In the name of God, the compassionate, the merciful

CERN and SESAME day

Isfahan University of Technology

Detector technologies at CERN: From particle physics to medical applications

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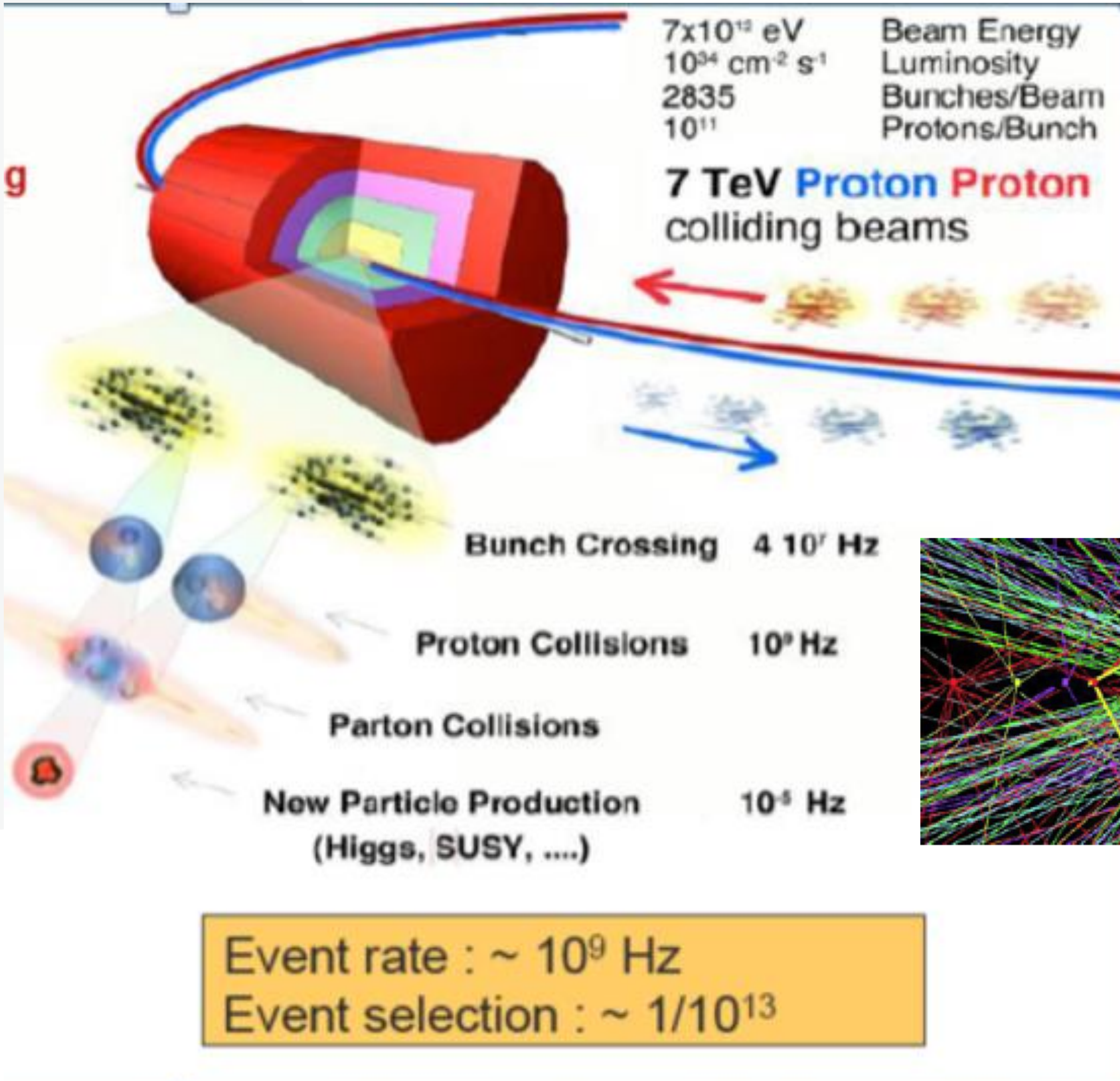
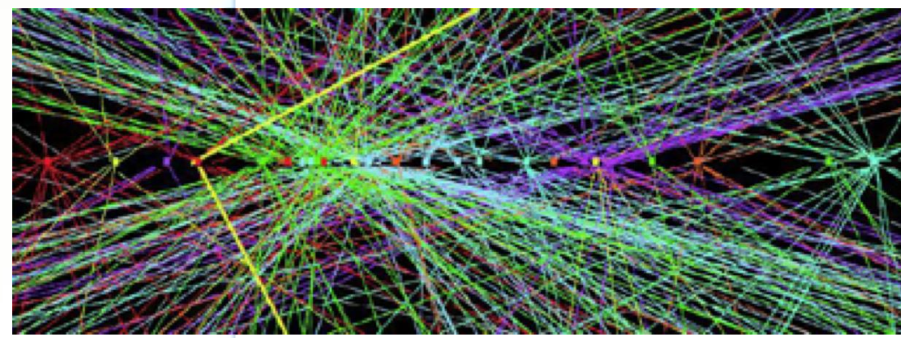
The CERN Large Hadron Collider (LHC)

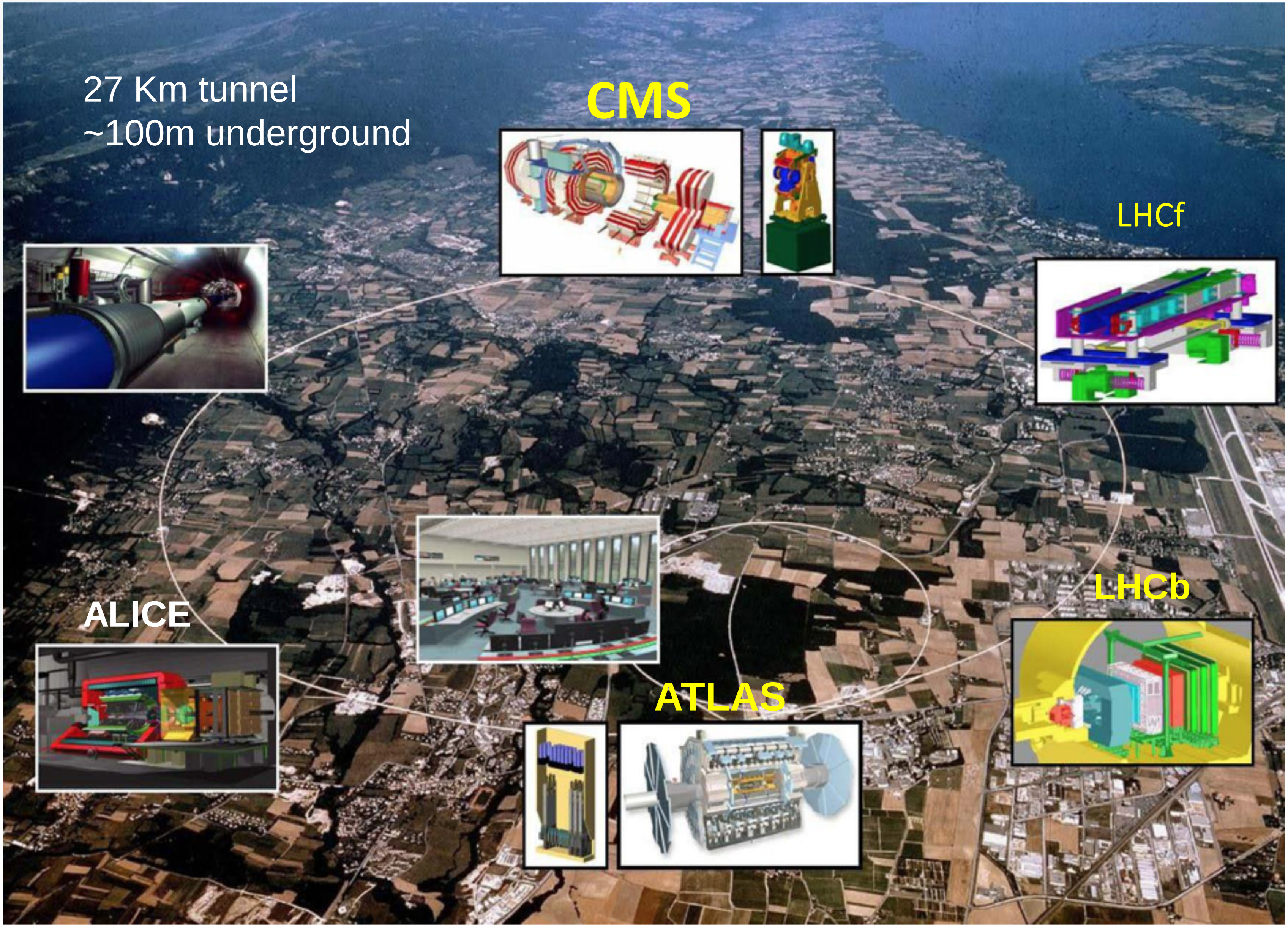


A microscope to observe Dimensions as small as 10^{-17}m!

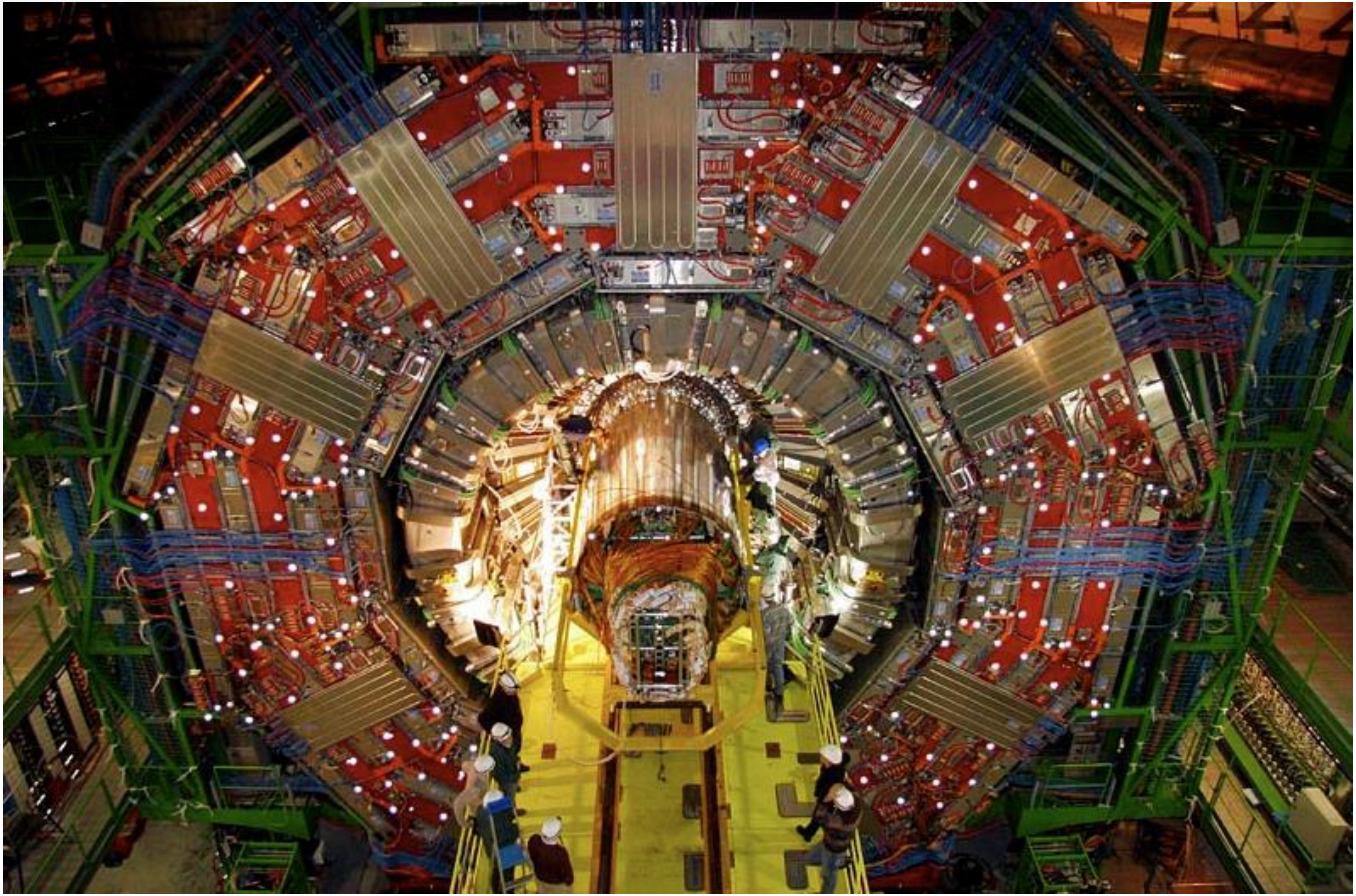


Z -> μμ event
at LHC CMS/ATLAS
15 April 2012

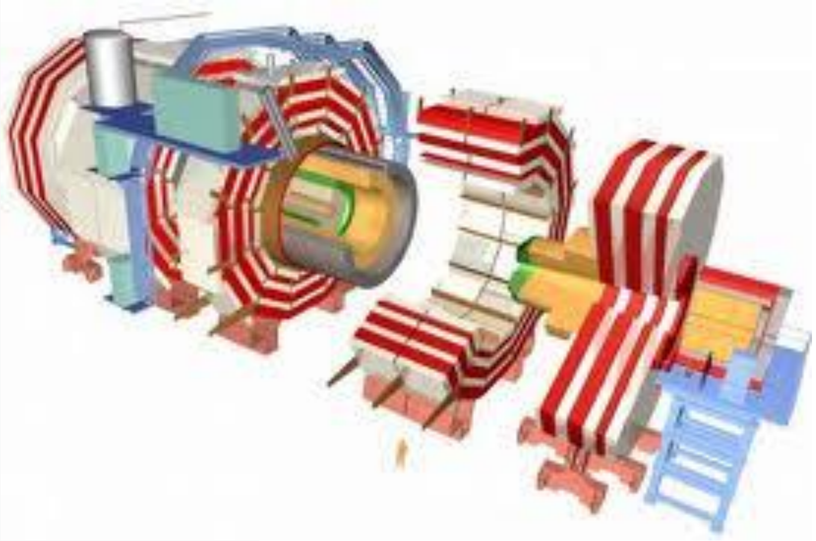
CERN-LHC



The CMS detector



A typical particle detector: CMS



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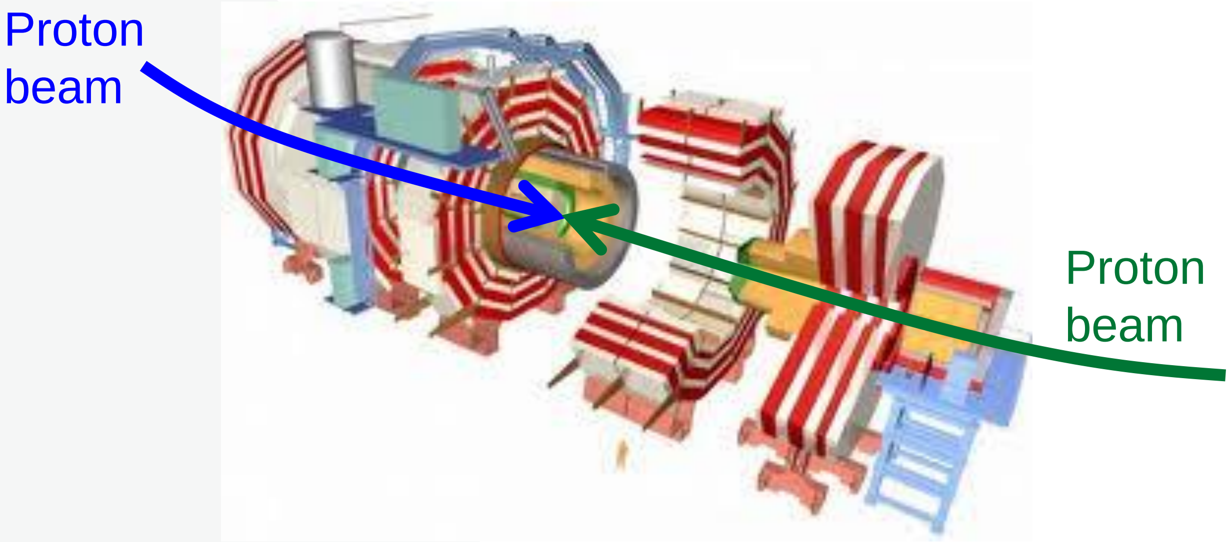

