Application of Micro-Pattern Gas Detector in Medical Imaging & Treatment

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Workshop on Advanced Radiation Detector and Instrumentation in Nuclear and Particle Physics
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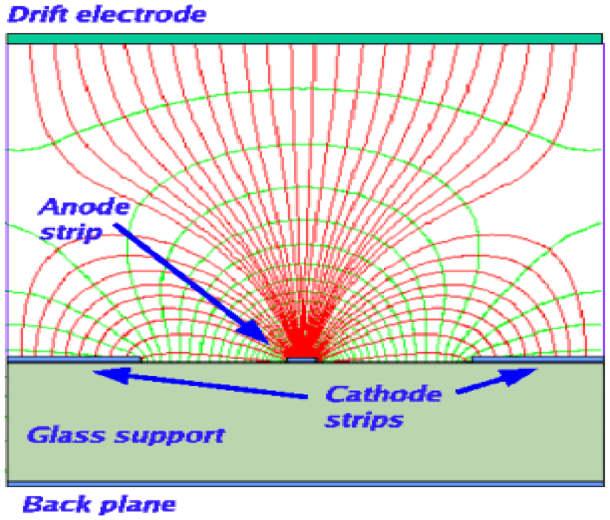
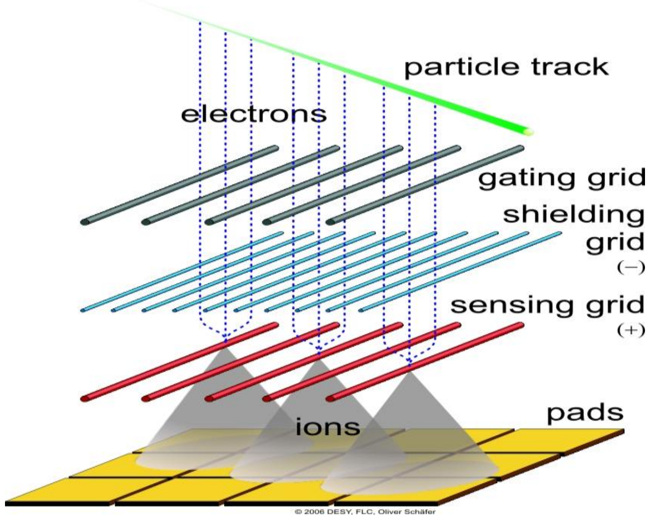
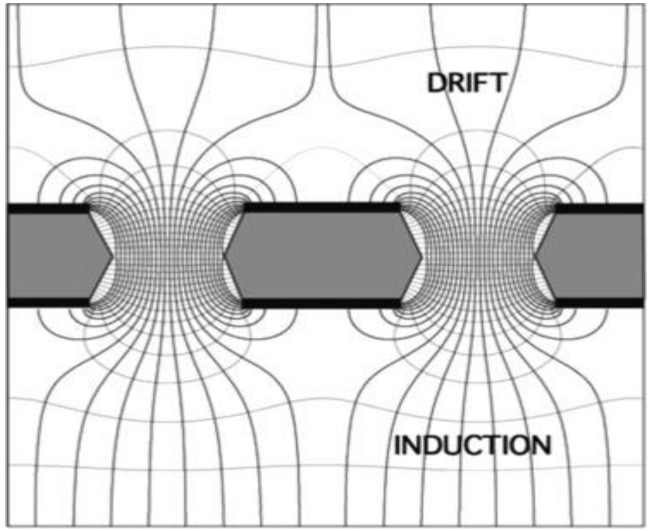
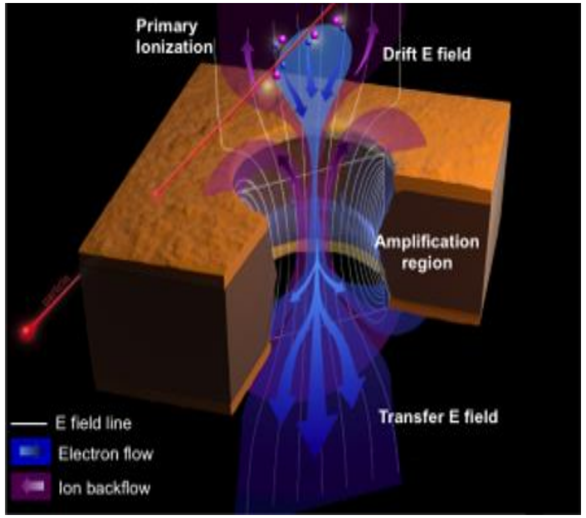
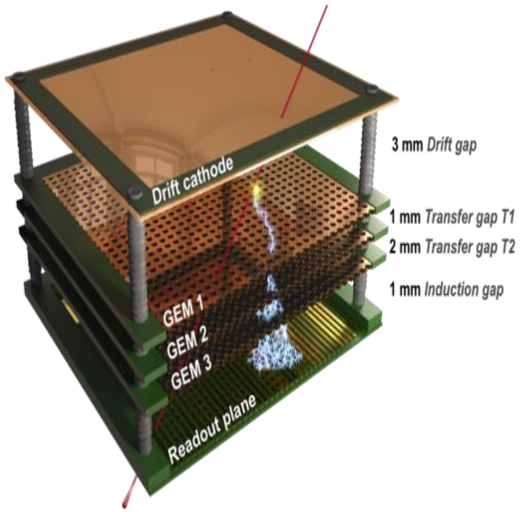
History of MPGD's

