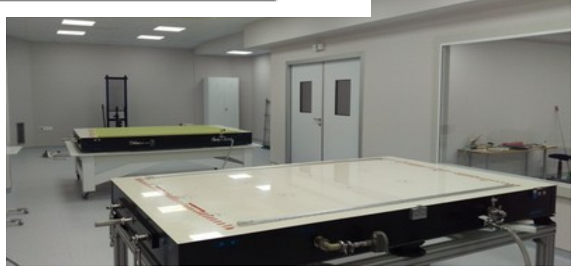
Micromegas made on a hybrid ceramic PCB, completely enclosed in the chamber.
100 channels prototype (10 × 10 cm^2) tested @ CERN

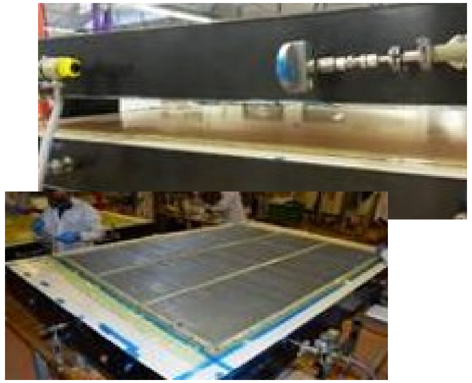


The ATLAS New Small Wheel panel construction principle: bulk Micromegas on a thin PCB, backed on a Alu honeycomb, and glued on super flat surface (vacuum or marble table, with flatness <10 μm)



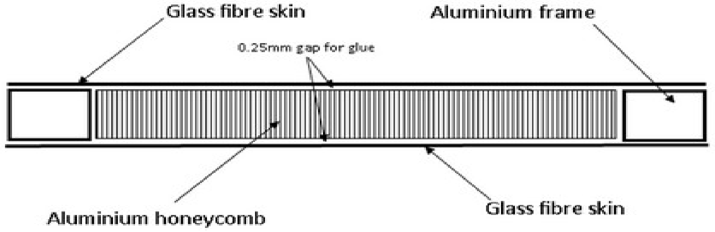
schematic of the honeycomb-stiffened PICOSEC detector





vacuum table technique

granite table + stiffback technique

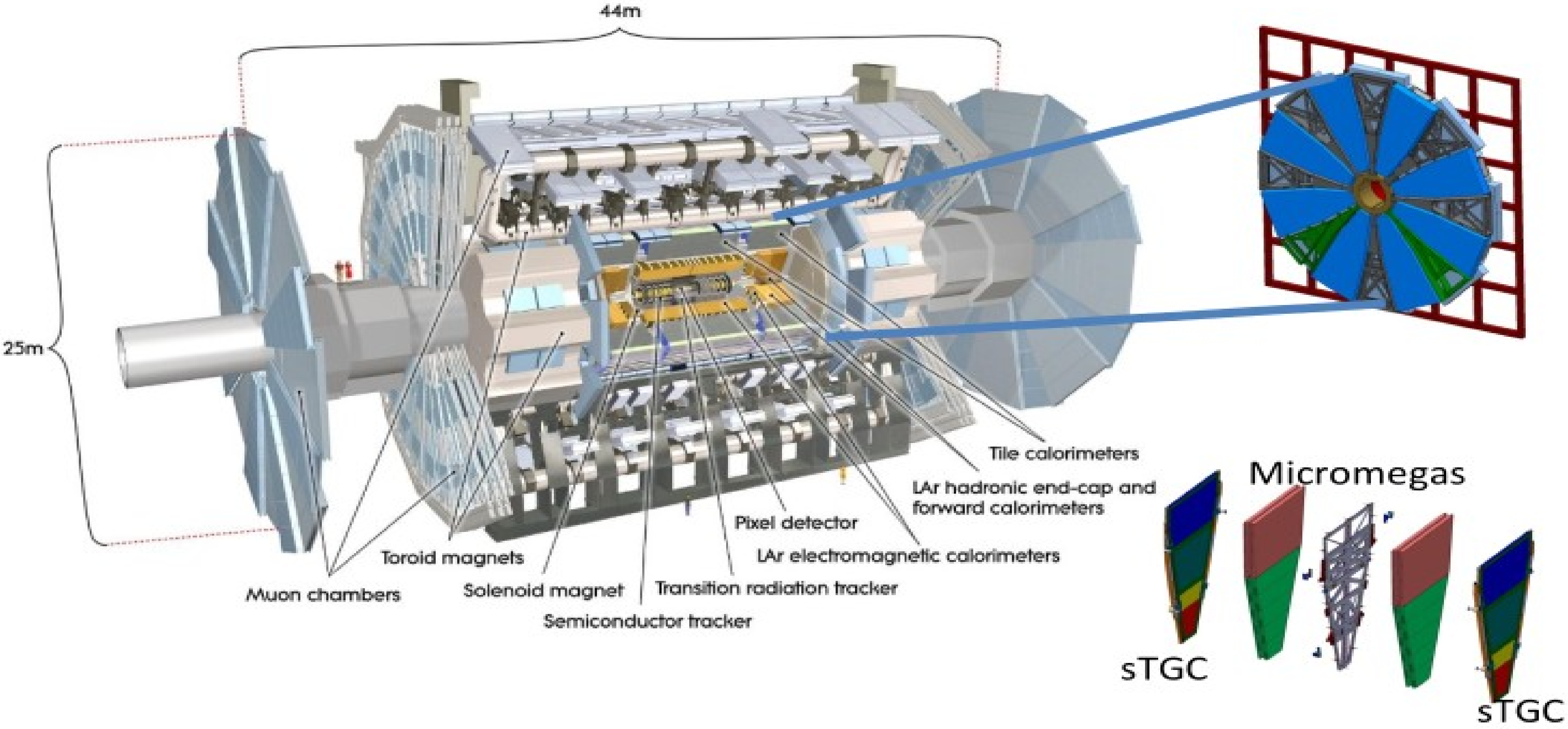


construction principle

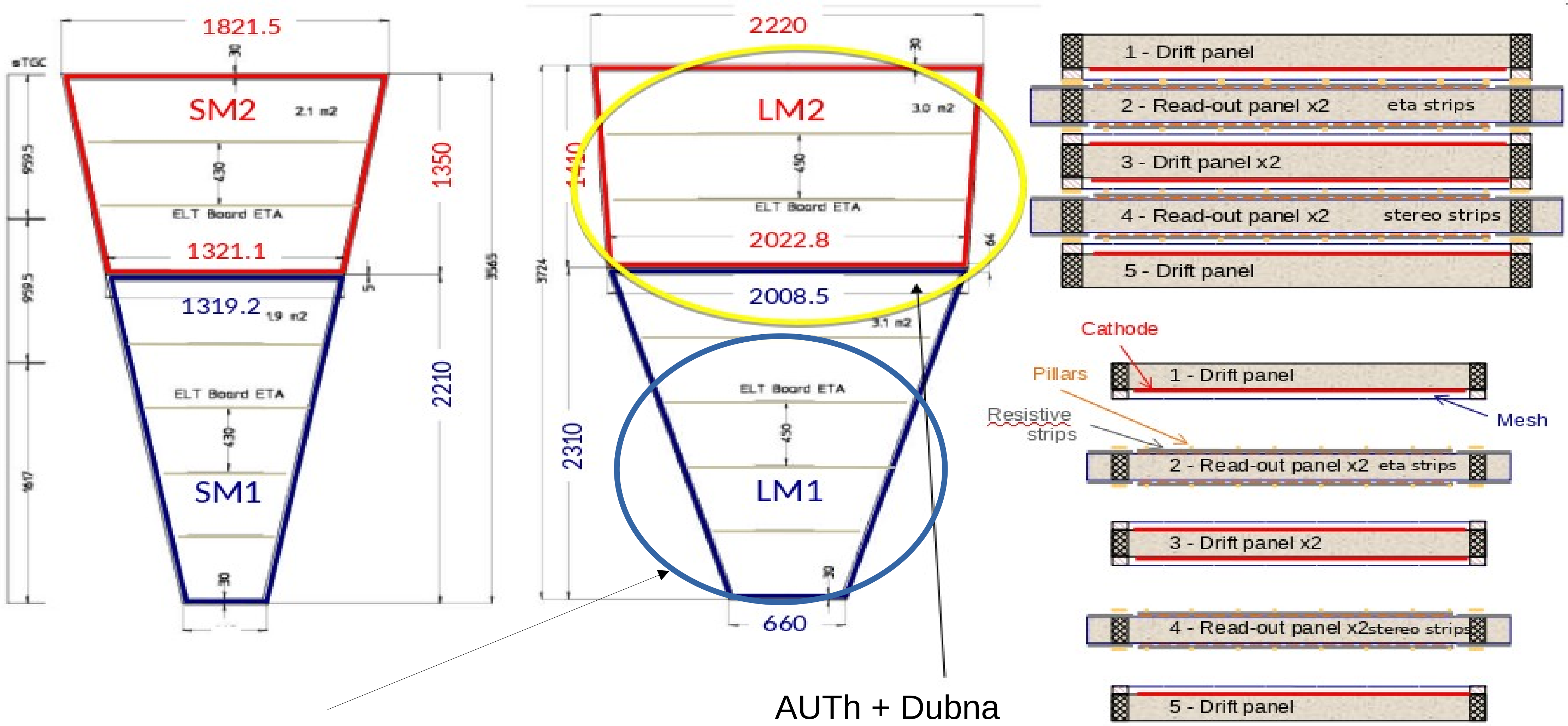
(Thomas Papaevangelou, IRFU - FCC meeting, January 2021)