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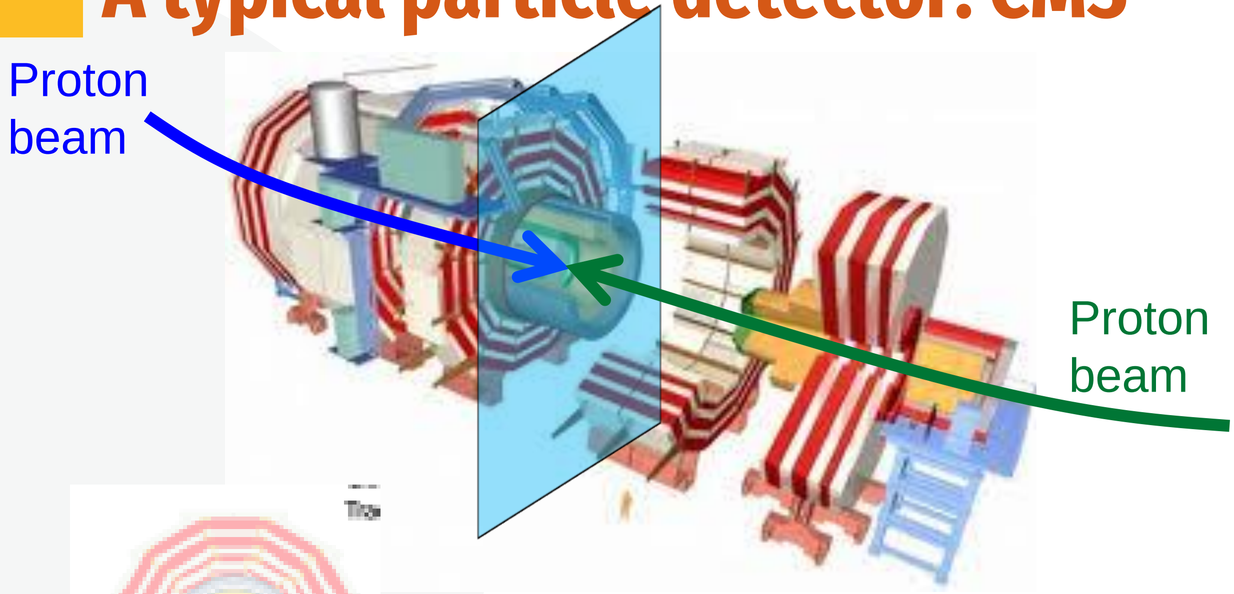

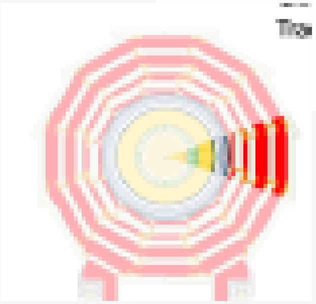

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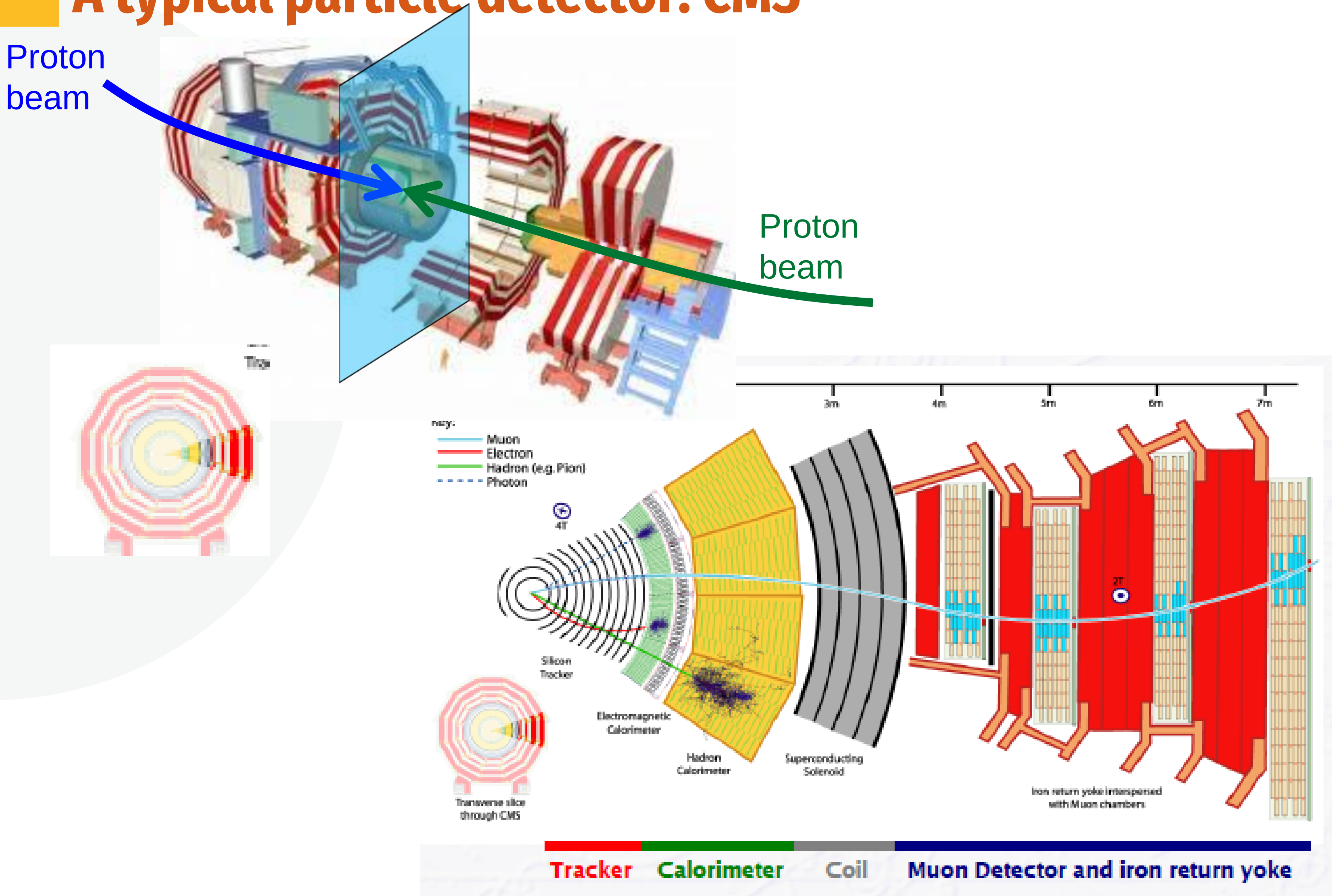

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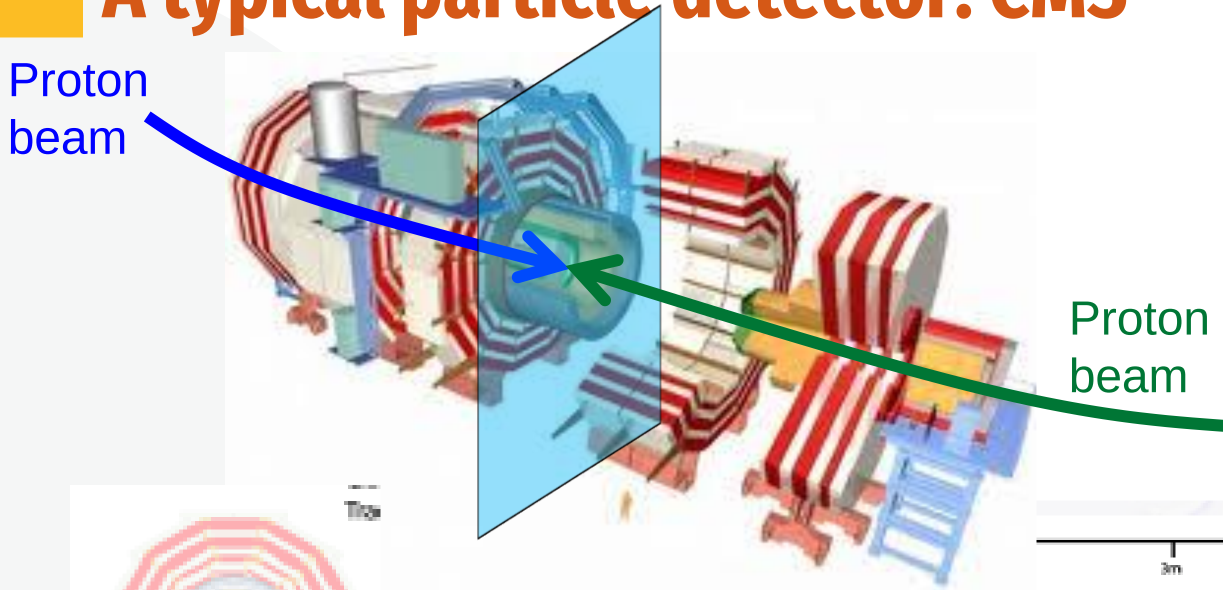
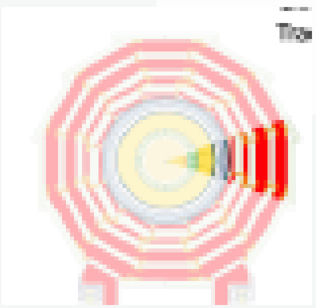
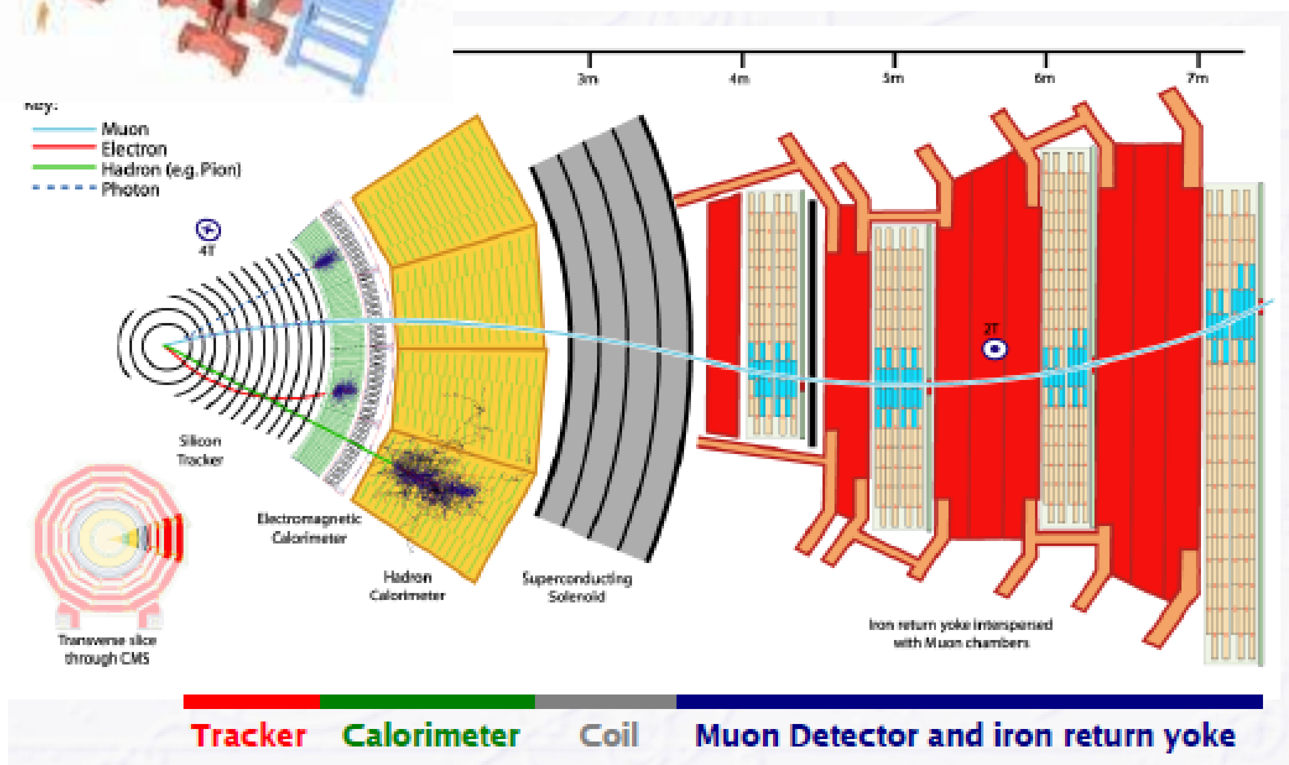






- Various effects lead to particle detect :
  - Gaseous ionization
  - Scintillation
  - Semiconductors

The radiation effects for detection

Radiation effects	observables	Detectors
ionization in gases, fluids	electrical charge, current	ionization chamber, proportional counter
ionization in solids	electrical charge, current	semiconductor detector
luminescence	spontaneous light emission UV emission from light exposure light emission from heating	scintillation detector, fluorescent screen storage foilsthermo-luminiscence dosimeter: LiF,BeO,CaF_2
chemical reactions	polymerization of organic molecules	radiochromic films with quantitative color change
photographic effect	optical density, tracks	film emulsion
heat	temperature difference	calorimeter
charge collection	electrical current	Faraday cup

Detectors: general properties

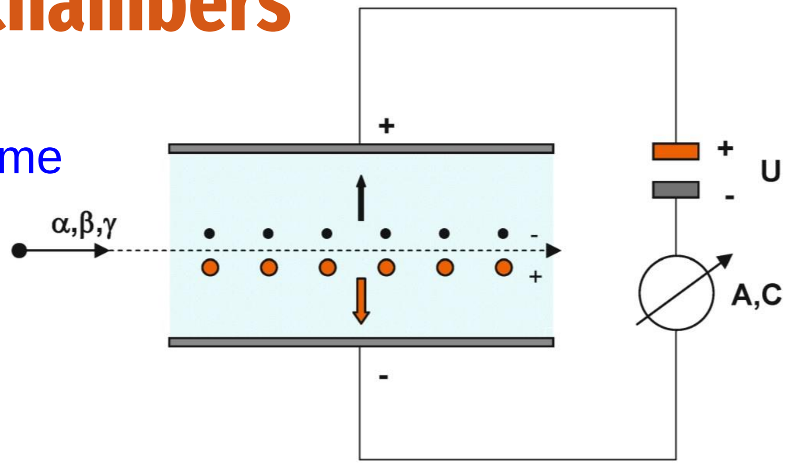
	main groups	sensitive for	detection medium
A	ionization- , proportional- , (drift-) chambers	ionization	gases (fluids)
B	scintillators	photons	crystals, fluids, gases
C	solid state detectors	ionization	semiconductors

group	energy deposition	speed	rate tolerance	price
A	++	+	+	x
B	++	+++	+++	x
C	+++	+++	++	xxx