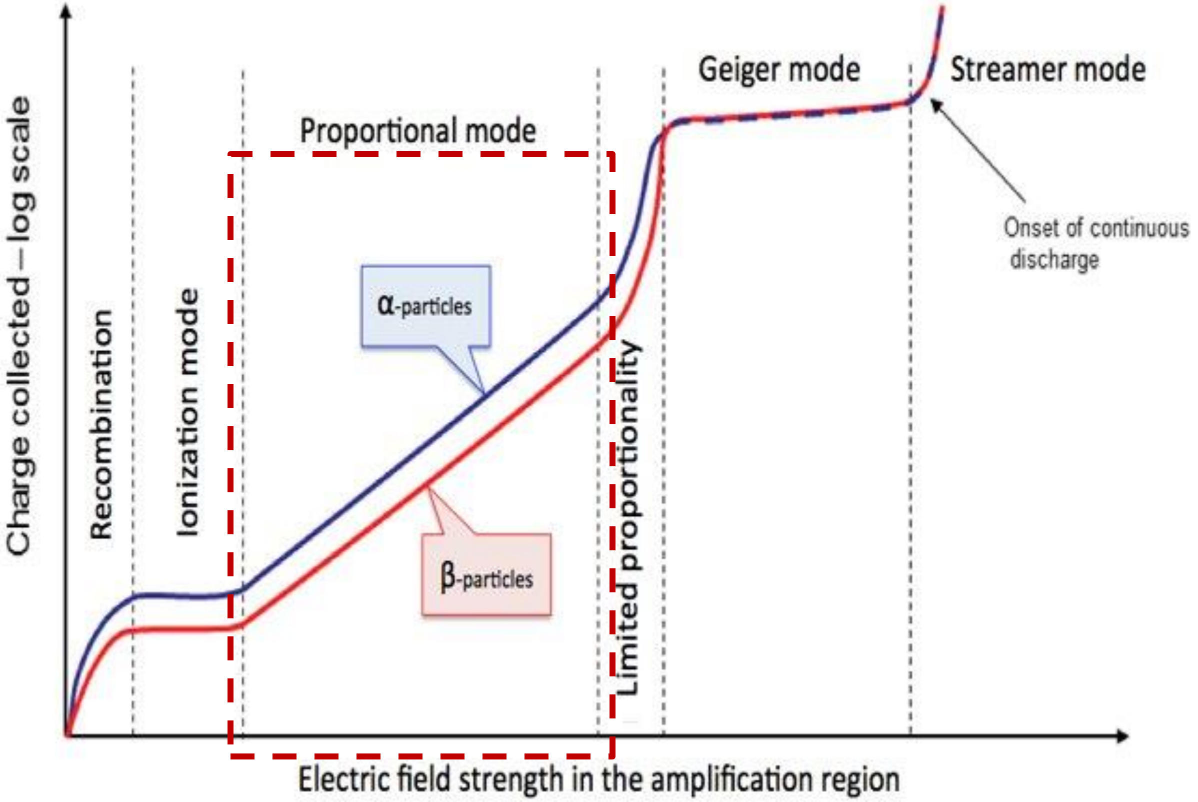
Micro-Strip Gas Chamber (MSGC)	Multi-Wire Proportional Chamber (MWPC)	Gas Electron Multiplier (GEM)
Introduced by **A. Oed** in 1988	Introduced by the **Georges Charpak** in 1968	Introduced by **F. Sauli** at CERN in 1997
made up of a sequence of alternating thin anode and cathode strips on an insulating support	thin wire at high potential in gas-filled tube	constructed of 50–70 μm thick Kapton foil clad in copper on both sides
Pitch (the repetition sequence) ~ 100-200 μm Width of anode strip ~10 μm Width of cathode strip ~ 85 -190 μm	Pitch ~ 2 - 5 mm Length of wire ~ 5 - 10 mm Radius of wire~ 20 - 25 μm	Holes pitch: 140μm Holes diameter in copper: 70μm +/-5μm Holes diameter in Kapton: 50μm +/-5μm
• Energy resolution: FWHM of 11-18% for the 6 keV X-ray emitted by ^{55}Fe; • Spatial Resolution: 30 μm;	• Energy resolution: FWHM of 24% for the 5.9 keV X-ray emitted by ^{55}Fe; • Spatial Resolution: 0.1 mm;	• Energy Resolution: FWHM of 15-20% 5.9 keV X-ray emitted by 55Fe ; • Spatial Resolution: 40 μm;
		