Applications: ATLAS New Small Wheel

Micromegas for ATLAS



Micromegas wedge and module



AUTh + Dubna

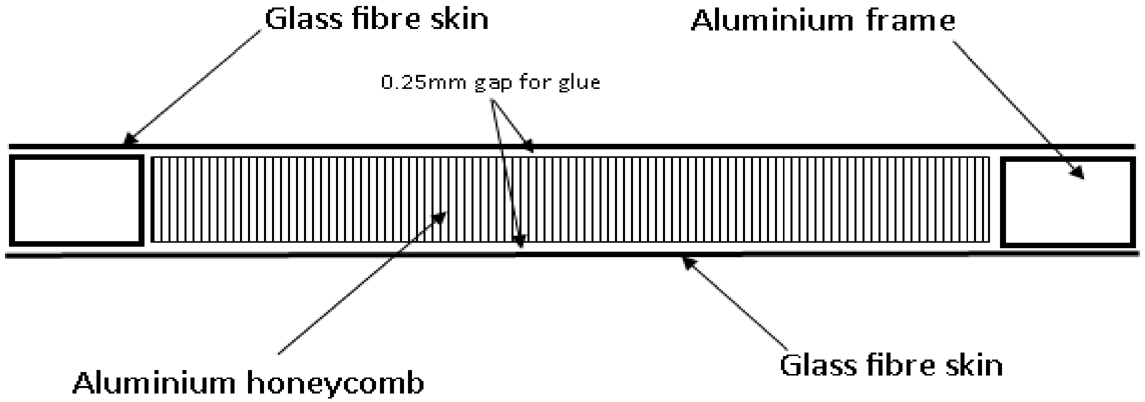
CEA Saclay

Contributed to both LM1 & LM2

NSW single panel construction basics

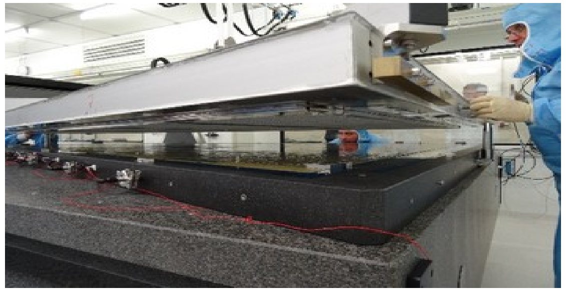
➔ Panel is a sandwich of two skins glued on a stiff plane without mechanical constraints

➔ It consists of two PCBs (500μm) with aluminum made honeycomb and frame in between



- Super – flat surfaces are required as reference planes
- Granite + Stiff – back or Double Vacuum tables methods applied
- Single or dual step processes

stiff – back



vacuum tables

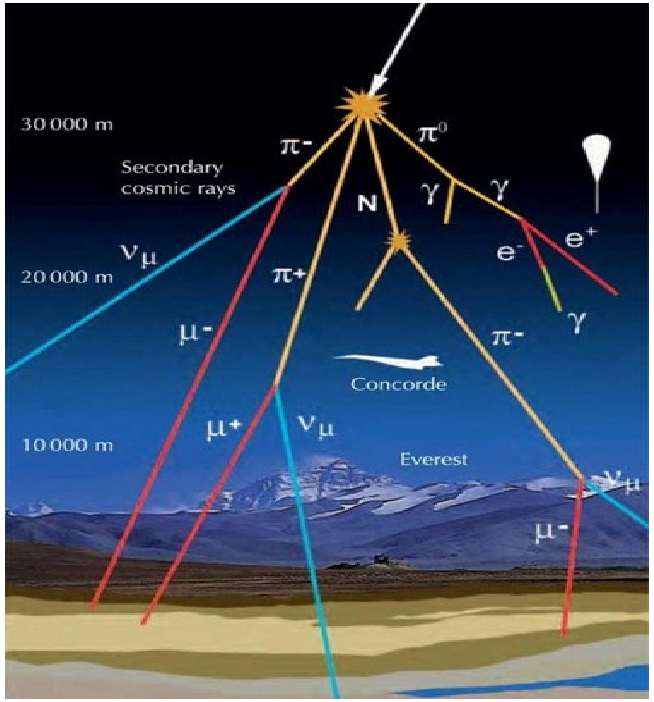
https://www.youtube.com/watch?v=uLJ60sPjOHg