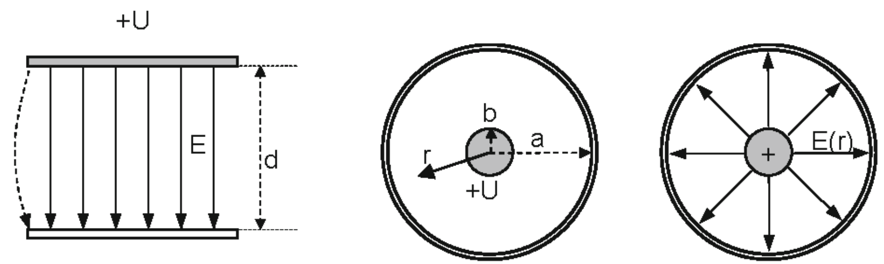
Let's quickly review these three categories

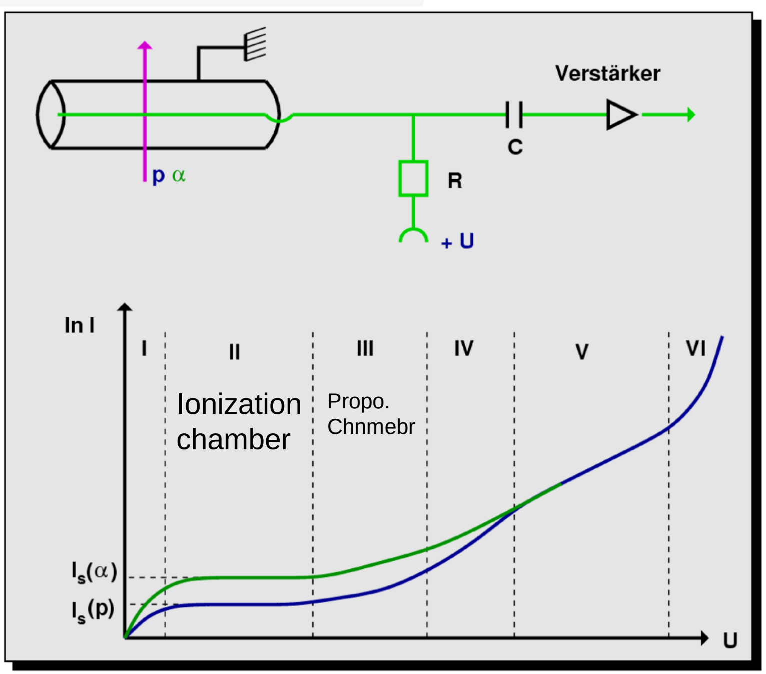
Group A- Gas-filled ionization chambers

- Incident radiation induces ionization in gas volume
- Simplest geometry: gas-filled plate capacitor
- Sensitivity determined by
  - chamber volume, counting gas, gas pressure
- mostly air-filled, but also tight high-pressure chambers with various counting gases



- Geometries of ionization chambers





Operational regimes of gas-filled ionization detectors:

I: Recombination regime:
recombination > collected charge

II: Saturation regime:
all charge carrier pairs contribute to the current

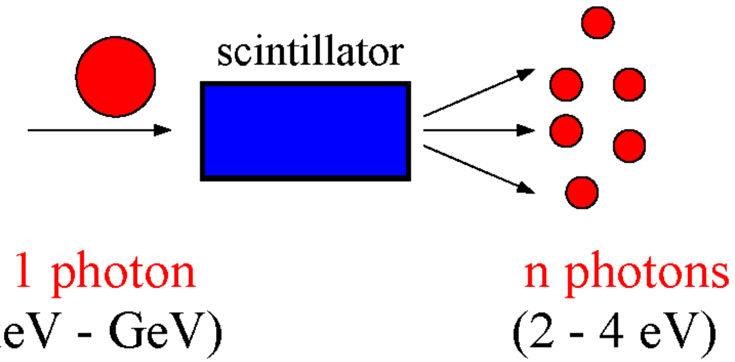
III: Proportional regime:
via secondary collisions: new charge carriers

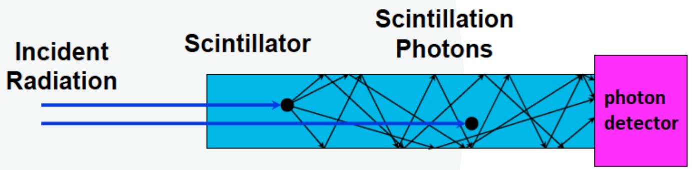
IV: Restricted proportional regime V: Release regime
avalanche creation

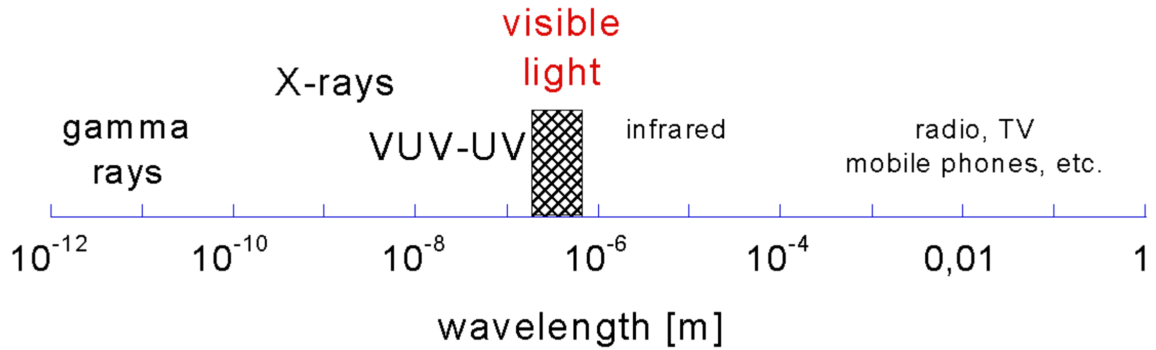
VI: Continuous discharge area

Group B - Scintillators

- Conversion of high-energy rays to low-energy photons (UV, visible)

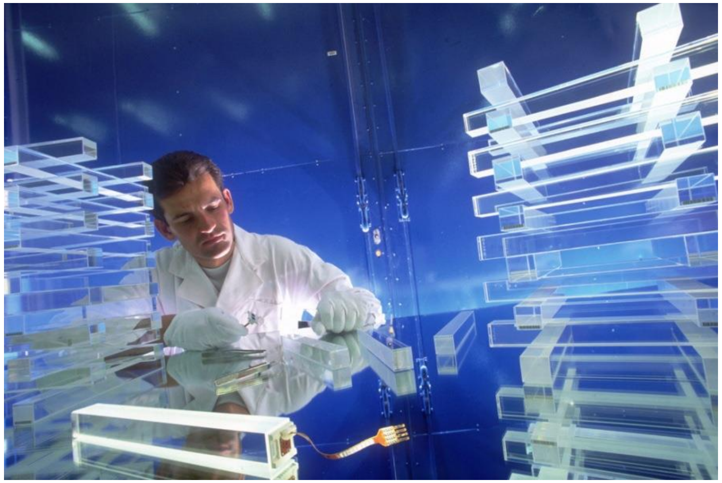




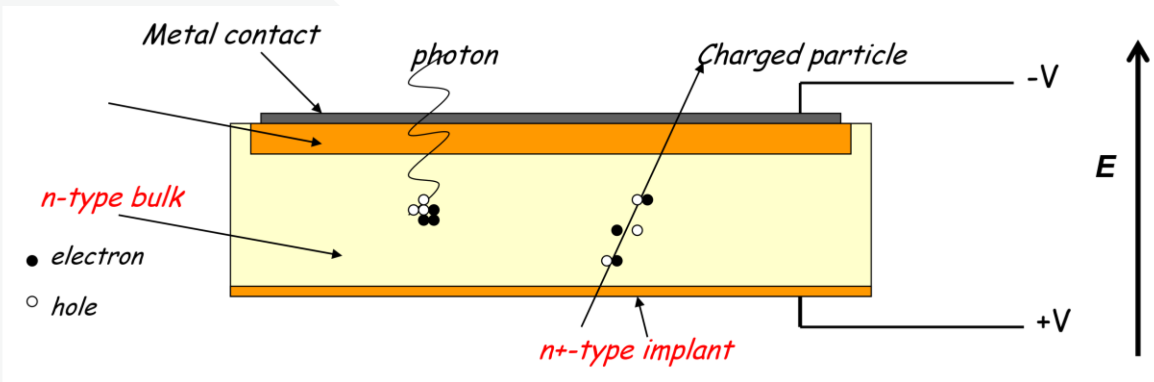


Important parameters:

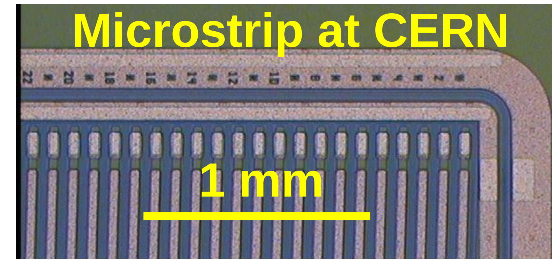
• high light output	Y (photons/MeV)
• scintillation speed	τ_s (ns)
• good energy resolution	R_{FWHM} (%)
• high density	ρ (g/cm^3)
• large size of crystal	10-100 cm^3
• low cost per cm^3	
• low afterglow	
• low intrinsic activity	



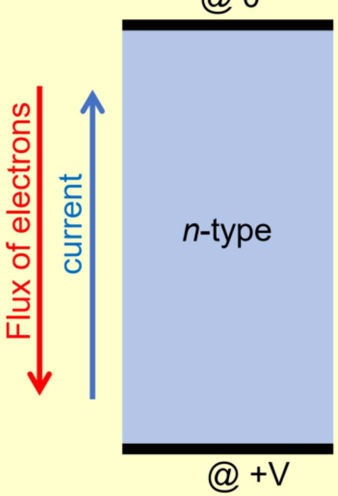
Group C - Semiconductor detector



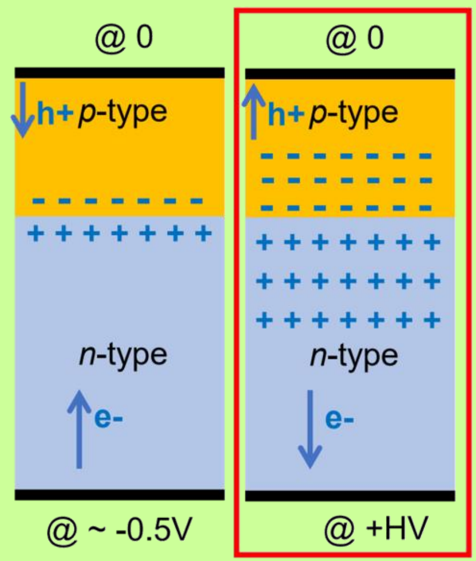
- Good linearity of the response vs. the deposited energy
- Tolerance to high radiation doses
- Speed of response (< 10 ns)



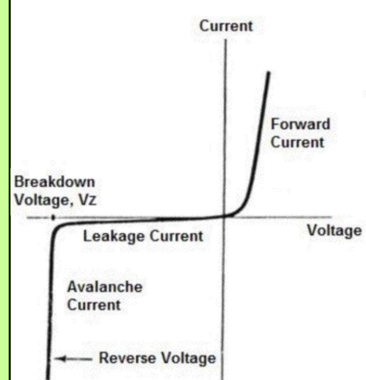
n-type silicon slab: essentially a resistor



n-type slab + *p*-type slab = Rectifying junction (**diode**)



Electrons (holes) are swept away from n- (p-) type silicon leaving a net positive (negative) charge



In forward bias, high currents flow.
In reverse bias, the current is blocked, so the Voltage must fall in a region with r≠0:

Several structures for each group

main groups	sensitive for	detection medium
ionization- chambers	ionization	gases (fluids)
scintillators	photons	crystals, fluids, gases
solid state detectors	ionization	semiconductors

- Gases ionization chambers
  - Drift tubes (DT)
  - Resistive Plate Chambers (RPC)
  - Cathode strip chambers (CSC)
  - Gas electron multiplier (GEM)

Mostly for muon detection

- Scintillators
  - Lead tungstate crystal + oxygen
    - Photodetectors glued on
  - Alternating layers of “absorber” + fluorescent scintillator
    - Collected by fibers + SiPM detector

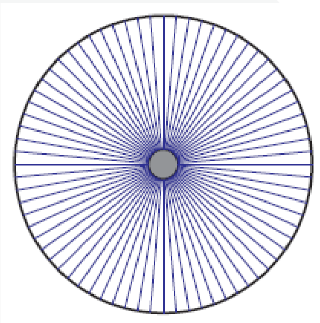
Mostly for Measuring Energy (HCAL and ECAL)

- Silicon detectors
  - Si Strip
  - Si Pixel
  - Si pad
  - Si photomultiplier → for HCAL

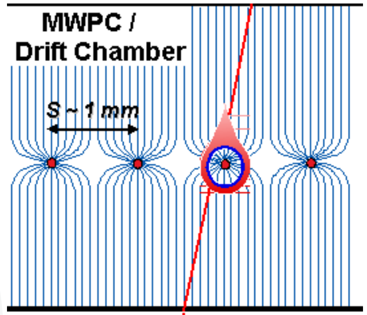
Mostly for Tracking

For ECAL + Luminosity measurement
IUT proposal for the FBCM detector:

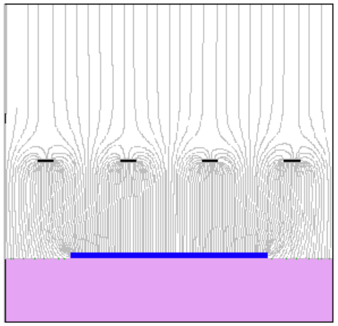
Variant of gases ionization detectors



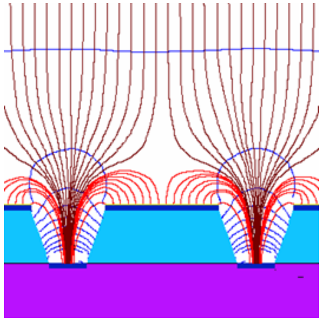
wire



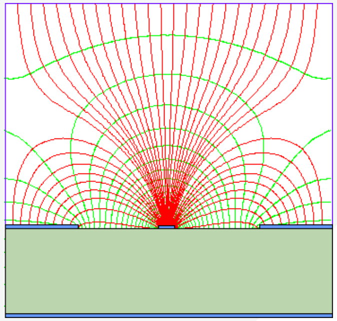
Multi Wire Proportional Chamber (MWPC)