Gas Electron Multiplier (GEM)

- GEM detector works in proportional region.
- Holes in the GEM foils are the accelerating points where an electron gets boosted for the multiplication.
- Addition of more GEM foils in the detector will increase the gain at the cost of timing and spatial resolution. So one must choose intelligently.
- Large electric potentials are created in the GEM detector in each gap.
- Suitable for detection of charged particle. Almost 98 % efficiency for muon.







GEM Detector uses

- GEM based detectors are used in the CMS experiment for the recent upgrade and is planned to be used for the future upgrades (ME0, GE2/1).
- Also used in the recent upgrade of ALICE experiment as Time projection chamber (TPC).
- Cylindrical GEM detector would be used in the BES III and KLOE-2 experiment.

Cylindical GEM detector (BES Ⅲ Experiment)

Cylindical GEM detector (KLOE-2 Experiment)

Time Projection Chamber (ALICE Experiment)

Triple-GEM Chamber (CMS Experiment)

GEM detectors can be used for the other application besides the High Energy Particle Physics Experiment:

Medical: radiology and Low energy Nuclear Medicine Imaging, dosimetry and portal imaging

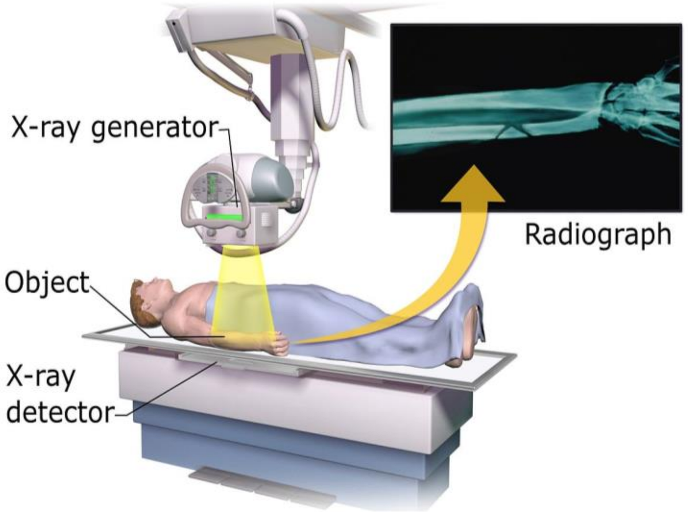
Cultural heritage studies: X-ray fluorescence