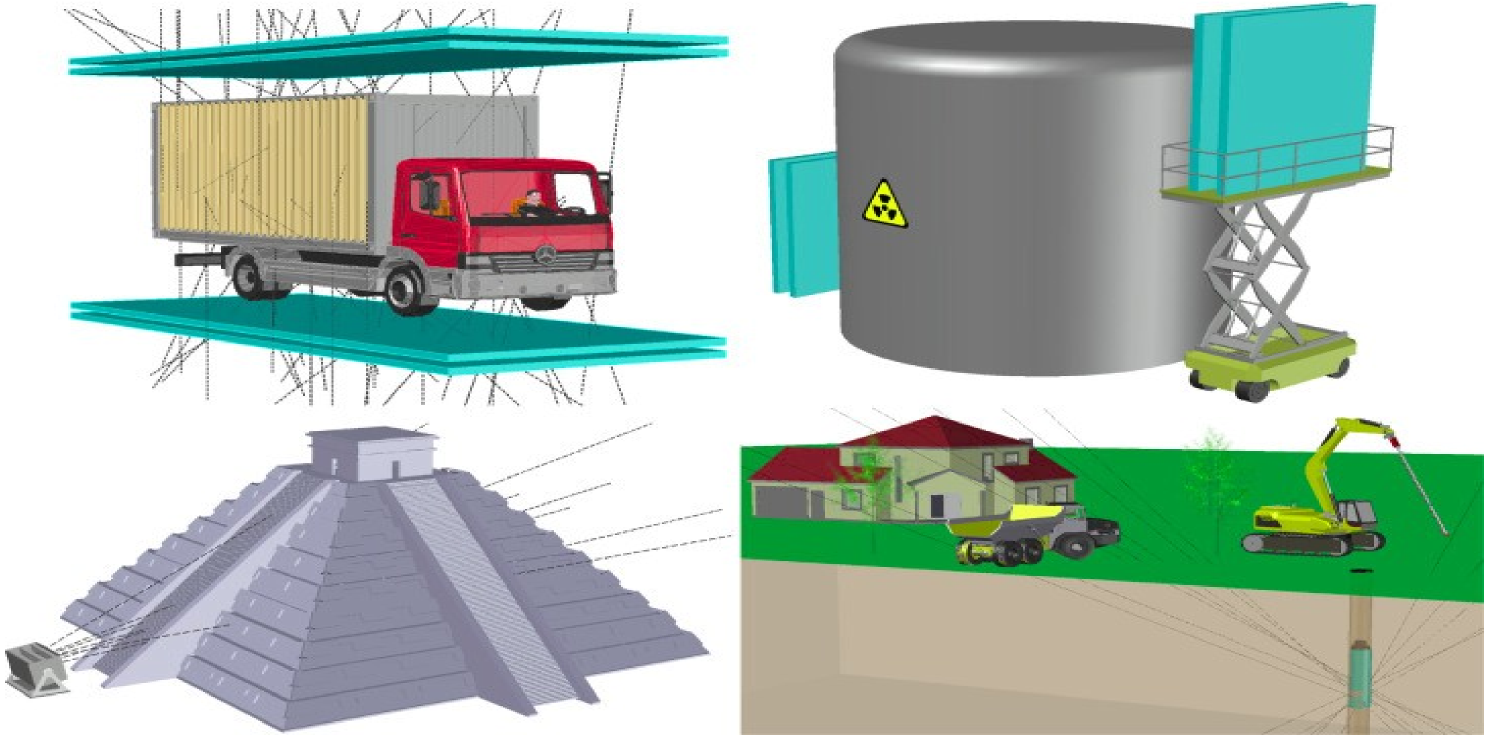
The NSW in place!

Applications: Muography

Atmospheric muons as an imaging tool

Exploit the abundant natural flux of muons produced from cosmic-ray interactions in the atmosphere.





Applications

Investigation of large geological structures
Homeland security: cargo scanning, detection of heavy elements
Safeguards: e.g. characterization of encapsulated nuclear waste
Natural hazard monitoring: volcanos

L.Bonechi et al. Review in Physics 5, 2020.

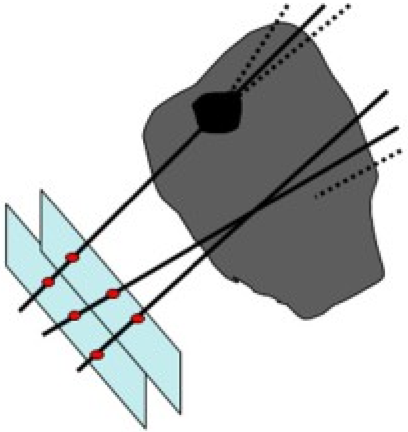
Muography: imaging based on muon detection

a non-invasive but penetrating imaging of density contrast using natural charged particles

Historical overview of Muography

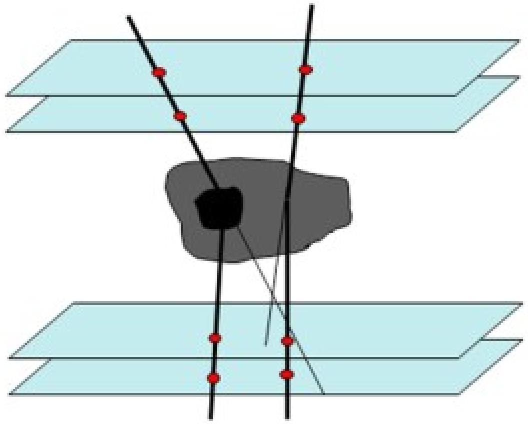
- Thickness of a mountain: George (1955)
- Hidden chambers in Chephren (or Khafre) pyramid: Alvarez (1970)
- Volcanology: Nagamine (1995), Tanaka (2001), Diaphane collaboration (2008)

S. Procureur, D. Attié / C. R. Physique 20 (2019) 521–528



Imaging via absorption

principle is similar to conventional X-ray radiography

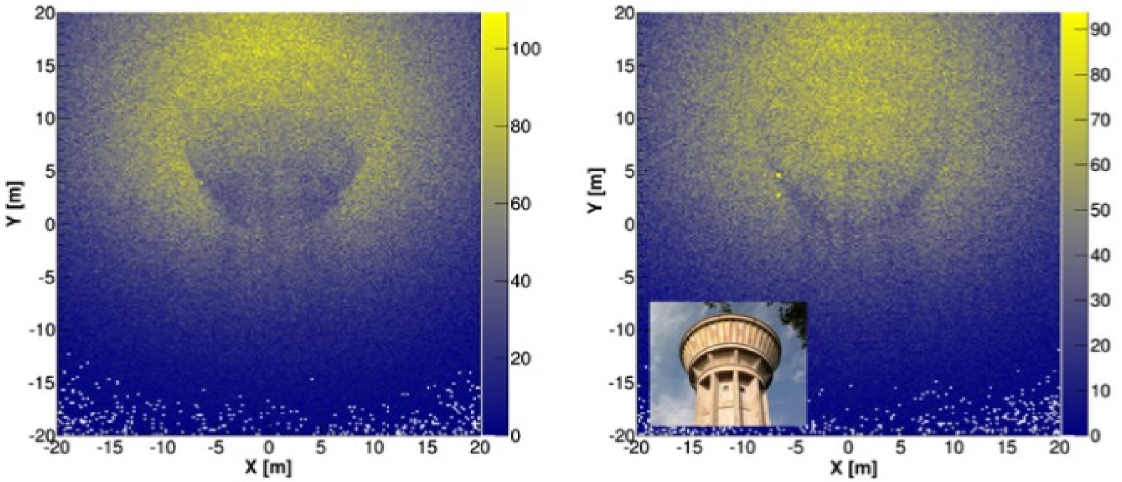


Imaging via scattering

analyze the angles of deflection before and after passing a volume

Muography: imaging from muon flux

S. Procureur,. Muon imaging: Principles, technologies and applications, Nuclear Inst. and Methods in Physics Research, A 878 (2018) 169–179

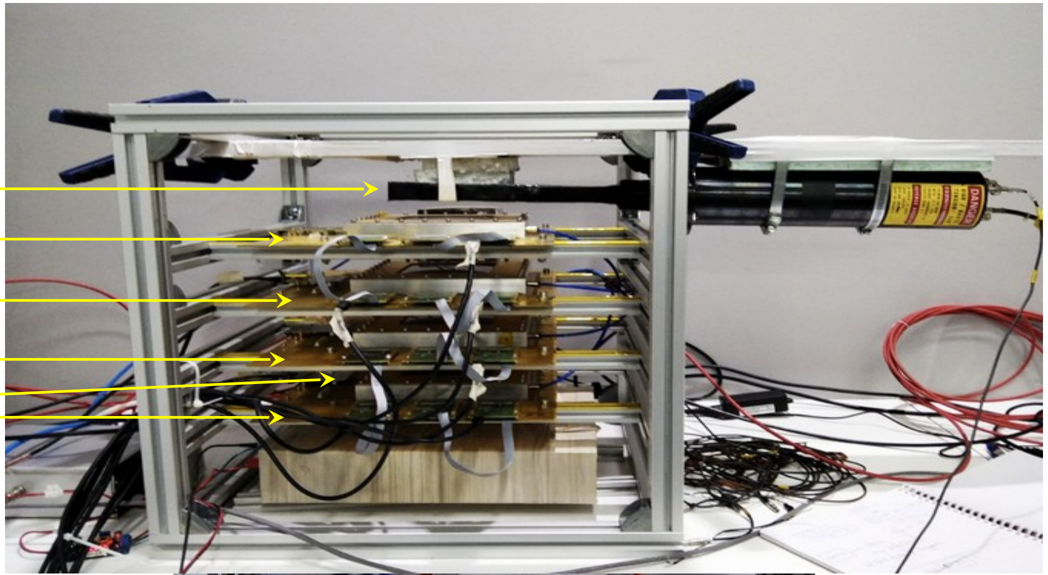


Raw muographies of the Saclay water tower, with (left) and without (right) water in the tank.