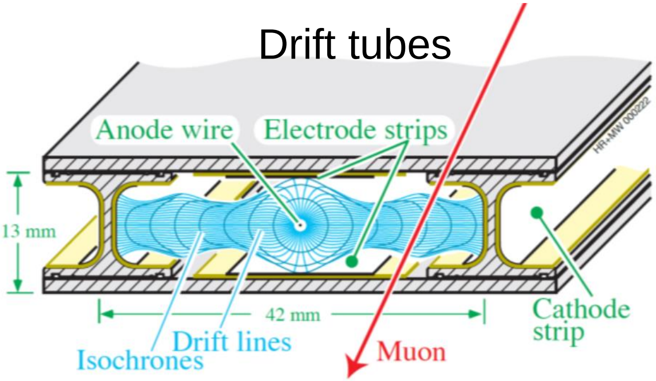
parallel plate

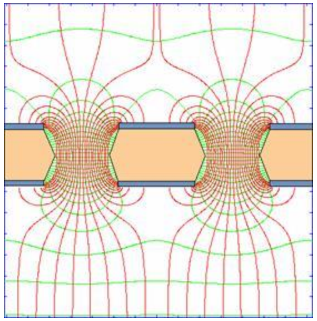


groove/well

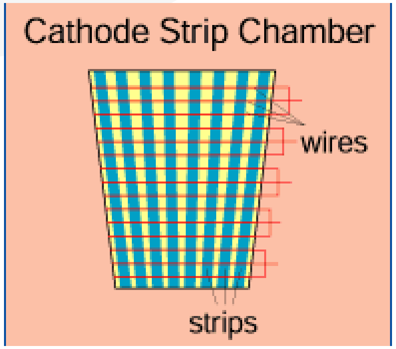


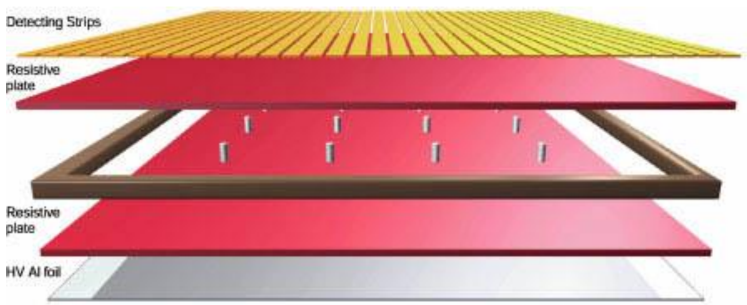
strip





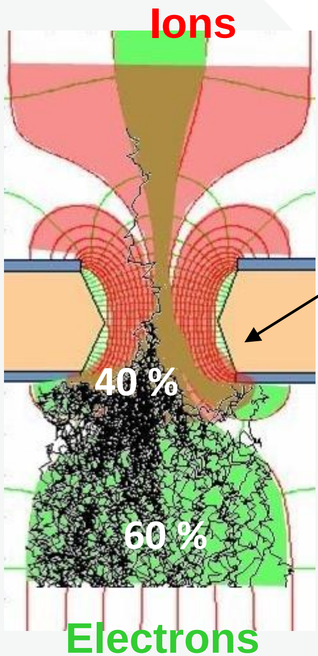
Hole, Gas Electron Multiplier (Next slide)

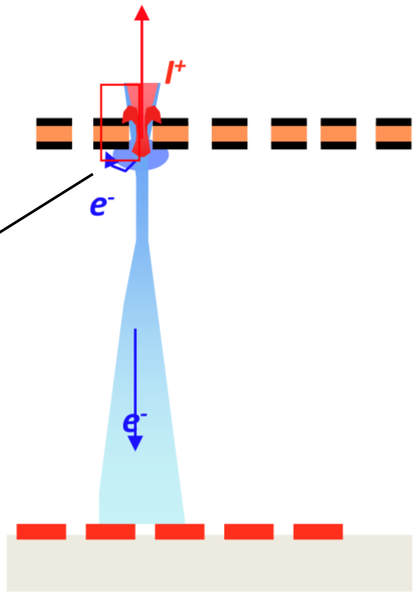


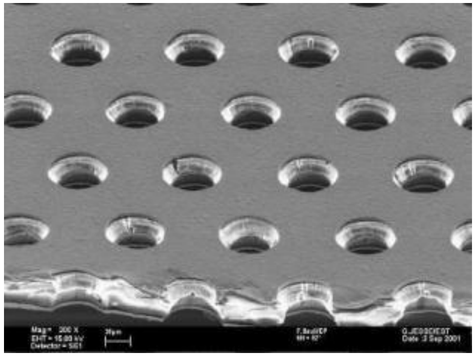


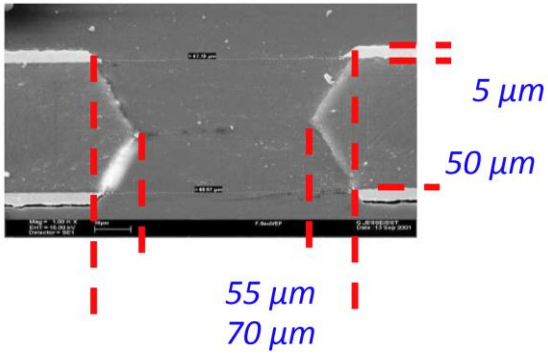
Resistive Plate Chambers
Next talk by Dr. Boghrati

GEM – Gas Electron Multiplier

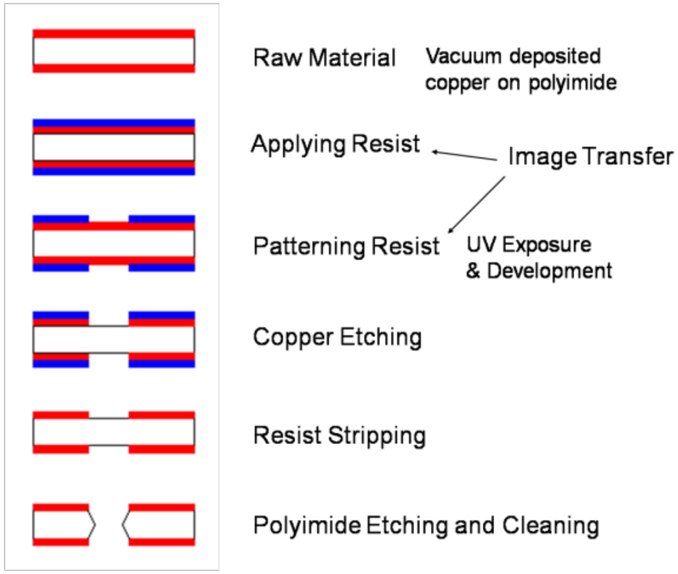








- Thin metal coated polyimide foil perforated with high density holes.
- Electrons are collected on patterned readout board. A fast signal can be detected on the lower GEM electrode for triggering or energy discrimination.
- All readout electrodes are at ground potential.
- Positive ions partially collected on the GEM electrodes.



Variant of silicon detectors (1)

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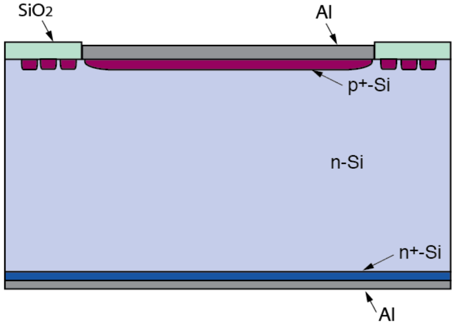
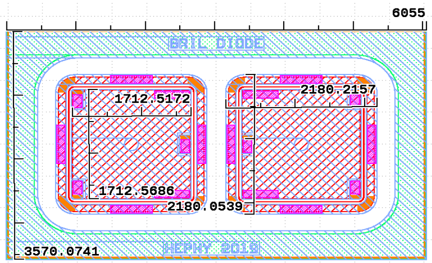
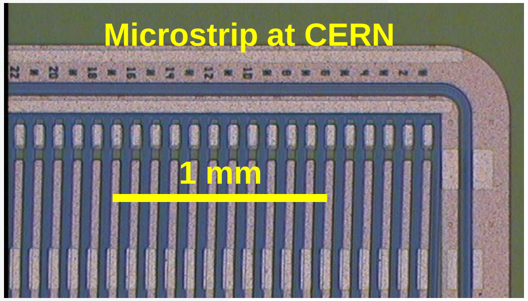
- **Silicon Pad**
  - Simplest one

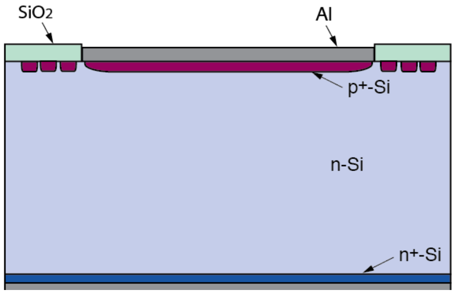


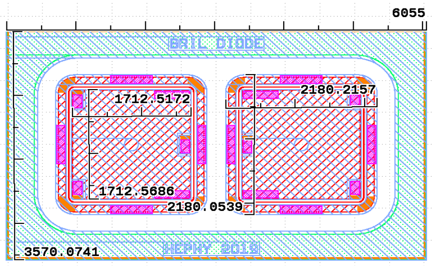


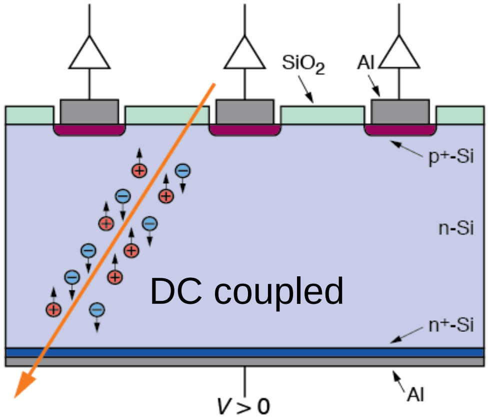
Variant of silicon detectors (1)

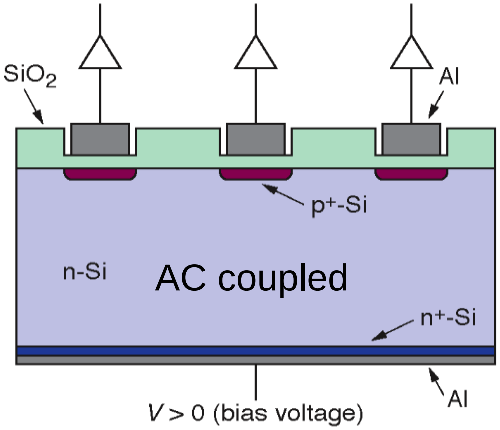
- **Silicon Pad**
  - Simplest one
- **Microstrip sensor**
  - DC coupled (left)
  - AC coupled (right)











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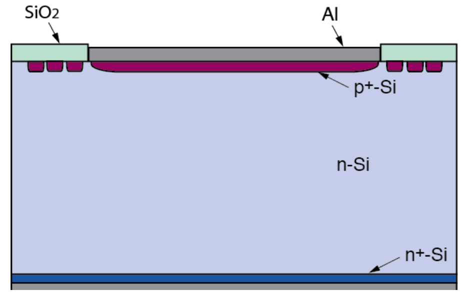

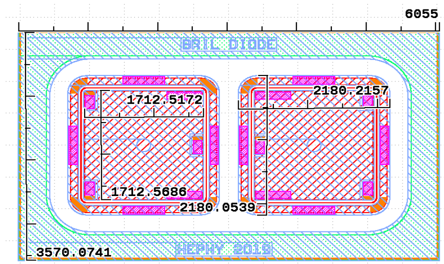

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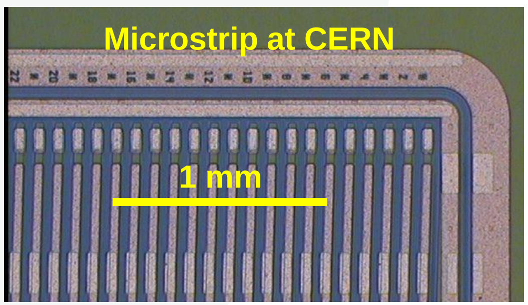
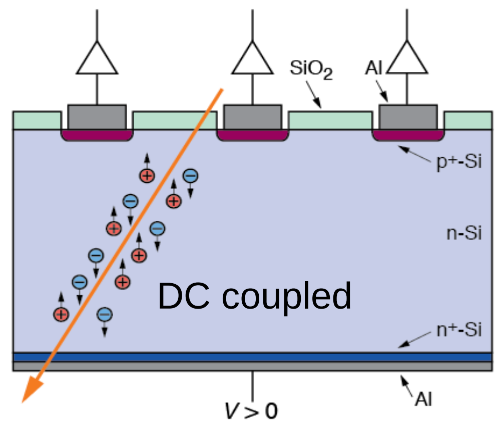
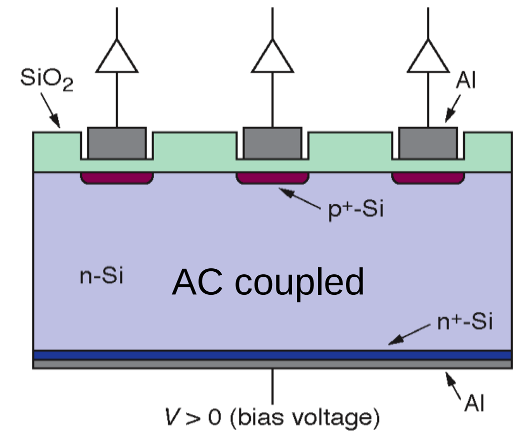
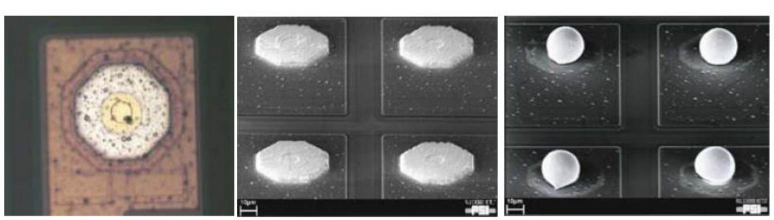
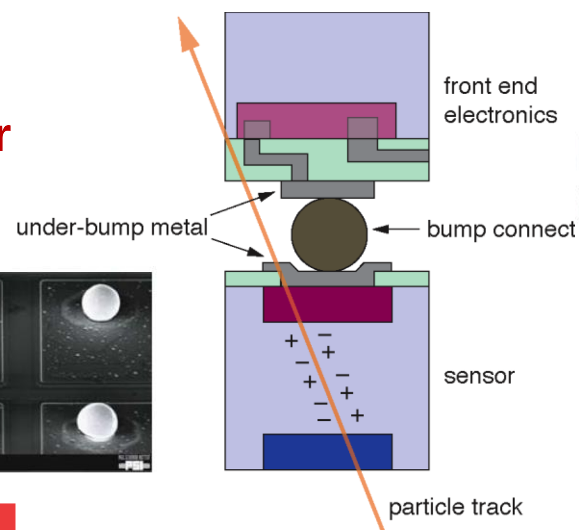


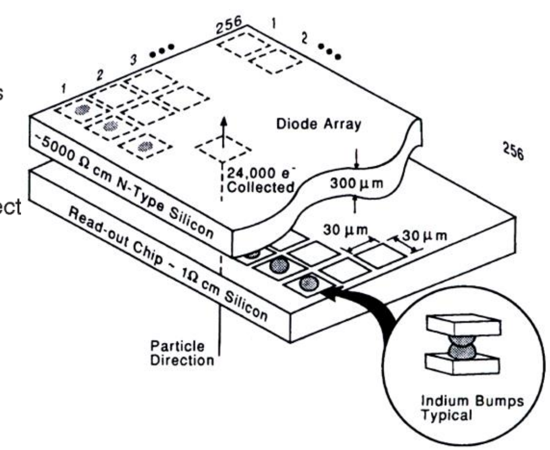




- **"Flip-Chip" pixel detector**
  - (hybrid Pixel)







Variant of silicon detectors (2)

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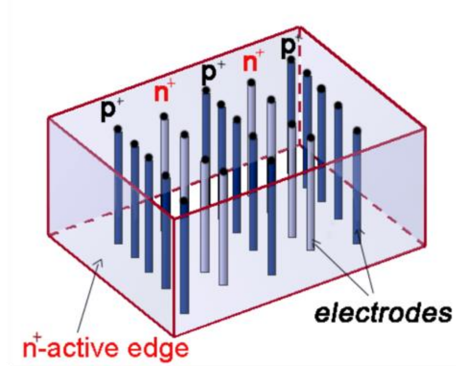
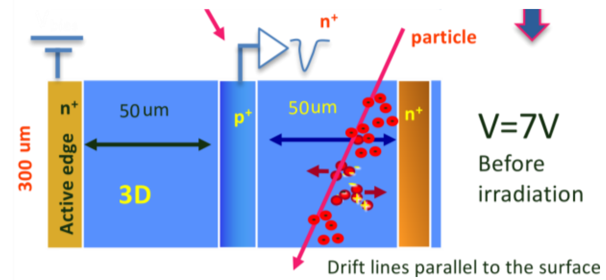
- **3D Silicon sensors**
  - low bias voltage, low power, reduced charge sharing and high speed,
    higher radiation tolerable