Muography: Archeology and nuclear reactor imaging

Astrophysical: X-ray polarimetry

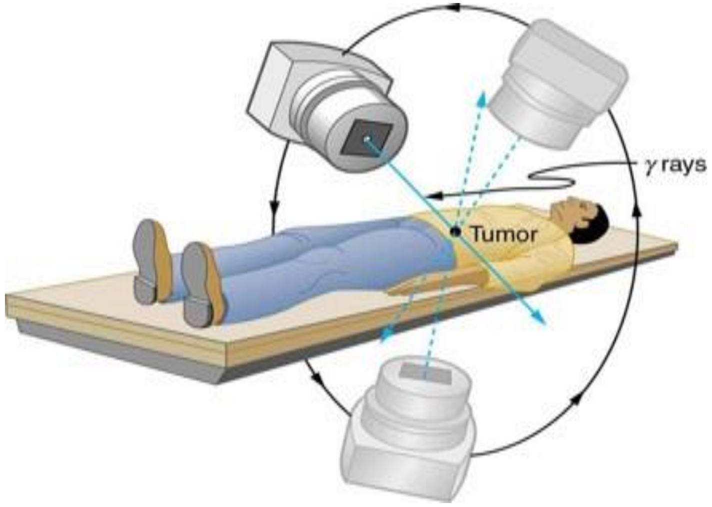
Medical Applications

Radiology (X-Ray)



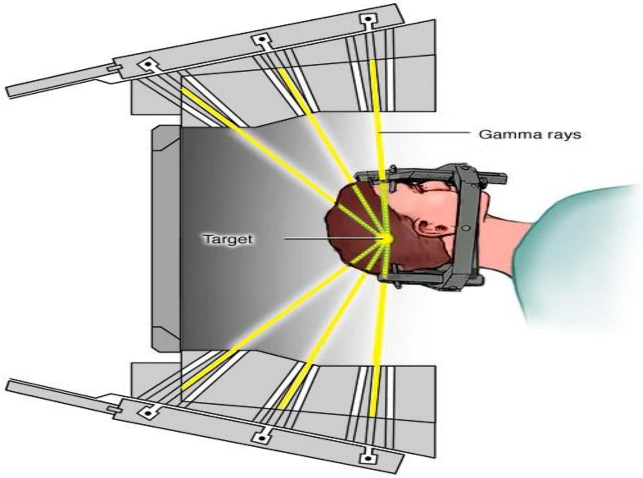
Radiation source is outside the patient's body

Nuclear Medicine



Radiation source is inside the patient's body

Radiotherapy



Irradiation of target cells by gamma/high energy X-Rays/hadrons

Detectors used are scintillators such as BaF_2, $Bi_4Ge_3O_{12}$ (BGO), Lu_2SiO_5 (LSO), or NaI(Tl) coupled to photomultiplier tubes. Semiconductor detectors such as CdZnTe (CZT).

Scintillators and Photomultiplier tubes are cost making for the modality.

Ionization Chambers are used for the dosimetry

Key Features of MPGD suitable for Medical Applications

Versatility:

MPGD's are versatile. Available in various shapes and sizes.

Low material budget:

Material involved in the production. Manufacturing of MPGD's are of low cost as compared to the scintillator based detectors.

High spatial resolution :

Have high spatial resolution of few μm

High-rate capability:

Can handle the high rate flux

Low energy threshold:

Have lower energy threshold as compared to scintillators

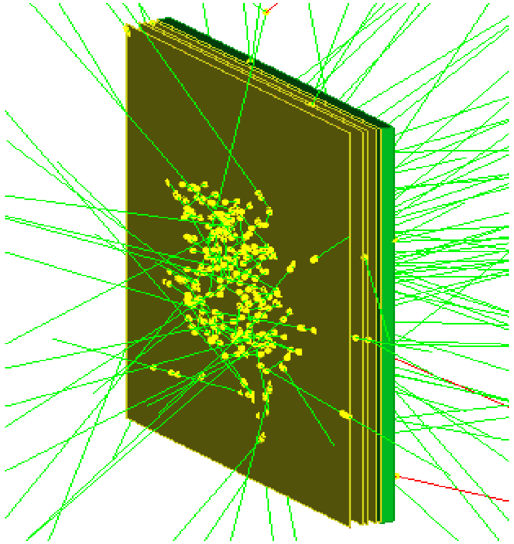
Radiation hardness:

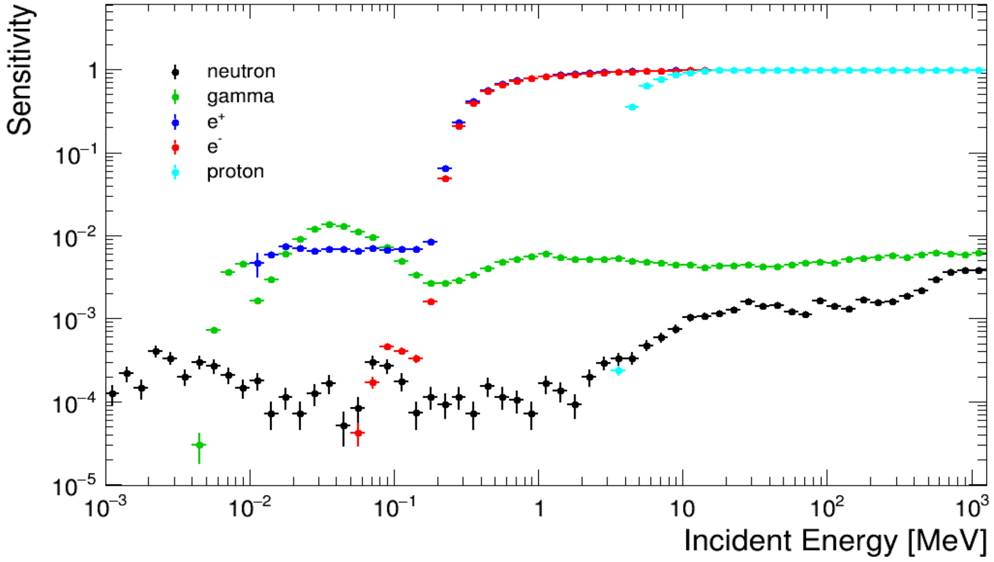
Hard to radiation in sense of aging

Simulation of 10 cm x 10 cm Triple-GEM detector

A GEANT4 simulation of 10 x 10 cm^2 Triple-GEM detector provides an estimation of sensitivity (using energy deposition method) for the different particles.

A mylar window with a fine copper drift is used as drift cathode.





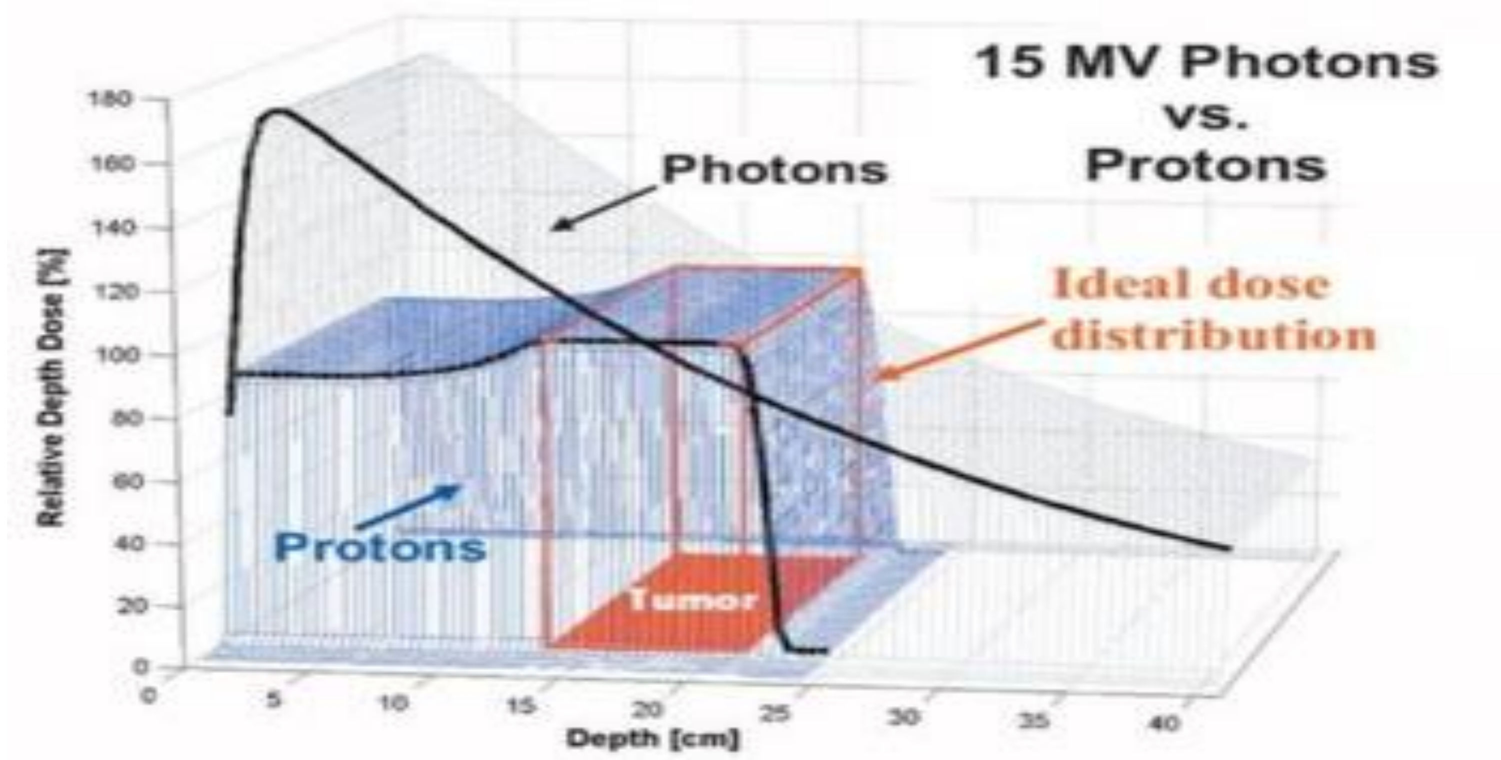
Detailed simulation can be done using the following simulation packages:

- **ANSYS**
  electrical field maps in 2D& 3D, finite element calculation for arbitrary electrodes & dielectrics
- **HEED *(I.Smirnov)***
  energy loss, ionization
- **MAGBOLTZ *(S.Biagi)***
  electron transport properties: drift, diffusion, multiplication, attachment
- **Garfield *(R.Veenhof)***
  fields, drift properties, signals (interfaced to programs above)
- **PSpice *(Cadence D.S.)***
  electronic signal

Hadron Therapy

Hadron therapy is becoming an increasingly popular and capable tumor treatment modality, due to its superior dose localization capability.

To fully exploit the dose localization possibility of particle beams, tumor location and extent and scanning pencil beam characteristics have to be known accurately and precisely.



Potential MPGD applications

- Proton Radiography
- Beam characterisation
- Scanning pencil beam tracking

Proton Radiography

Proton radiography provides high quality images to determine organ location.

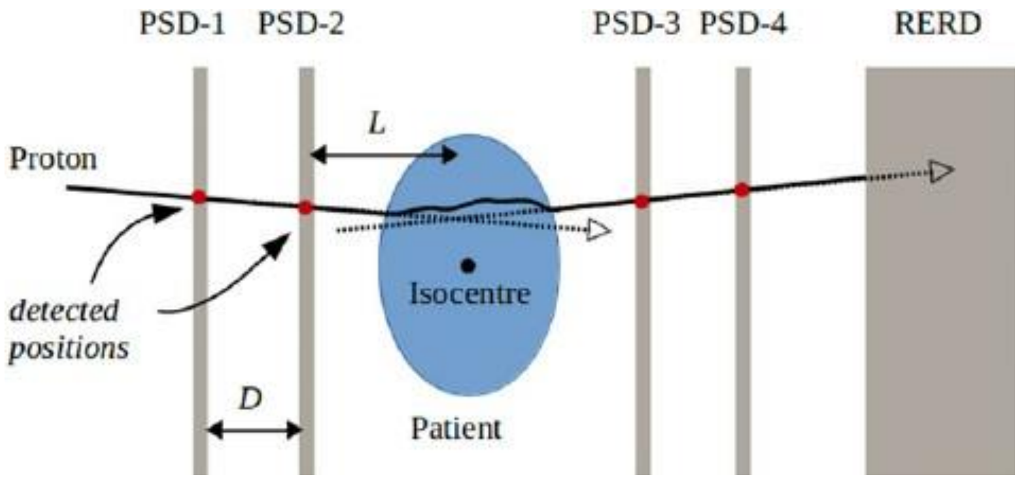
- Accurate patient positioning
- Minimise dose for tumour tracking

Detectors for proton radiography need to provide:

- High granularity
- Low material budget
- High-rate capability
- Moderate active area

Additional application:

Interaction vertex imaging (IVI) dosimetry record secondary protons emerging from the target.