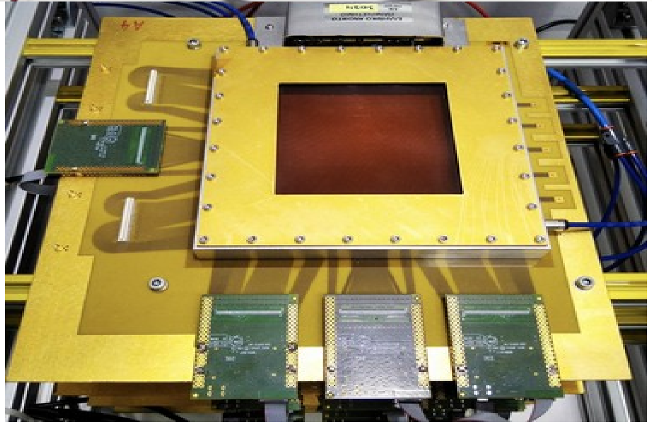
Scan of the Khufu pyramid of Giza (CEA - Saclay)

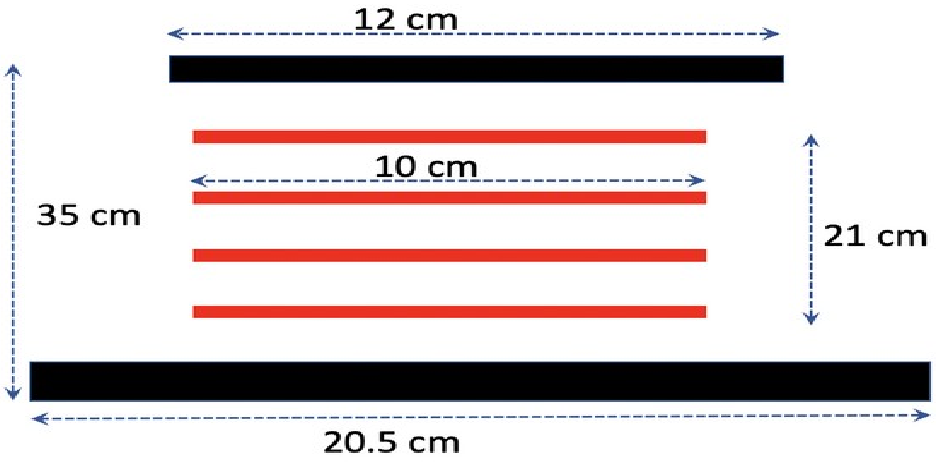
S. Bouteille, et al. A Micromegas-based telescope for muon tomography: The WatTo experiment, https://doi.org/10.1016/j.nima.2016.08.002

The “mini” Micromegas telescope (CIRI – AUTh)



12 x 10 cm^2
Scintillator 2
MM4
MM3
MM2
MM1
Scintillator 1
20.2 x 23 cm^2

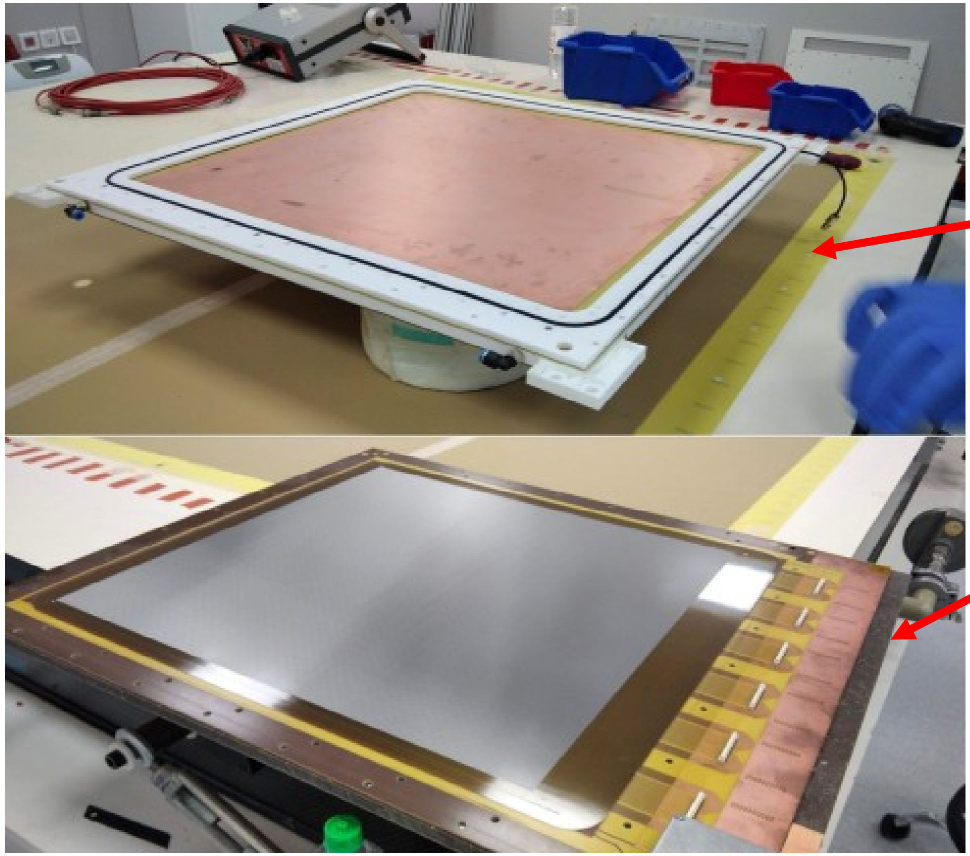




4 Micromegas (10 x 10 cm^2 active area)

- anode board: XY 2-dimensional ~ 384 strips
- detection medium: Ar – CO_2 gas 93%-7%
- APV25 readout cards (x6 per XY plane)
- signal reception via SRS (Scalable Readout System)
- trigger using 2 scintillators in coincidence

Towards a larger telescope: MM Chambers



A single MM module consists of:

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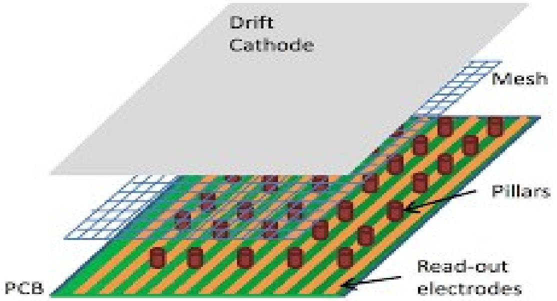
Aristotle University of Thessaloniki

- A Drift panel
- Gas gap frame (with 2 o-rings) mounted on the Drift panel
- A Read-Out panel



- Resistive BULK Micromegas on 2mm board
- outer size 580mmx 700mm
- active area 460mm x 460mm
- 768 strips per detector
- strip 0.45mm
- 0.6mm pitch
- 6 Panasonic connectors

Individual MM chamber test bench

Lab tests: module validation

- Power Supply (CAEN Mod. A4531)
- Data Acquisition (APV25 & SRS)
- Trigger (scintillators)
- NIM units