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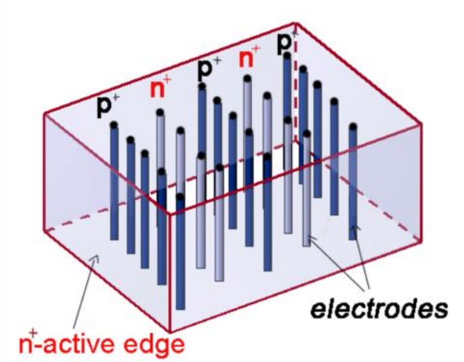
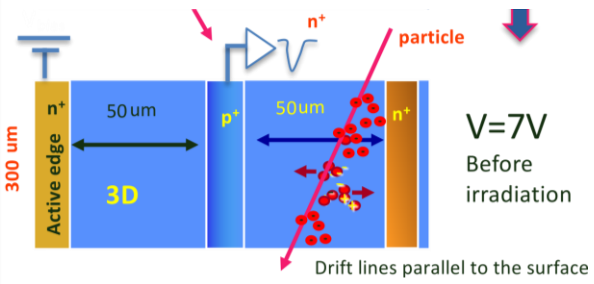
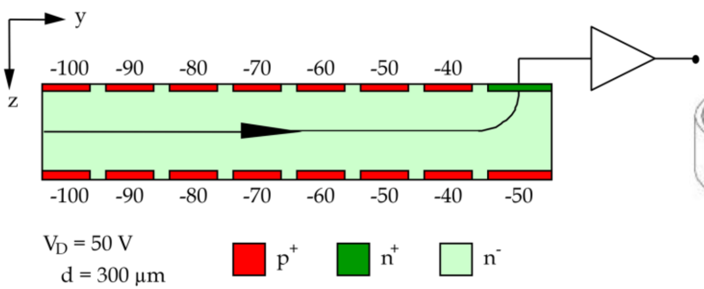
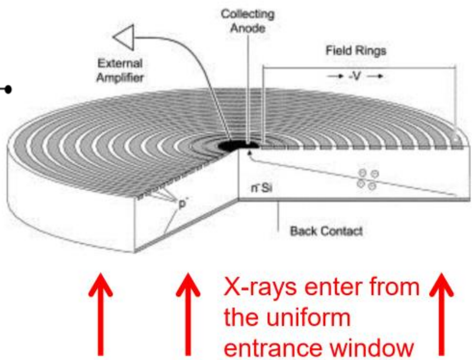




- **Silicon Drift Detectors**
  - Very low C and therefore very low noise





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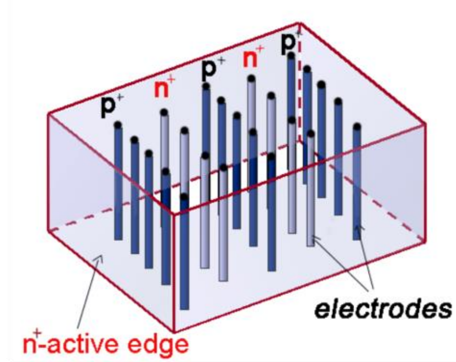

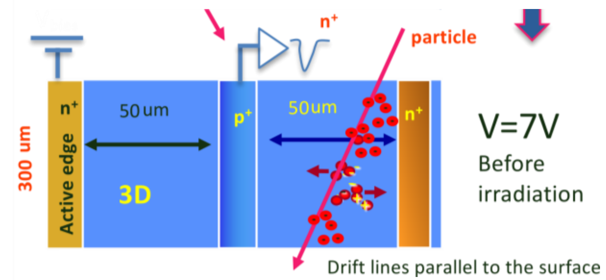

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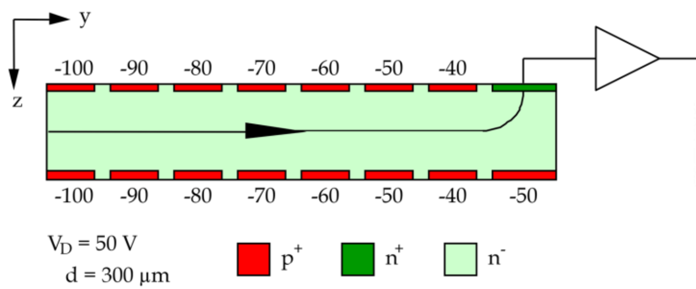
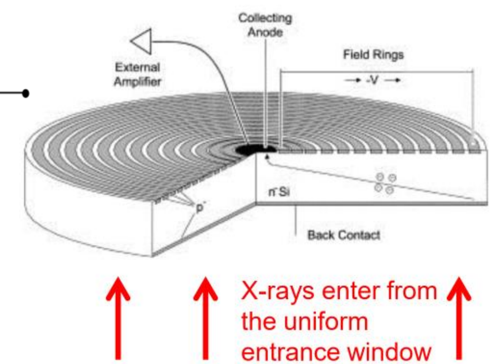
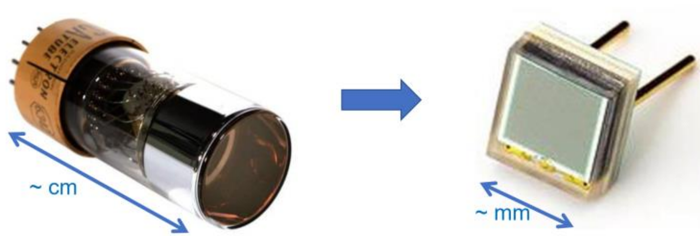
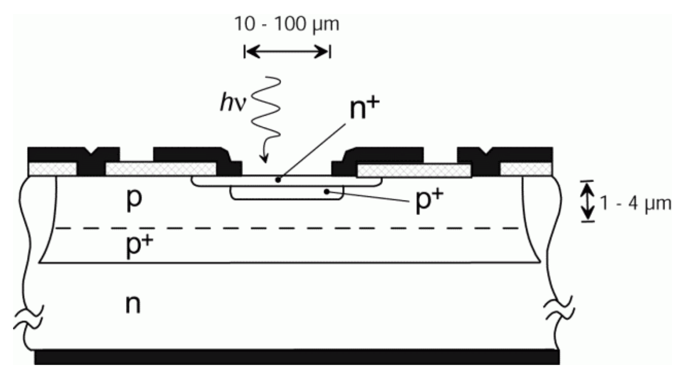
  - Very low C and therefore very low noise





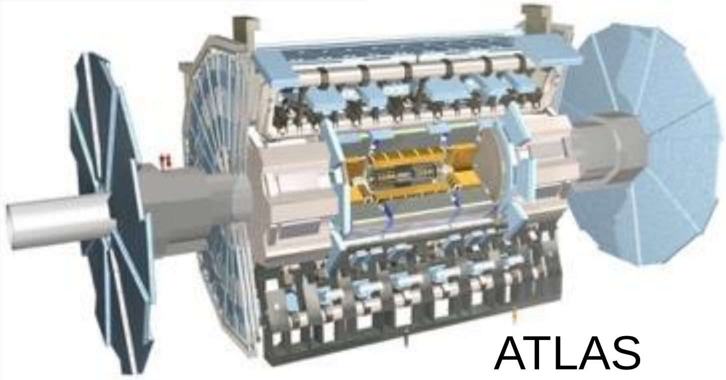
- **Silicon photomultiplier (SiPM)**
  - Single avalanche PD cell.
  - smaller, insensitive to magnetic fields, low V, cheap, but high dark count rate



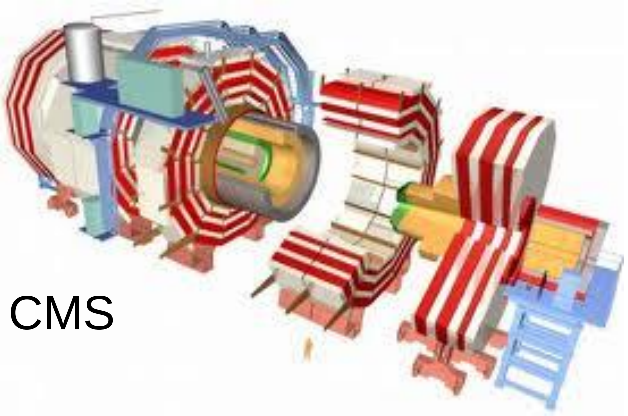


Silicon sensors are widely used at CERN

- ATLAS and CMS use alone more that **250 m²** of Silicon Strips to "image" charged particles



ATLAS



CMS

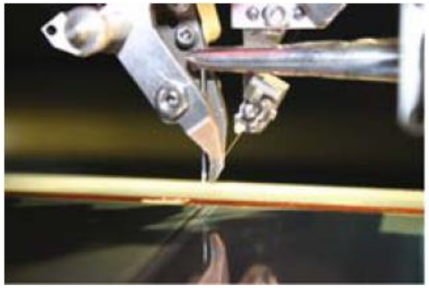
Strips
61m2 of silicon.
6.2million channels 4 barrel layers + 9 disks per endcap
30cm < R < 52cm

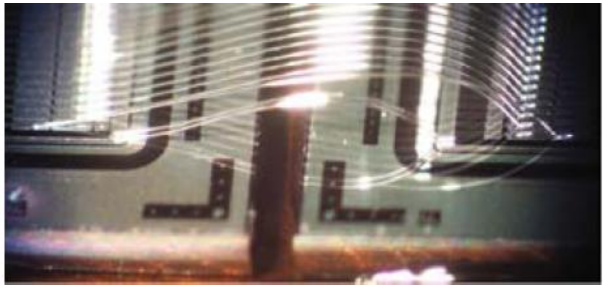
Pixels
3 Barrel layers
(r=5,9,12 cm)
2 end caps each with 3 disks
80Mpixels
50x400um2
Digital I/O

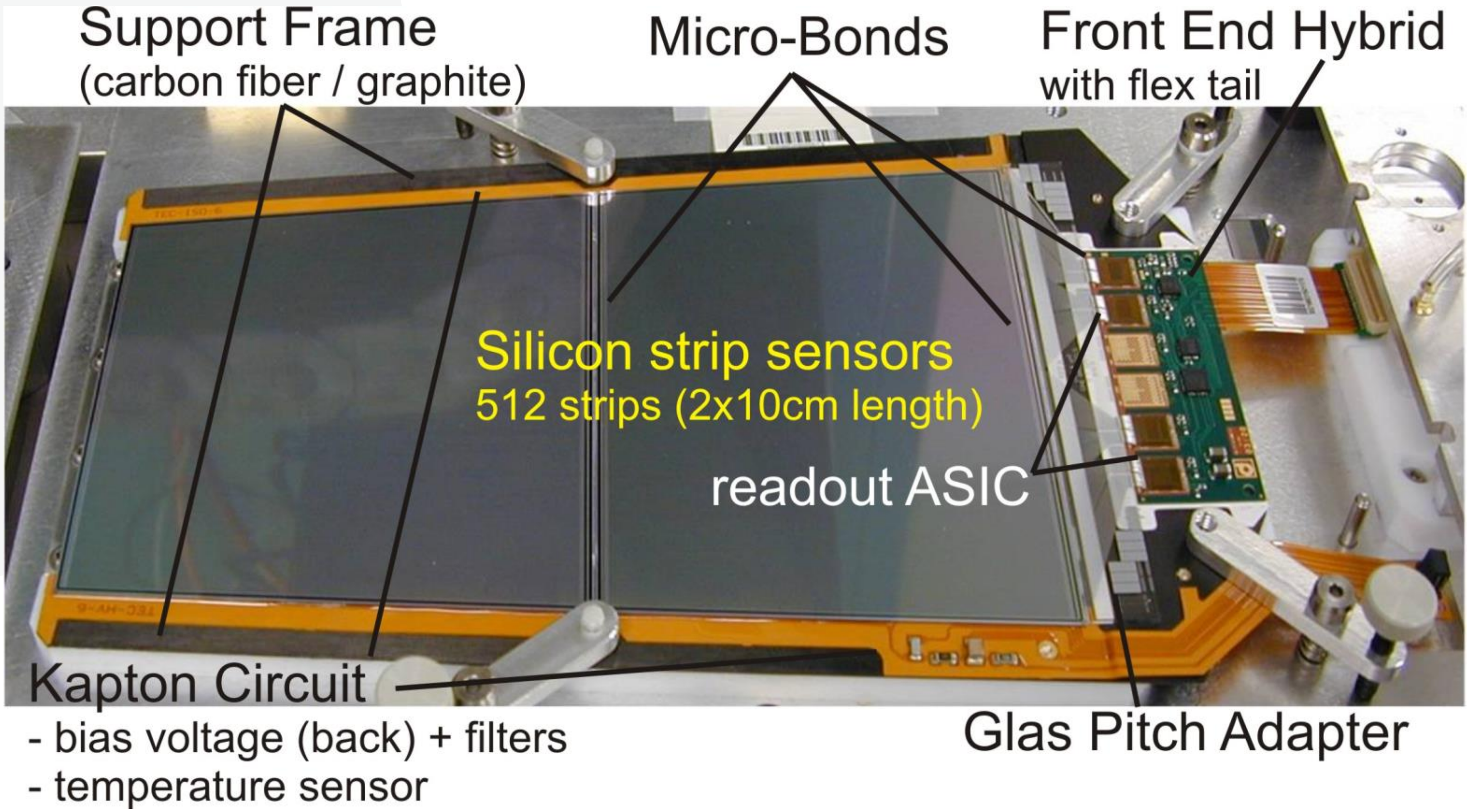
Pixels
3 barrel layers
2 end caps each with 2 disks
66 Mpixels 150 x 100 um^2
Analog I/O

Strips
198 m2 of silicon,
9.3 million channels
Inner : 4 barrel layers,
3 end-cap disks
Outer: 6 barrel layers,
9 weels
22cm < R < 120cm