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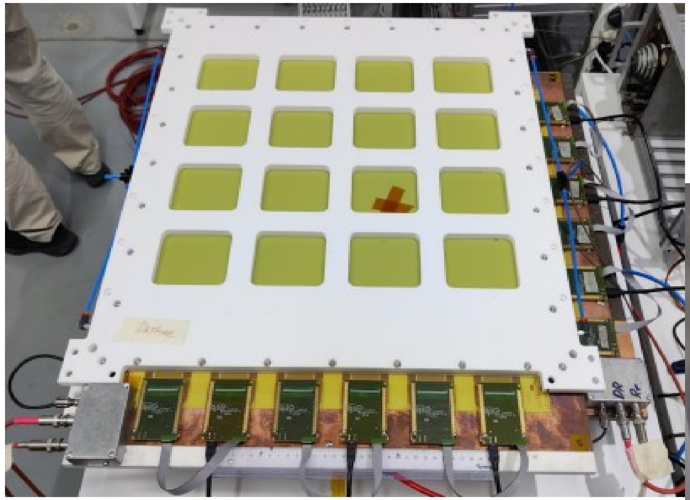
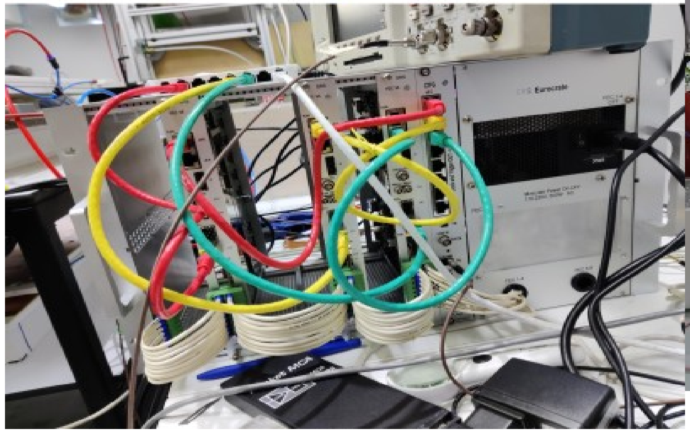
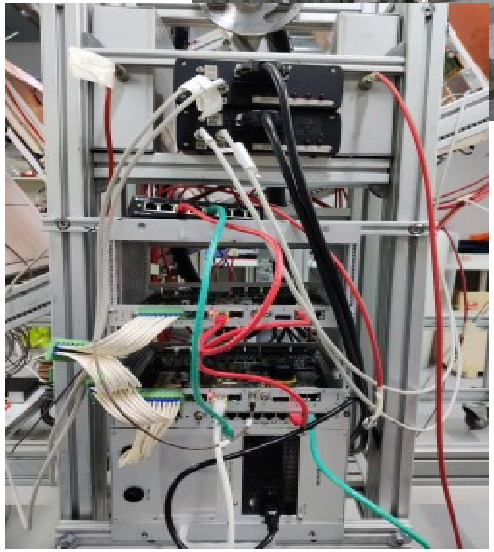




MM Telescope: full system installation

Custom made electronics (A. Tsirigotis H.O.U.)



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DAQ system

Gas bottle

- Mounting of detectors
- Cables routing (Gas & HV)
- Mounting of peripherals (HV supplies, Gas bottle etc.)

MM Telescope at the Apollonia tumulus

- Power: Solar panels & power box
- Full system powered ON
- Addition of temperature sensors
- Telescope set @ 20 degs
- Test (trigger system + MM pedestal run)

EKATY project

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Closing Remarks

Purpose of **Radiation Detectors** in keywords:

- **Detect** (verify the presence/passage of particle(s))
- **Identify** (determine the type, charge, mass)
- **Track** (follow the movement)
- **Measure** (quantify intensity and/or energy of radiation)
- **Record** (store data for treatment and future use)
- **Evaluate** (assess effects)

Closing Remarks

Method + Detector combination requires lots of things to consider

type of radiation, energy range, efficiency, resolution requirements, rate capabilities, resources, measuring conditions, duration of use, size and portability, costs and maintenance, **hardness**, safety issues….

Closing Remarks

Method + Detector combination requires lots of things to consider

type of radiation, energy range, efficiency, resolution requirements, rate capabilities, resources, measuring conditions, duration of use, size and portability, costs and maintenance, **hardness**, safety issues….

Will you buy off the shelf...OR build ?

design, choose materials, estimate budgets, search markets, create tooling, establish procedures, outsource, train people, evaluate...

Closing Remarks

Method + Detector combination requires lots of things to consider

type of radiation, energy range, efficiency, resolution requirements, rate capabilities, resources, measuring conditions, duration of use, size and portability, costs and maintenance, safety issues….

Will you buy off the shelf...OR build ?

design, choose materials, estimate budgets, search markets, create tooling, establish procedures, outsource, train people...

There is no “best or perfect” system, every detector has its advantages and limitations

References (random order)

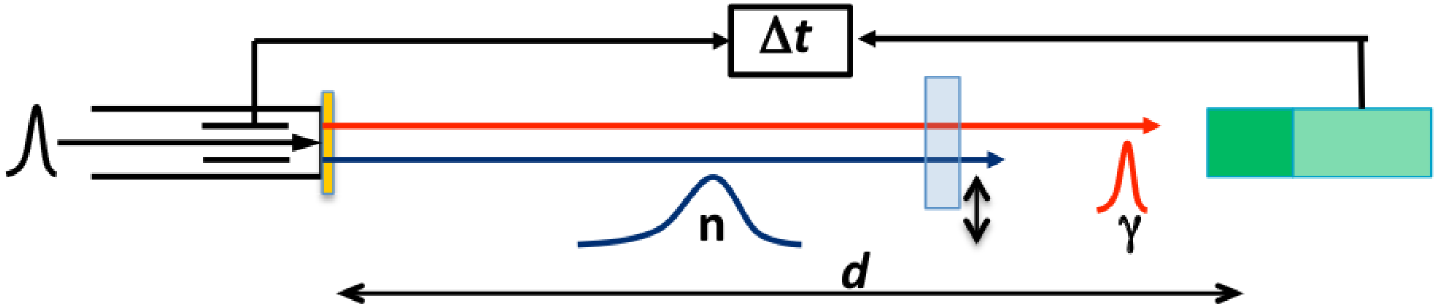
- W. R. Leo, Techniques for Nuclear and Particle Physics Experiments, 2nd Ed. Springer-Verlag (1994)
- G. Knoll, Radiation Detection and Measurement, Fouth Edition, Wiley
- W. Blum, W. Riegler, L. Rolandi - Particle detection with drift chambers- Springer (2008)
- F. Sauli, Principles of operation of multiwire proportional and drift chambers, CERN-77-09
- S. Ahmed, Physics and Engineering of Radiation Detection 2nd edition
- Particle Detectors, Fundamentals and Applications, H. Kolanoski – N. Wermes, Oxford University Press
- C. Grupen and B. Shwartz, Particle Detectors 2nd edition
- Practical Gamma-ray Spectrometry, Gordon R. Gilmore, 2nd edition

Thank you!