Strip Sensor to Module

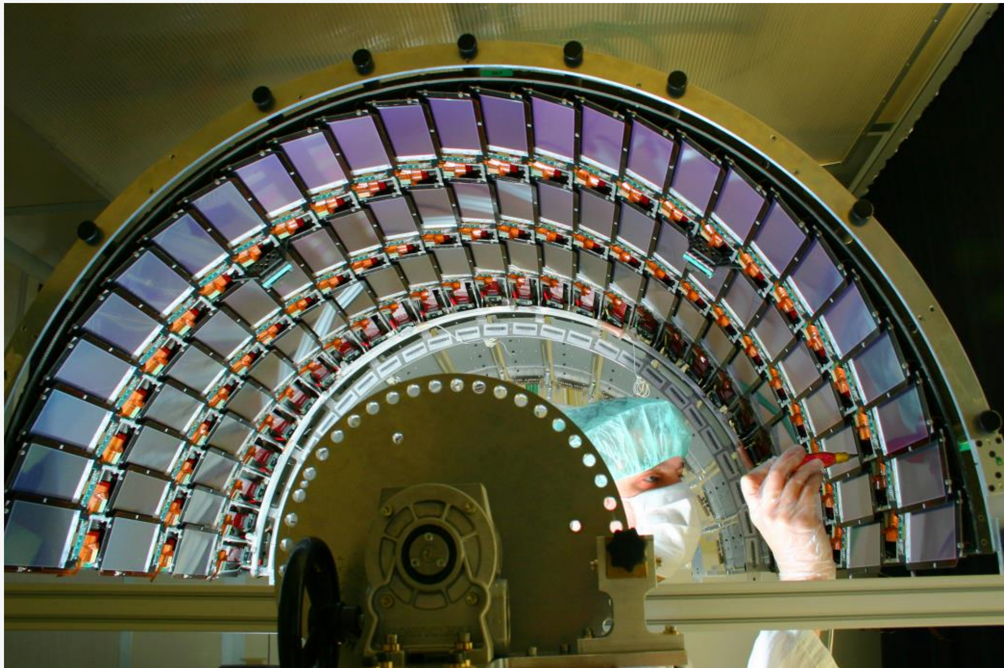


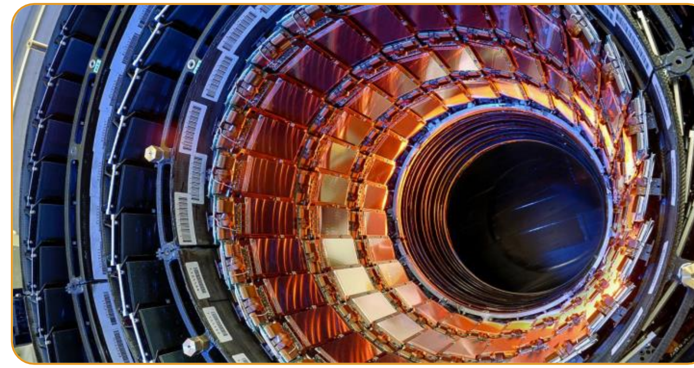


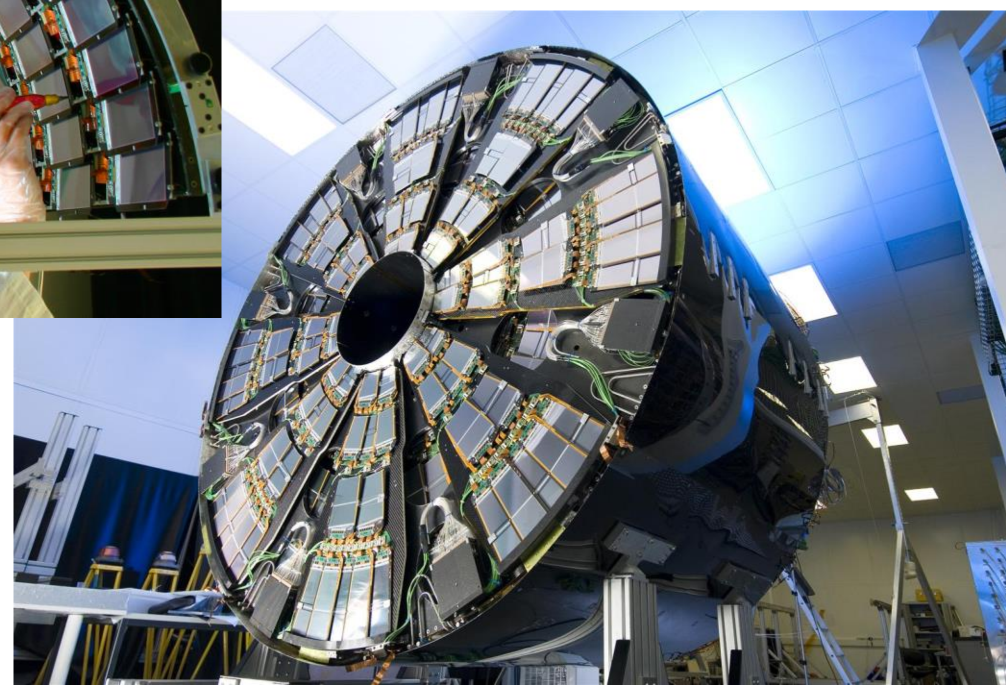


The CMS Tracker using Silicon sensors (Strip + pixel)

- The largest Silicon Device, 200 m2, >70 million channels







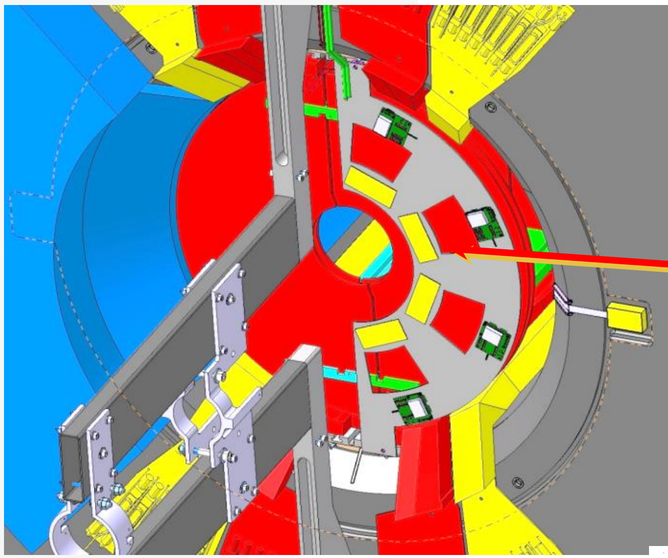
Timepix on Probe Board

The FBCM detector using Silicon Pads

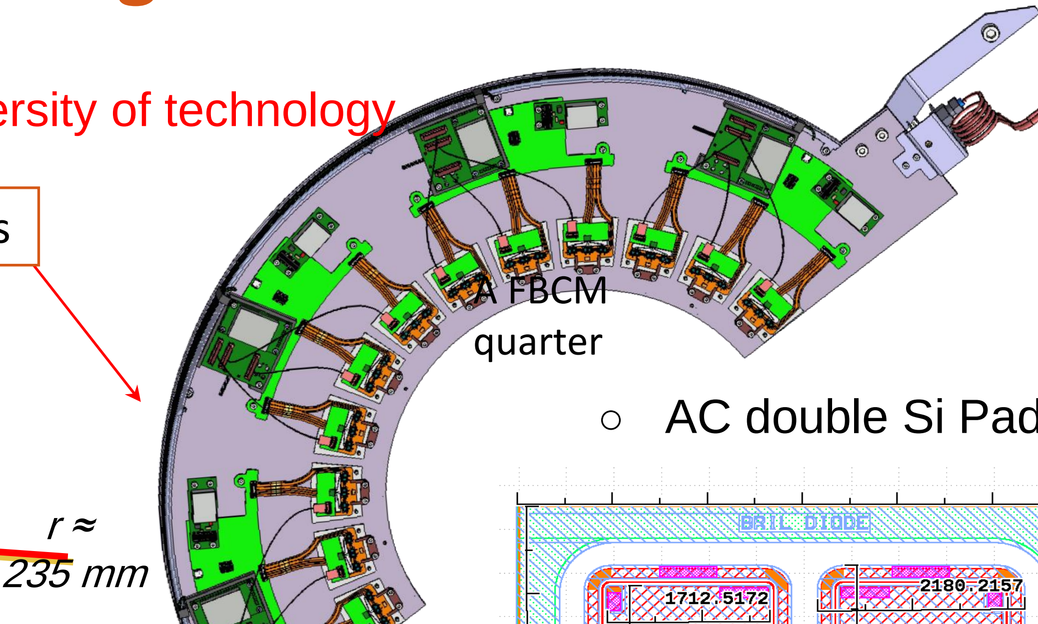
for Luminosity Measurement

Initially proposed by Isfahan University of technology

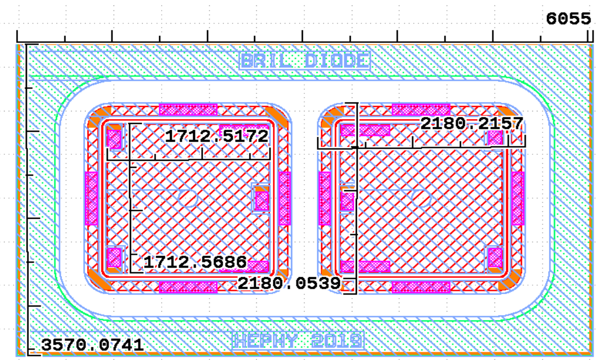
Front-end modules

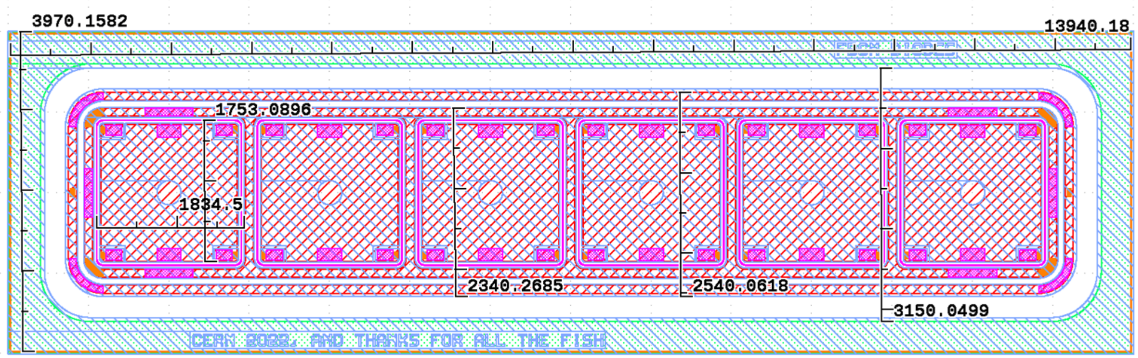


r ≈ 235 mm



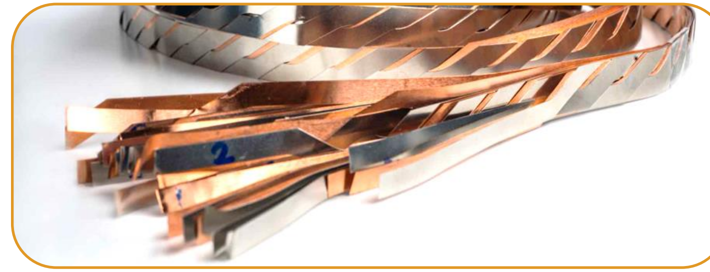
- AC double Si Pads





- DC merging of six
  Si pads on a single die
- Dual guard rings

From high energy Physics to other applications

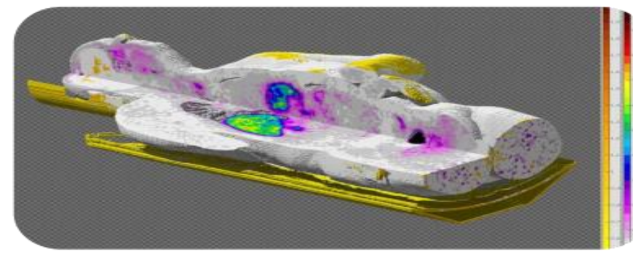


- High temperature superconductors
  - Improved power transmission

ROOT Data Analysis Framework

Geant 4

- Simulation and analysis tools
  - Medical applications
  - Nuclear Power Plant (re)commissioning
  - Hazardous environment management
  - Big data analysis



- Accelerator technologies
  - synchrotron light source for X-ray imaging

- Sensor
  - Dose monitor (aerospace, Cosmic, Nuclear)
  - Aerospace equipment
  - Medical applications

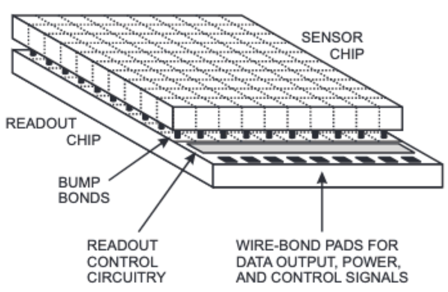
Particle detector applications beyond the particle physics

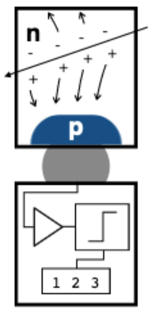
Aerospace applications

- Aerospace and particle physics share many technical similarities
  - Both sectors need components capable of functioning in harsh radiation environments, extreme temperatures and high vacuum conditions.
- Moreover, they both need to be able to handle large amounts of data quickly and autonomously.
- Aerospace-related competences & expertise:
  - Radiation **monitoring and dosimetry**
    - Space **RadMon** → to measure in realtime radiation effects such as total ionizing dose, upsets and latchups
    - Optical fibres for large-scale spacecraft dosimetry
  - **Radiation-hardened** components + Radiation-tolerant systems
    - DC-DC converter modules (FEAST and bPOL systems);
    - Optical transceivers
    - General purpose FPGA-based radiation tolerant boards
  - **Superconducting and cryogenic** systems
    - high temperature superconductive (HTS) materials
    - Thermal management, advanced materials and processes
    - Big data handling and analysis tools
    - Irradiation and cryogenic testing facilities

Timepix Hybrid Pixel Detectors for Aerosapce

- Hybrid pixel detectors like **Timepix** consist of a pixellated semiconductor sensor connecte to an underlying signal processing ASIC

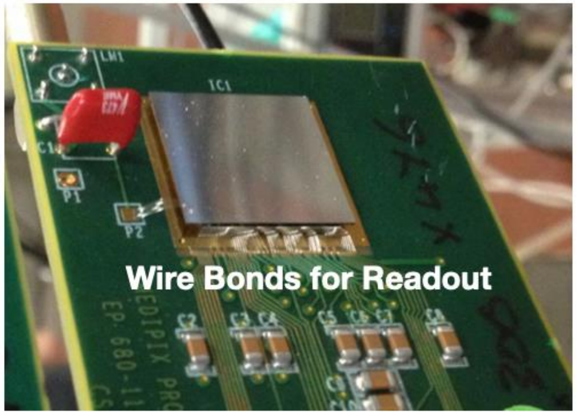




- The time over threshold is measured by and the resultant clock counts can be converted to an energy deposit in the pixel

- In the case of the Timepix detectors, the sensor is 256 x 256 pixels of 55um pitch and 500um thickness.

- When particles traverse a Timepix detector, the effect is much like solid state nuclear emulsion.



Timepix on Probe Board

List of NASA Timepix Based Flight Hardware

Name Date Flown	Mission	Location	Objective	Vehicle	Number TPX
REM 2012	ISS	LEO	Demo	ISS	**5**
BIRD 2014	Orion EFT-1	LEO/MEO	Demo/Science	Orion	**2**
REM2 2018	ISS	LEO	Ops	ISS	**7**
MPT 2017	ISS	LEO	Science	ISS	**2**
Biosentinel 2020	ISS	LEO	Science	ISS	**1**
ISS-HERA 2018	ISS	LEO	Demo	ISS	**3**
AHOSS 2020	ISS	LEO	Demo/Ops	ISS	**3**
LETS(1) 2023	Astrobotic 1	Lunar Surface	Science	Peregrine	**1**
LETS(2) 2024/5	Berensheet 2*	Lunar Surface	Science	Berensheet 2	**1**
HERA 2022	Artemis 1	Lunar Orbit	Ops	Orion	**3**
Biosentinel 2022	Artemis 1	Solar Orbit	Science	Cubesat	**1**
HERA 2023	Polaris Dawn	MEO	Science	Crew Dragon	**1**
HERA 2024	Artemis 2	Lunar Orbit	Ops	Orion	**6**
HERA 2025	Artemis 3	Lunar Orbit	Ops	Orion	**6**
ARES 2025	Artemis 3	Lunar Surface	Ops	Starship	**>=1**
LEIA ~~2024	CLPS Lander	Lunar Surface	Science	TBS Lander	**1**
ARES 2026	Artemis	Lunar Orbit	Ops	Lunar Gateway	**2**

Evaluating mission possibility

> 23 Timepix in Space to date

Highly successful technology transfer from CERN, powering NASA missions for the last 10 years, and likely for the next 10

From High Energy Physics (HEP) to Medical applications

- Medical Imaging has partially benefitted from new technologies developed for **telecommunications** and **High Energy Physics**

- New Scintillating crystals and detection materials
  - CMS → (Crystal Clear column)

- Electrinos & signal treatment → Highly integrated
  - Fast, low noise, low power preamp
  - Digital filtering and signal analysis

- Triger/ DAQ
  - High level of parallelism and event filtering algorithm
  - Pipeline and parallel read-out, trigger and on-line treatment

- Computing
  - Modern and modular simulation software using worldwide recognized standards (GEANT)

Areas of involvement in medical applications

- The most obvious field:
  - Nuclear medicine (e.g. as tracers, etc.)
  - **PET**: Positron Emission Tomography
  - **SPECT**: single-photon emission computerized tomography
- Diagnostic tools (early detection of abnormalities, such as cancer)
- Beam radiation therapy (proton and ion beams, and the latest promise of antiprotons)
- Monitoring chemo- and radio-therapy
- Organ specific imagers:
  - Brain
  - Breast
  - Prostate

HEP for medical applications

- HEP for medical applications history
  - **1977**: First **PET** image taken at CERN
  - **1980's**: The start of medical **accelerator** development at CERN
  - **2002**: Year that CERN started using **grid computing** for medical applications
  - **2018**: The first **3D color** X-ray image of the living human body taken with Bioimaging, using **Medipix** technology

- Detector technologies used in medical imaging
  - Silicon, Selenium - (X-ray)
  - CdTe, CdZnTe – (X-ray, gamma, PET)
  - Crystal scintillators (gamma, PET)
  - Cherenkov – (TOF-PET)
  - PIN diodes
  - Avalanche photodiodes (APD)
  - "Silicon photomultipliers" – SiPMs, Geiger avalanche diodes
  - Time of Flight PET
  - Compton gamma imaging

Digital Radiography with Multi Wire Proportional Chamber

An Efficient, Gaseous Detector with Good Low-energy Resolution for (≤50 keV) Imaging

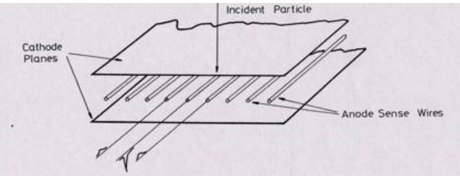
Nguyen Ngoc Hoan, S. Majewski, G. Charpak, and A.J.P.L. Policarpo

Institut National de Physique Nucléaire et de Physique des Particules, Orsay, France, University of Warsaw, Warsaw, Poland, and University of Coimbra, Coimbra, Portugal

An imaging detector with good energy resolution and reasonable spatial accuracy has been designed for biomedical applications. It is based on a scintillating proportional gas chamber. The energy resolution is typically 5.4% (FWHM) at 27 keV and the spatial resolution is 2.7 mm (FWHM) for 22-keV x-rays. The physical processes involved in this detector are discussed along with its main limitations and merits.