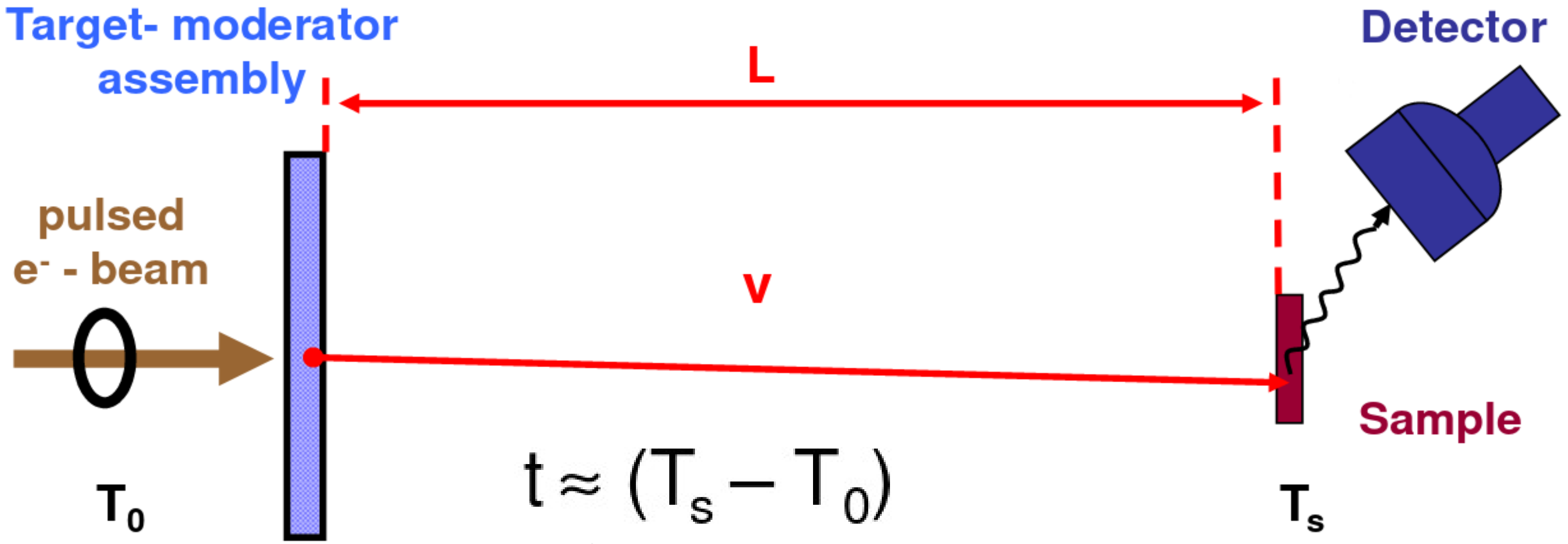
Questions are welcome!

Backup slides

Neutron Time Of Flight



TOF principle



$$t \approx (T_s - T_0)$$

Neutron racing

t_{start}

t

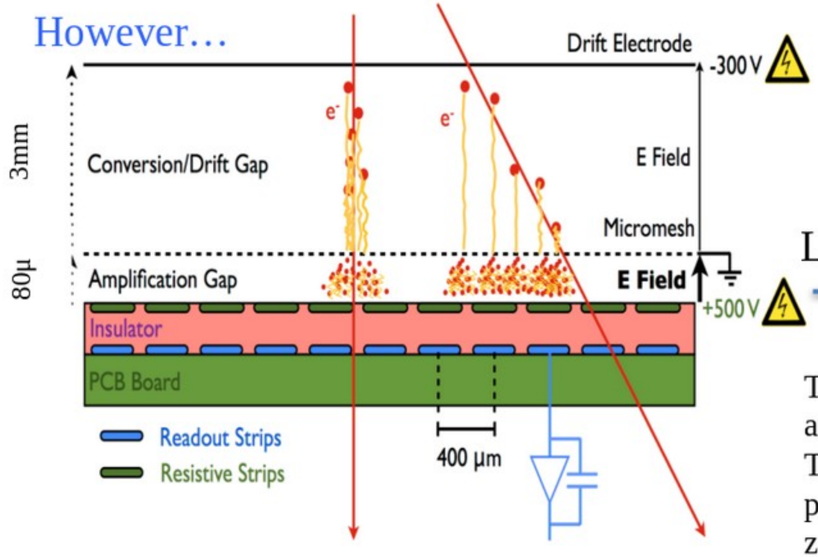
Neutron racing: resolve

t_{stop}

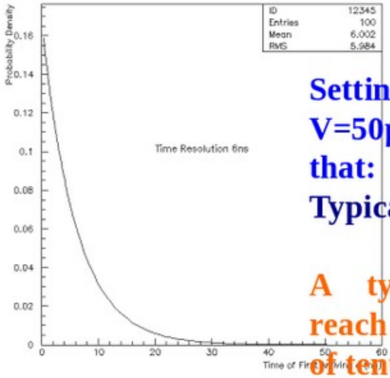
Flight path lenth ?!

Limitations: reminder

However…



Using the drift velocity (V), we express the probability that the first electrons will reach the anode at time t as: $A^n_{first}(t) = n(V/L)e^{-nVt/L}$



Setting typical values, i.e. V=50μm/ns and n=10 we conclude that:

Typical Time Resolution ~6ns

A typical MicroMegas cannot reach timing resolution at the level of tenths of ps

$$P^n_k = \frac{n^k}{k!}e^{-n}$$

The probability that an e-ion pair has been produced at Z=z is the same for any value of Z; **p=1/L**

Then, in case that k pairs are produced, the probability that the jth pair has been produced at Z= z is given by the binomial distribution

$$D^k_j(x) = \frac{k!}{(k-j)!(j-1)!}(1-x)^{k-j}x^{j-1}$$

where **x=z/L describes the probability that a pair is produced in the region 0-z**

The probability that the jth pair has been produced at Z= z for any total number of e-ion pair

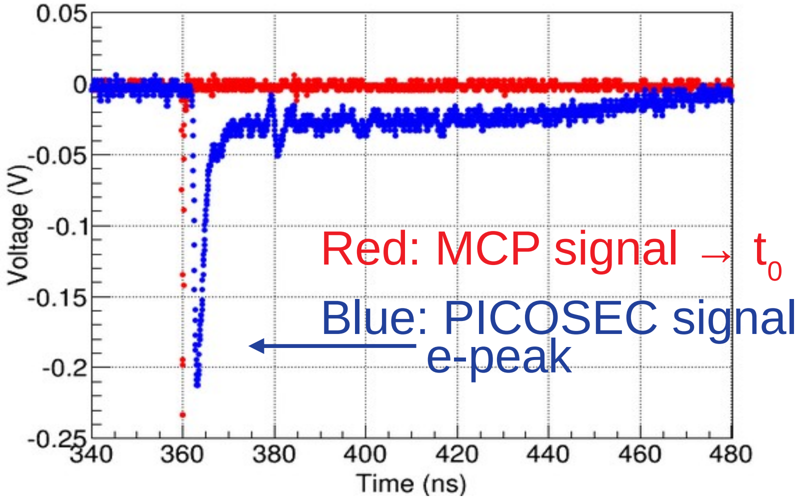
$$A^n_j(x) = \sum_{k=j}^{\infty} P^n_k D^k_j(x) = \frac{x^{j-1}}{(j-1)!}n^j e^{-nx}$$

The probability that the last pair (i.e. the closest to the edge 0) has been produced at Z= z is given by (j-1=0):

$$A^n_{last}(x) = ne^{-nx}$$

$$A^n_{last}(z) = ne^{-nz/L}$$

The PICOSEC concept



Small drift gap (~200 μm) + High E-field:

- ✓ Pre-amplification possible
- ✓ Limited direct ionization
- ✓ Reduced diffusion impact

Cherenkov radiator/Photocathode:

- ✓ Photo-electrons emerging the photocathode simultaneously (fixed distance from the mesh)
- ✓ produce sufficient number of photo-electrons

Effect: improved timing resolution

Cherenkov radiator + Photocathode

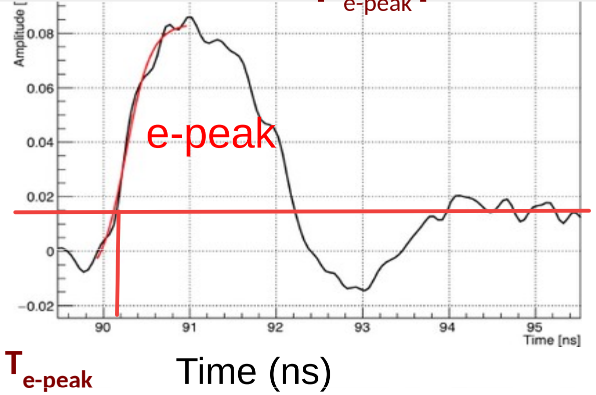
- ✓ Particle produce Cherenkov light
- ✓ Photo-electrons emerge from photocathode
- ✓ Electrons amplified by a two-stage Micromegas