J Nucl Med 20: 335–340, 1979

Fig. 6.7. Basic configuration of a multiwire proportional chamber. Each wire acts as an independent proportional counter. The signal on the firing wire is negative while the signals on the neighboring wires are small and positive



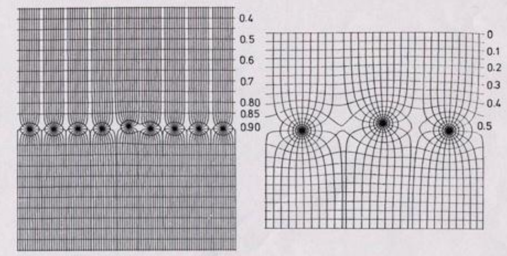
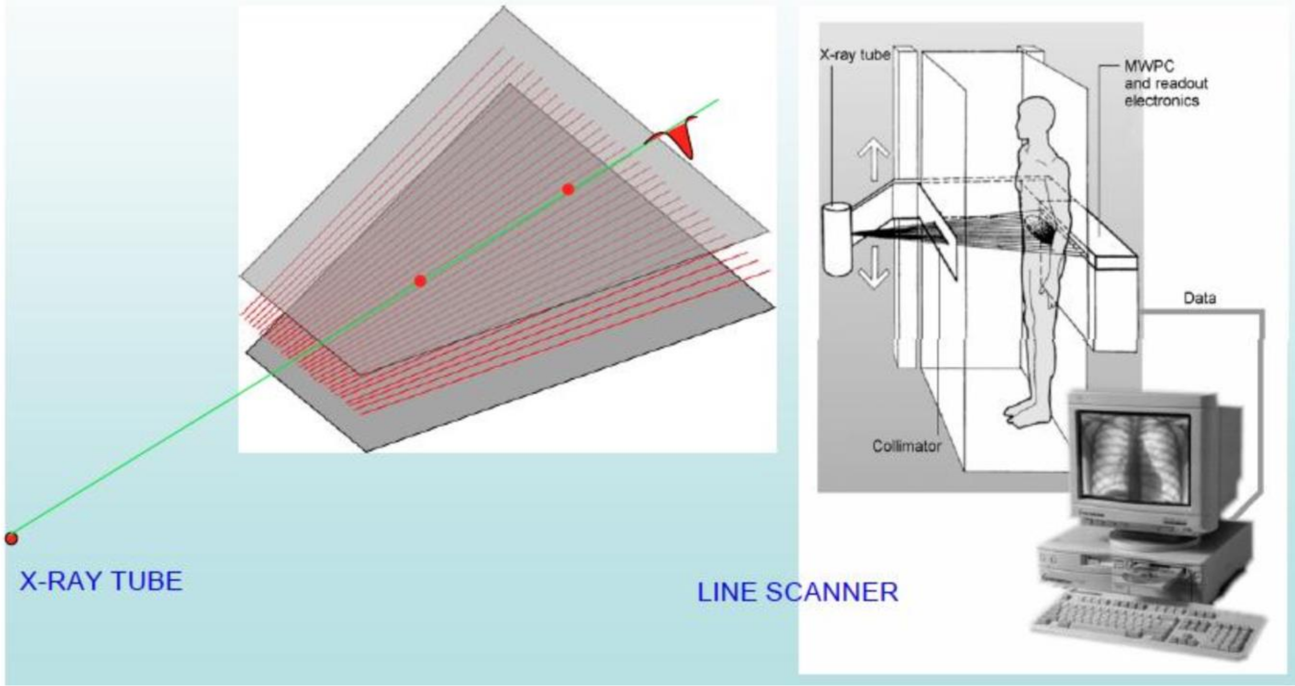
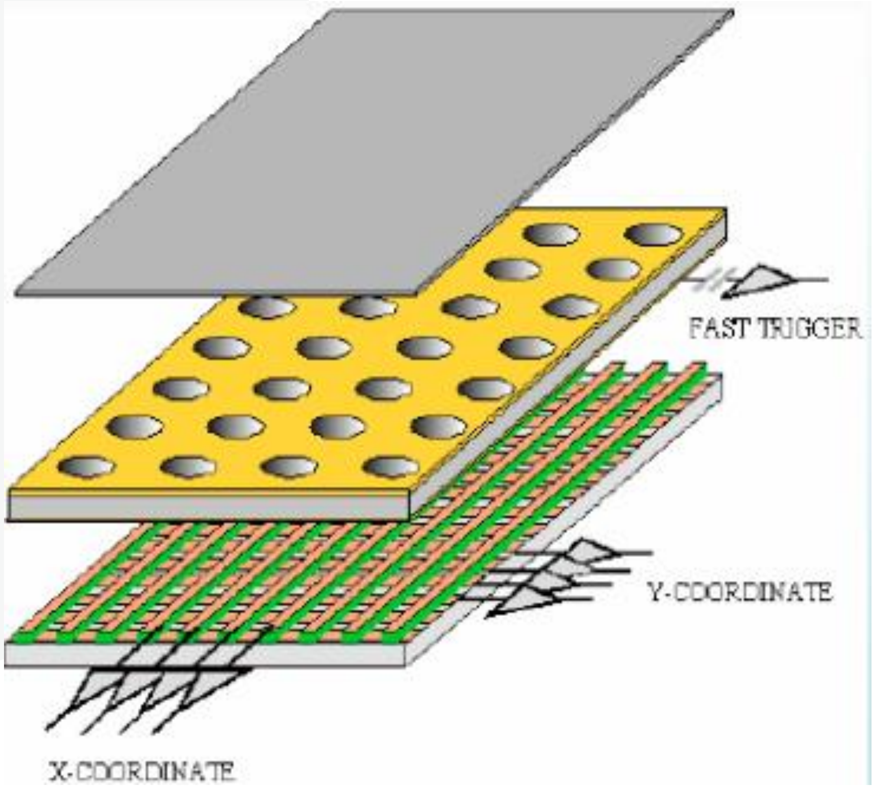
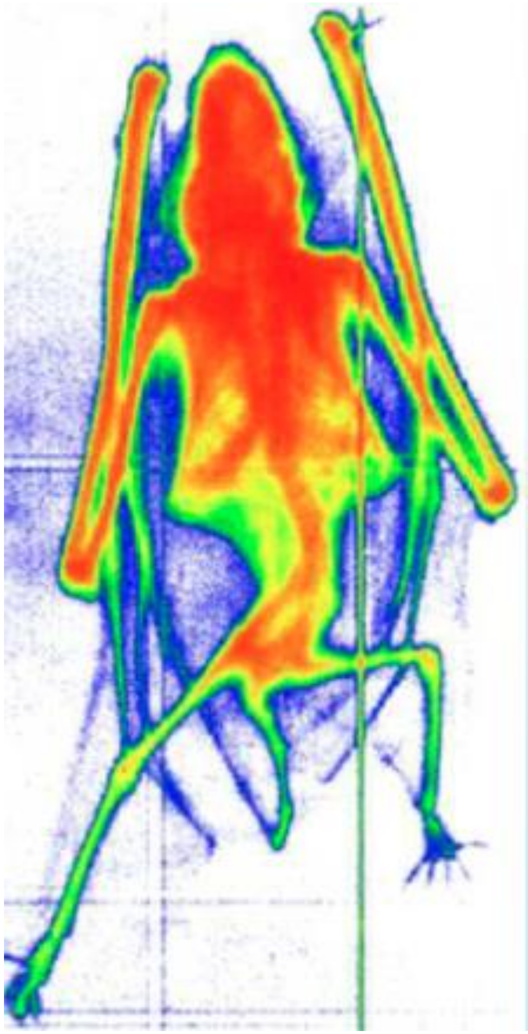


Fig. 6.8. Electric field lines and potentials in a multiwire proportional chamber. The effect of a slight wire displacement on the field lines is also shown (from *Charpak* et al. [6.16])

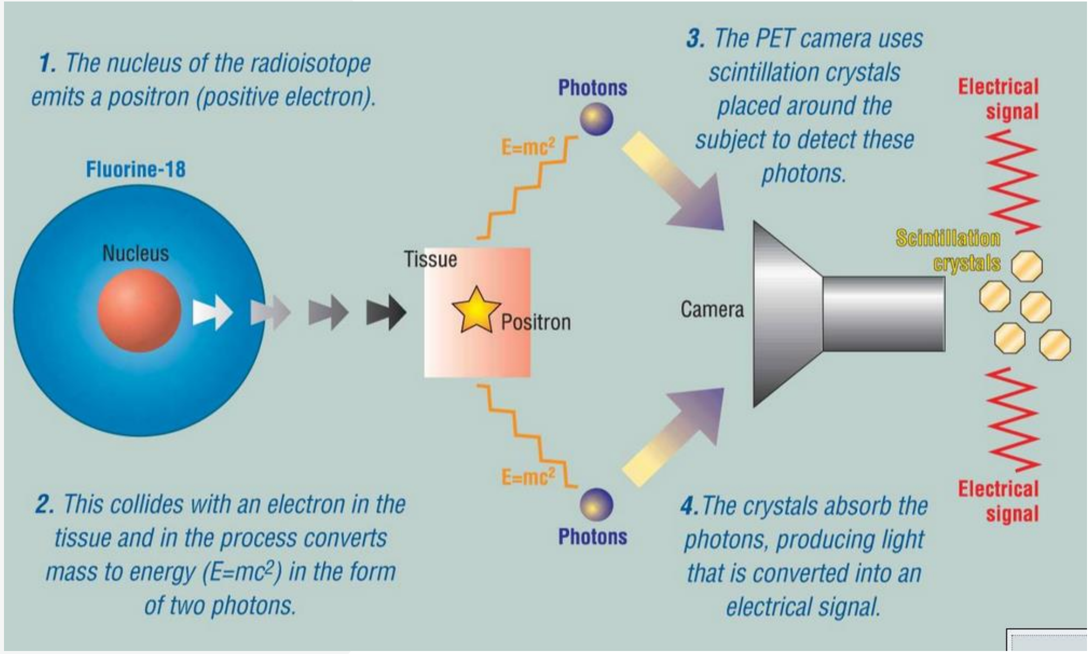


Digital radiography with GEM detectors





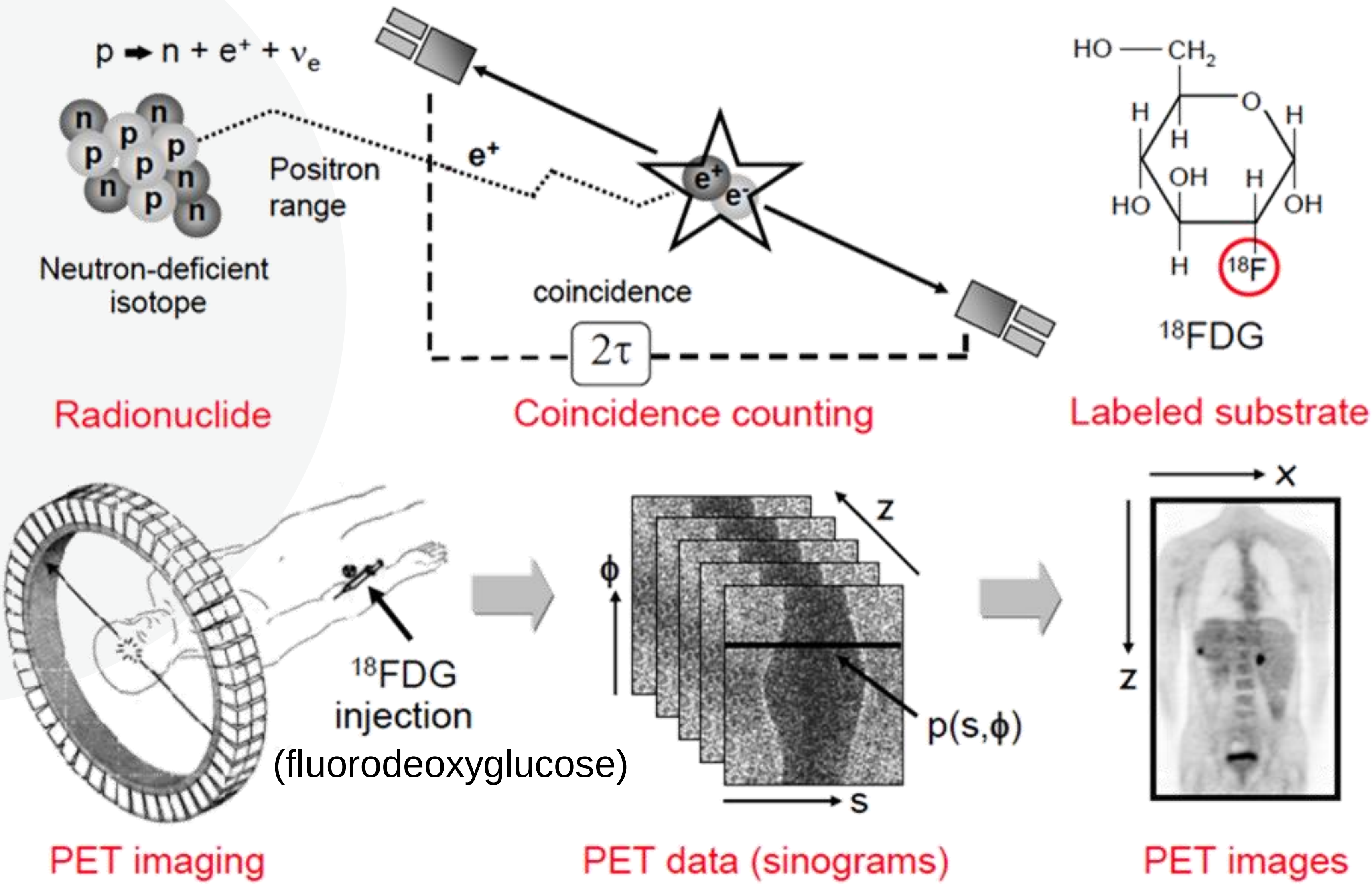
Positron Emission Tomography (PET) Application



PET Detectors
- Scintillation Detector
  - Photomultiplier tube (PMT)
  - Avalanche photodiode (APD)
  - Silicon photomultiplier (SiPM)
- High Density Semiconductors
  - CdTe or CZT
  - Ge
  - TlBr

- A radioisotope attached to a drug—is injected into the body as a **tracer**.
- When the undergoes beta plus decay, a positron is emitted, and when the positron collides with an ordinary electron, the two particles annihilate and gamma rays are emitted.

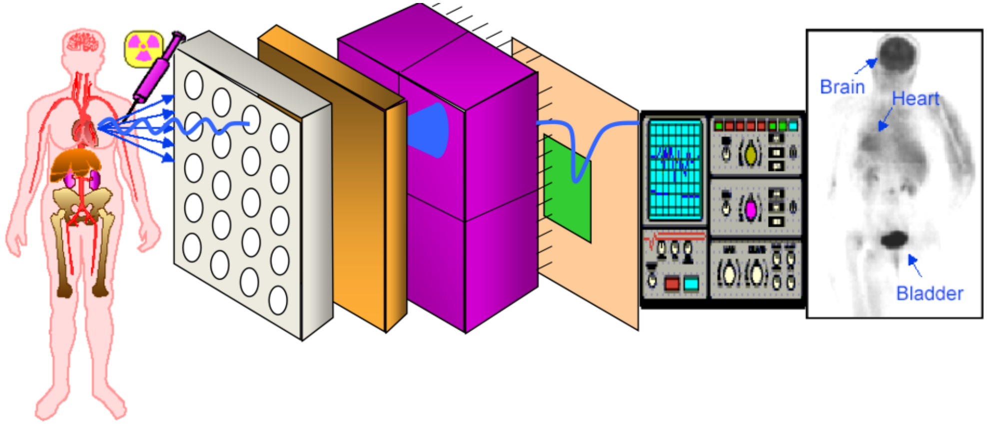
PET imaging

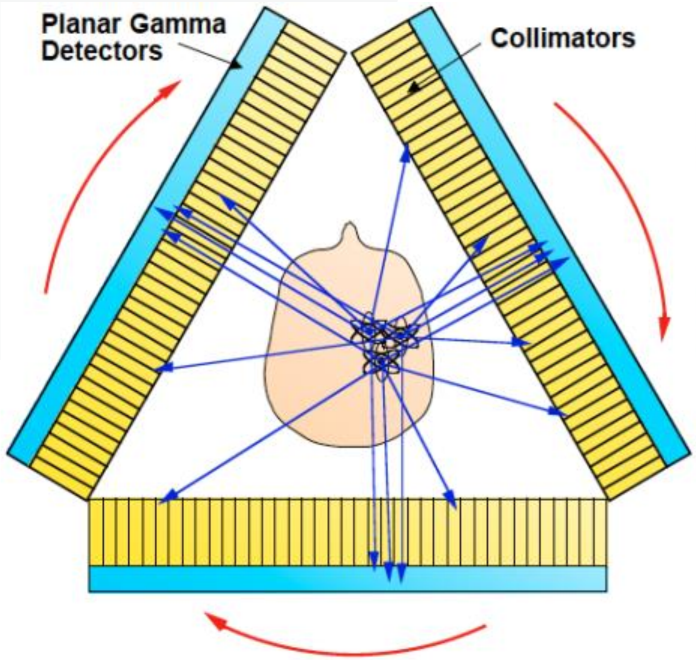


p → n + e+ + νe
n
p
Positron
range
Neutron-deficient
isotope
Radionuclide
e+
e-
coincidence
2τ
Coincidence counting
HO — CH2
O
H
OH
HO
18F
18FDG
Labeled substrate
18FDG
injection
(fluorodeoxyglucose)
PET imaging
ϕ
z
p(s,ϕ)
s
PET data (sinograms)
x
z
PET images

Single photon Emission Computed Tomography (SPECT)

- Patient injected with radioactive drug emitting **Gamma rays**.
- Drug localizes according to its metabolic properties.
- **Gamma rays**, emitted by radioactive decay, that exit the patient are imaged.

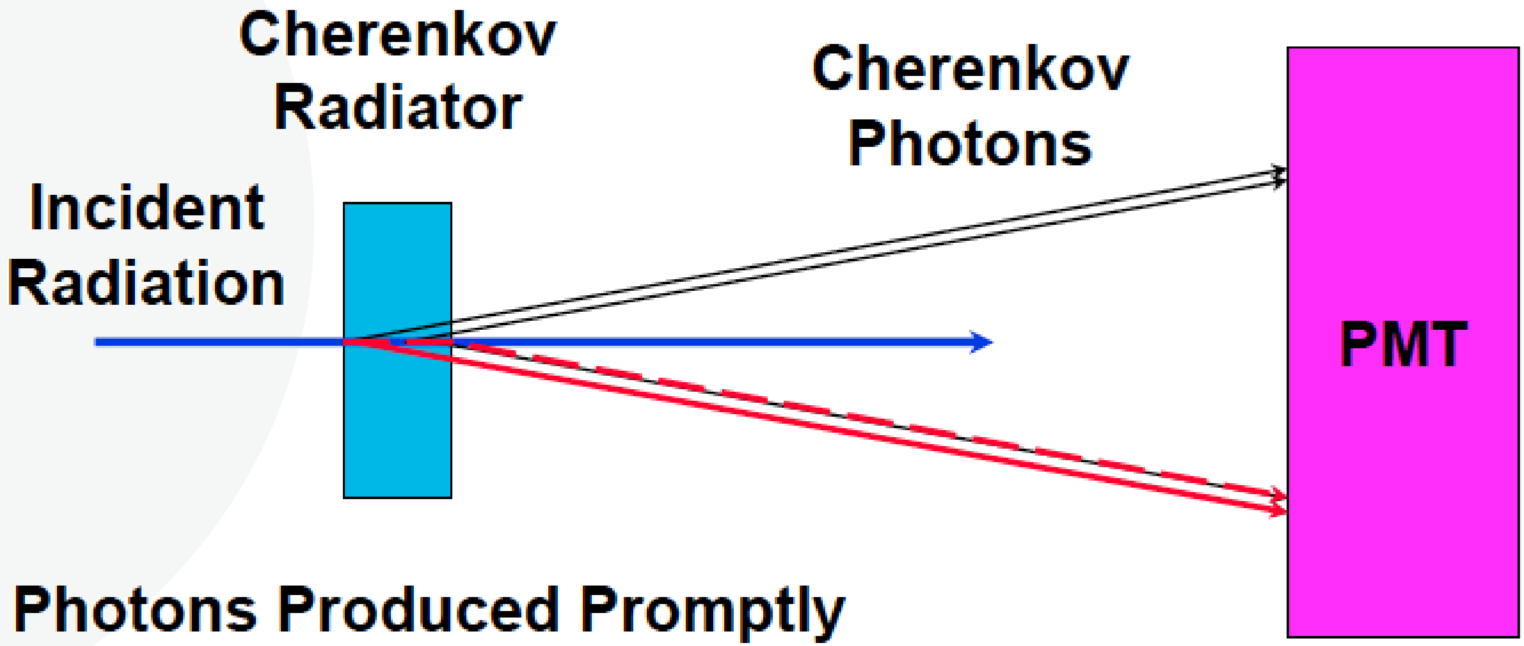




- One, two, or three imaging heads (cost / performance tradeoff)
- Parallel hole collimators.
- Multiple views obtained by rotating the imaging heads around the patient.

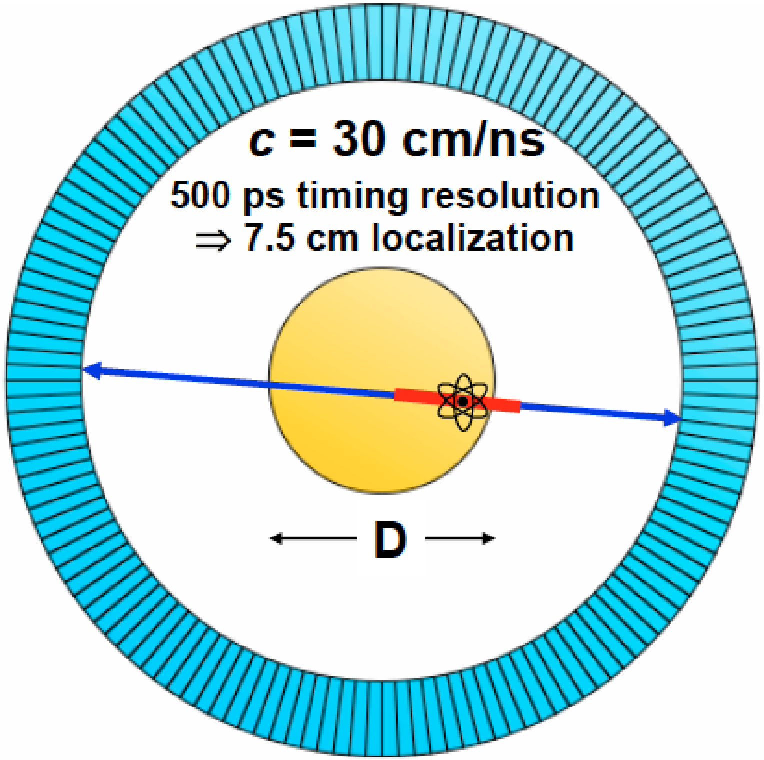
Time-of-flight in HEP

- Receiving particles arrive at different times



- Photons Produced Promptly
- Photons Travel in ~Same Direction
- Small Time Variations due to Path Length Difference
- Small Variations due to Photon Production Position

Time-of-flight in PET

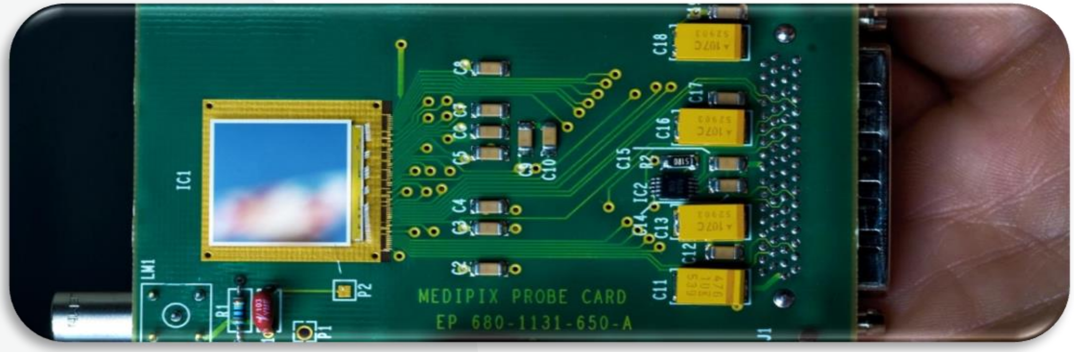


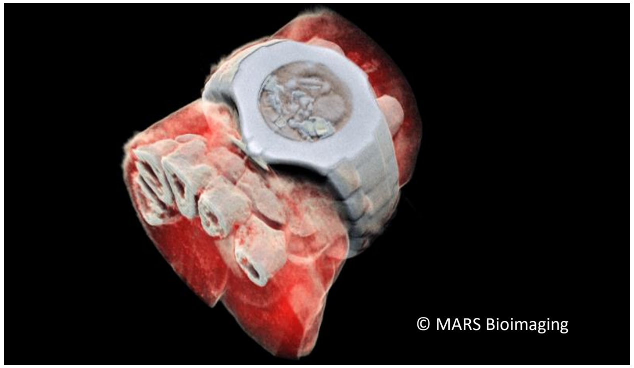
- Can localize source along line of flight.
- Time of flight information reduces noise in images.
- Variance reduction given by 2D/cΔt.
- 500 ps timing resolution
  ⇒ 5x reduction in variance!

- Time of Flight Provides a *Huge* Performance Increase!
- Largest Improvement in Large Patients

Medipx chip is able for this aim

Medipix chip family

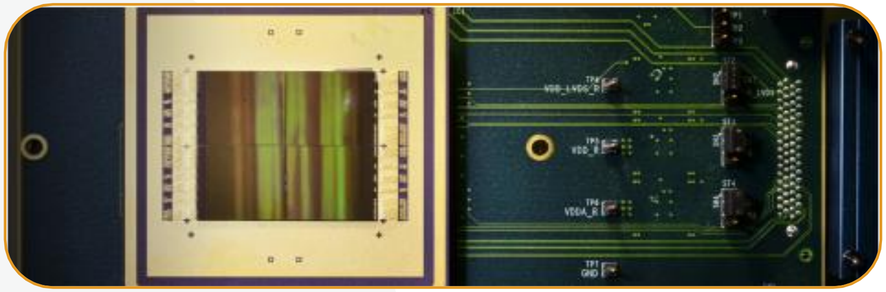


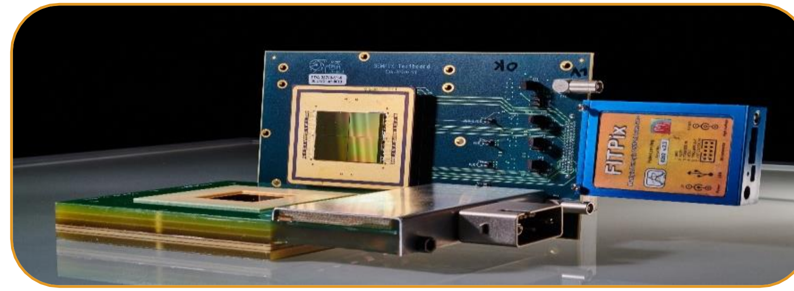


A family of pixel detector read-out chips for particle imaging and detection developed by a consortium lead by CERN. Medipix works like a camera, detecting and counting each individual particle hitting the pixels. This enables high-resolution, high-contrast, noise hit free images. The Medipix chip family aims at frame based imaging and spectroscopic x-ray imaging.

- Medical imaging: CT, SPECT, gamma imaging
- Previous use cases include x-ray CT, digital mammography, CT imagers for mammography, beta and gamma autoradiography
- Dosimetry: beam studies and treatment planning

Key technology: GEMPix





A combination of existing CERN technologies: the gas electron multiplier **(GEM) and Timepix**.

The resultant technology is a gaseous detector able to detect different types of radiatioan with a high spatial resolution. Purpose of the technology is to measure and visualize the energy deposition. CERN has unique know-how and facilities for R&D and production of gaseous radiation detectors.

- Gaseous detector with high spatial resolution: 3D image of the energy deposition in water for hadron therapy
- Very low energy threshold: 5.9 keV X-rays from ^{55}Fe well detectable
- Radiation hardness: measurements in a therapeutic beam

- Dosimetry, microdosimetry and sub-microdosimetry
- Radiobiology; analysis of biological effects of radiation on tissue samples
- Conventional radiation therapy and hadron therapy
- 2D beam imaging in radiation therapy
- 3D energy deposition reconstruction in hadron therapy
- Measurements of ^{55}Fe content in samples of radioactive waste at CERN

Summary

- Aerospace applications
- Gas detectors and Silicon detectors are used in medical imaging
- PET invented many years ago but only from 2001 it got full recognition for its unique clinical role after it was combined with CT (power of multi-modality)
- SPECT and PET imaging as molecular imaging is providing critical assistance with patient diagnosis and treatment, as well as with work on understanding disease origin and cures (also in small animal studies)
- Rebirth of TOF PET
- New technologies: scintillators, photodetectors, solid state materials – spin-offs from particle physics

Thank you