Signal components: Fast <1ns (electron peak) &
Slow ~100ns (Ion-tail)

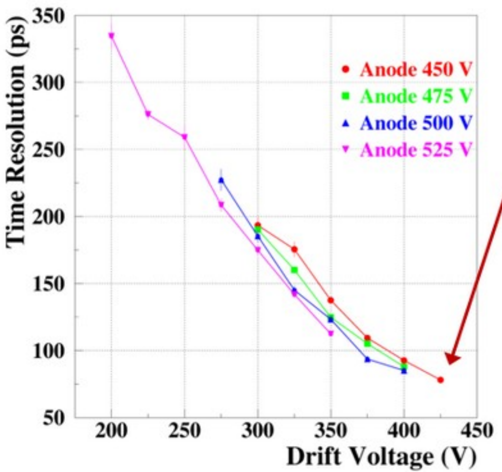
$T_{e\text{-peak}}$ = Signal Arrival Time (SAT)

* SAT of a sample of events = $<T_{e\text{-peak}}>$

* Time Resolution = RMS[$T_{e\text{-peak}}$]



Achievements in timing: single-anode



Best time resolution for **1 photo-electron**:

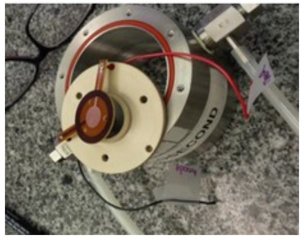
76.0 ± 0.4 ps @ Vd/Va = -425V / +450V

improves strongly with higher drift field, less with anode field

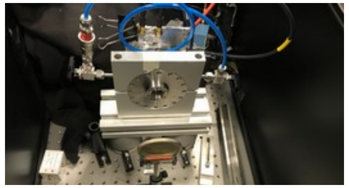
The Signal Arrival Time (SAT) depends on the e-peak charge:

- bigger pulses ➔ smaller SAT
- higher drift field ➔smaller SAT

Shape of pulse is identical in all cases ➔ timing with CFD method does not introduce dependence on pulse size



IRAMIS/LIDYL laser facilities @ CEA Saclay



Main goals

- Time resolution for single PE in laser tests
- Time resolution for muons
- Photocathode quantum efficiency
- Optimize the detector

Single – anode PICOSEC: single PE (laser tests) + muons @ SPS

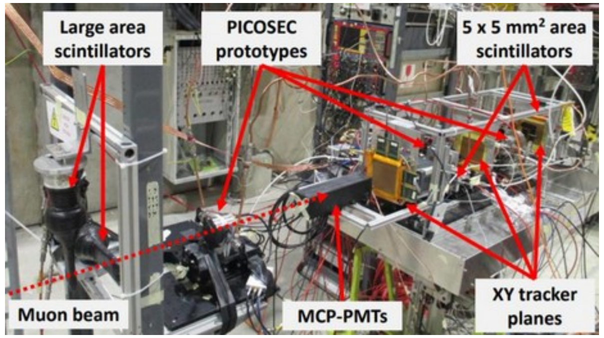
Same detector as for Laser tests:

MgF2 radiator 3 mm thick

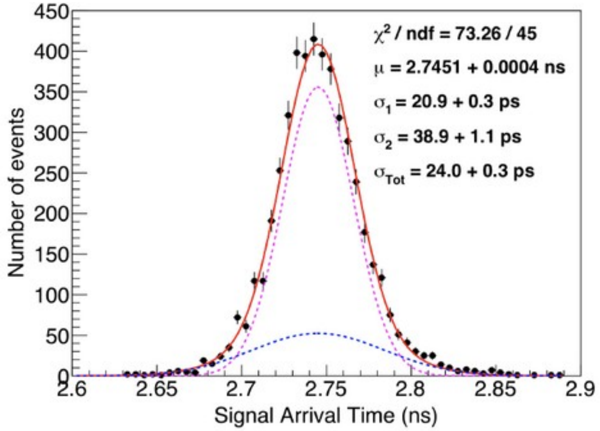
18 nm CsI on 5.5 nm Cr

Bulk MicroMegas

“COMPASS gas”



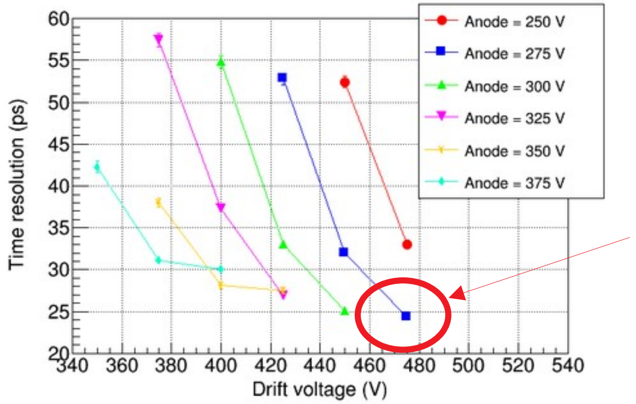
CERN SPS H4



Optimum operation point: V_{drift}/V_{anode}: -475V/+275V

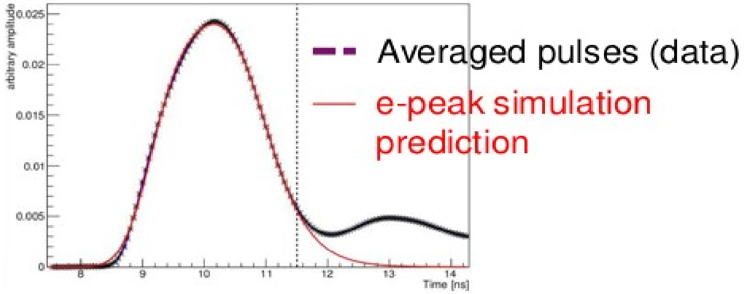
Best result: **24 ± 0.3 ps**

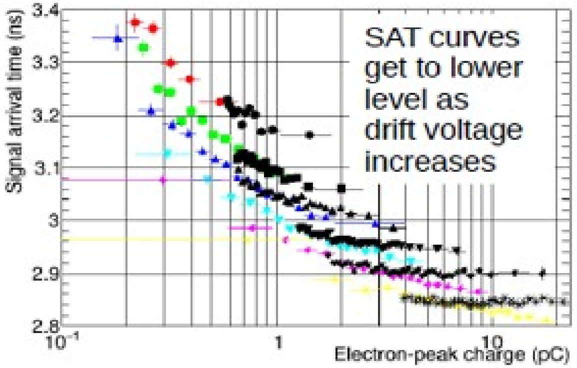
$N_{p.e.}$ = **10.1 ± 0.7**

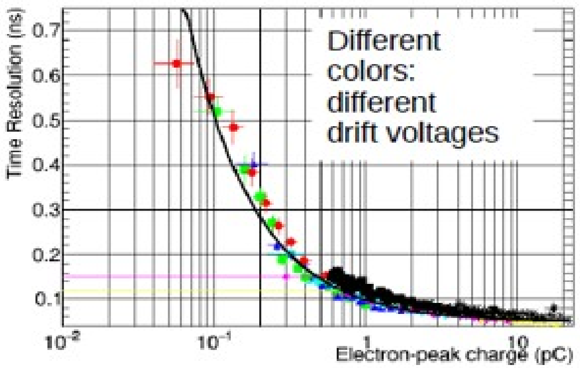


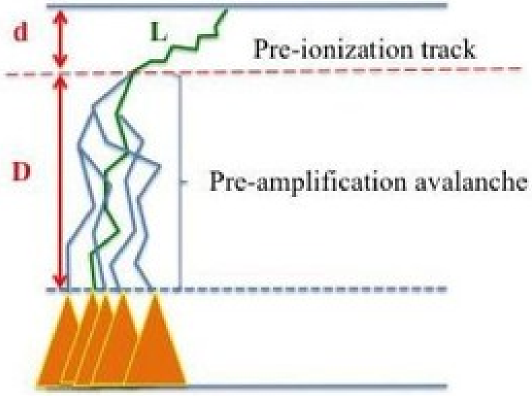
Modeling & simulation: thorough understanding of the detector

Phenomenological model describing stochastically the dynamics of the signal formation

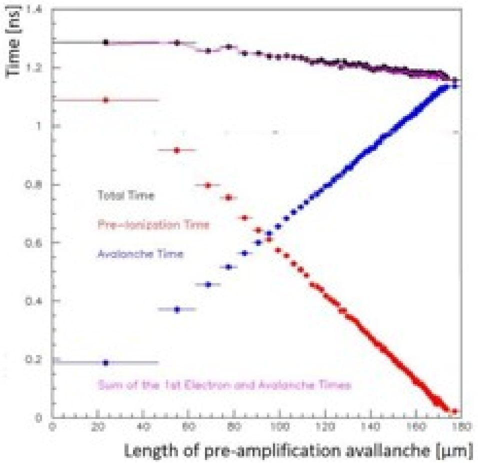








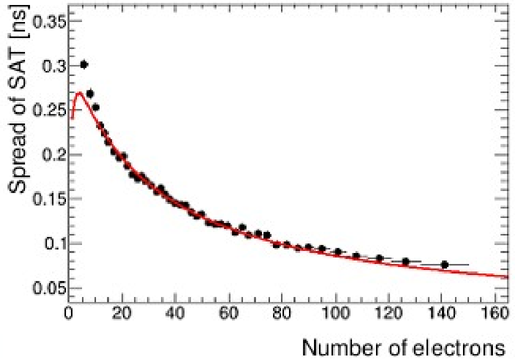
The model describes **SAT** and **Resolution** vs. **avalanche length** & vs. **number of electrons** in avalanche (i.e, e-peak charge)



Avalanche speed = 154 µm/ns

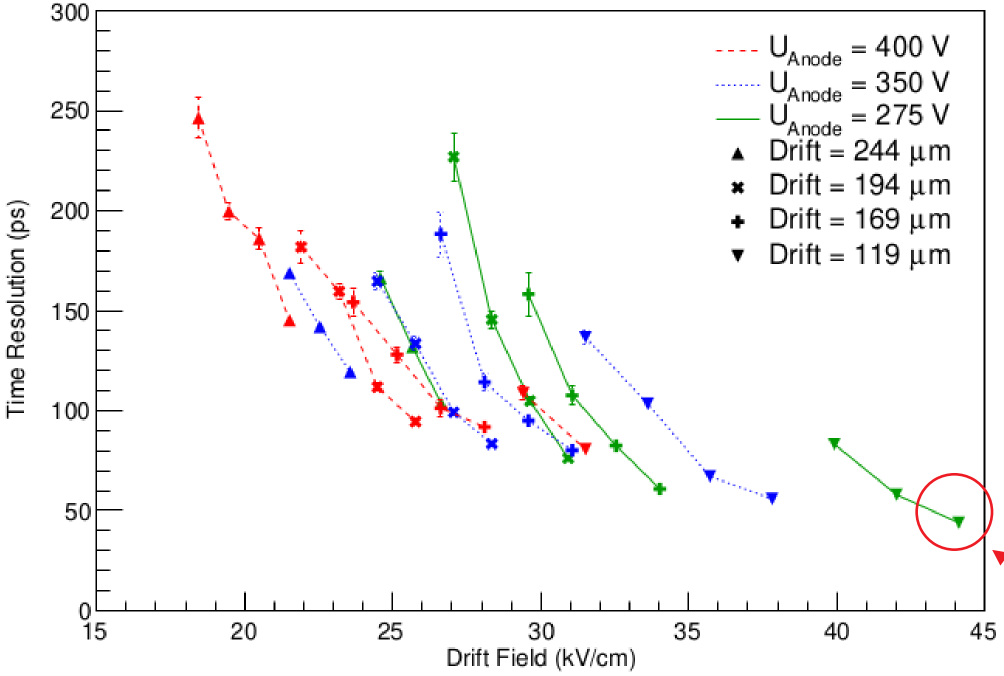
Electron speed = 134 µm/ns

Detailed Garfield++ simulations reveal the same behaviors as seen in single p.e. laser data!



Model driven optimization of the detector

Deep understanding of the PICOSEC detector: reproduce results with detailed simulation, apply the phenomenoligal model to explain the observed experimental behavior and use it to optimize parameters



- **Drift gap:** The majority of the tests was done with **200 μm** gap. Reducing it is expected to **improve avalanche size and stability**. *Tests were performed in May 2019 at the fs laser* for gaps of **120**, **170** , **195** and **245 μm**
- **Gas composition**. CF$_4$ is increasing drift velocity, however is decreasing the maximum gain. **Ne or He mixtures with only C$_2$H$_6$ as quencher** are expected to increase maximum gain
- Gas pressure: decreasing pressure is equivalent with decreasing the amplification gaps.

Reducing the drift gap at **119 μm** (highest stable field setting of 44 kV/cm) yields a time resolution of **44±1 ps** for single photoelectrons.

Lukas Sohl Ph.D. thesis, CEA Saclay 2020

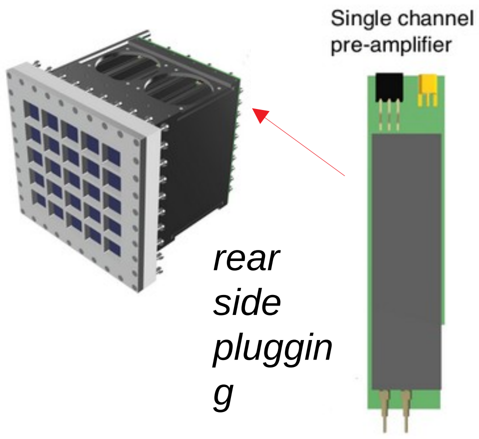
Readout electronics I

Scheme during first test period (single cell and 1st multipad PICOSEC prototype):

CIVIDEC broadband amplifier, 2 GHz, 40 dB, (*https://cividec.at/electronics-C2-HV.html*) **+**

LECROY WR8104 oscilloscope, operated at 1.0 GHz analogue bandwidth, sampling rate of 10 Gsamples/s, Waverunner 8000, Teledynelecroy, *(http://cdn.teledynelecroy.com/files/pdf/waverunner8000-datasheet.pdf)*

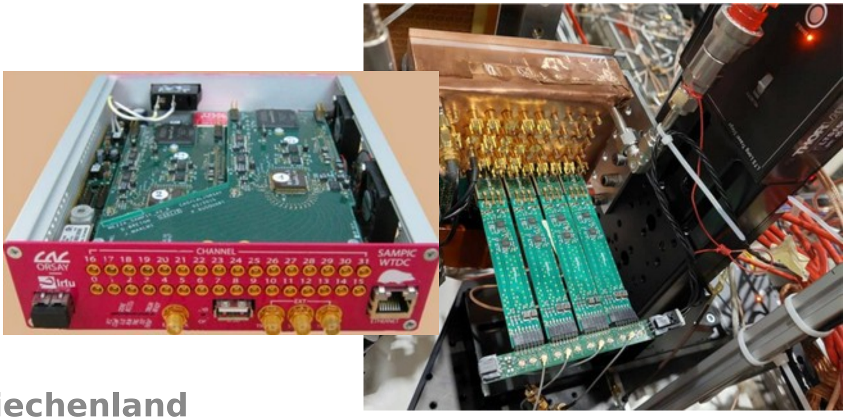
Costly and not convenient solution for multi-channel application.



“Home-made” preamp circuit (Philippe Legou – CEA) tested and proved compatible to PICOSEC timing requirements **+ ASIC**

One card per channel

SAMPIC considered as solution for digitisation with sampling rates ~8GS/s



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