https://www.birpublications.org/doi/pdf/10.1259/bjr.20150134

30x30cm^2 active area 2D readout anode (800μm strip pitch)
https://doi.org/10.1016/j.nima.2012.10.046

Fast readout of GEM detectors for medical imaging
M. Bucciantonio (TERA, Novara and Bern U., LHEP), U. Amaldi (TERA, Novara), R. Kieffer (TERA, Novara), N. Malakhov (TERA, Novara), F. Sauli (TERA, Novara) et al.
DOI: 10.1016/j.nima.2012.10.046
Published in: Nucl.Instrum.Meth.A 718 (2013), 160-163

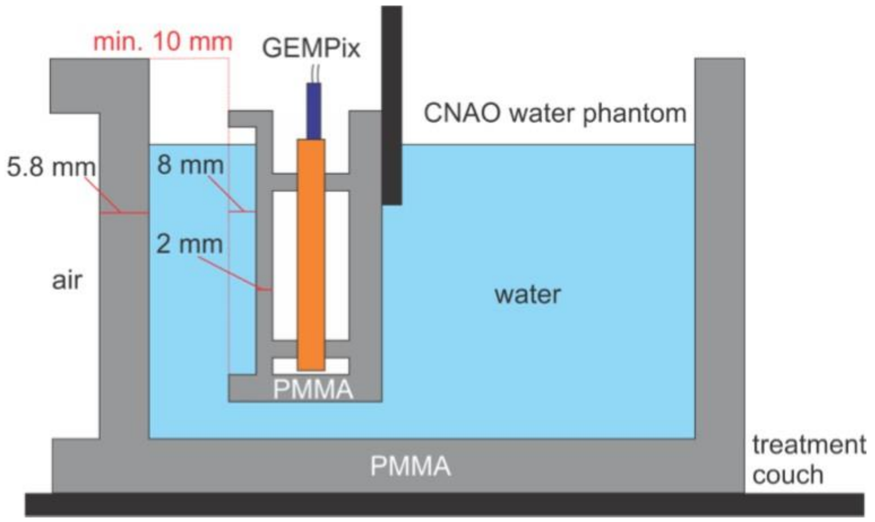
Beam Characterisation

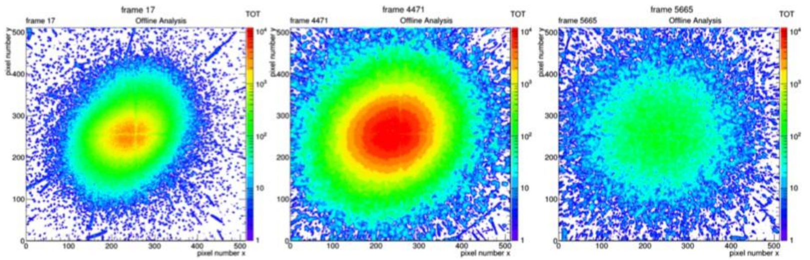
Ionisation chambers (ICs) are commonly used for energy deposition measurements in hadron therapy. To overcome the limited spatial resolution of IC arrays (≈5mm), a GEM can be coupled to a Timepix ASIC.

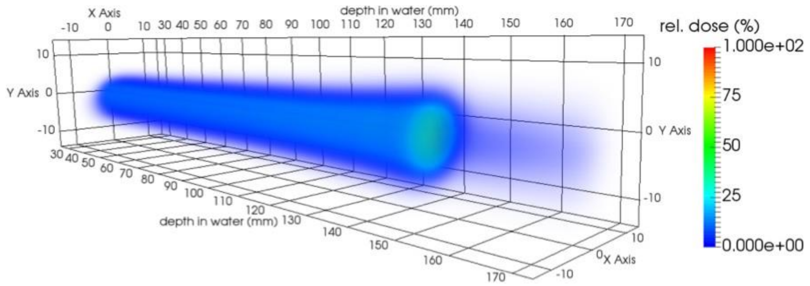
Timepix: 55µm pitch pixelated readout (512x512 pixels)

Operated in Ar:CO_2:CF_4 (45:15:40) gas mixtures and tested in carbon beams (280-332 MeV) at CNAO 3D energy deposition profile of carbon beam in water phantom obtained in 15 min

Mismatches between Bragg curve measured and reference may be due to small active area of detector, heating of the ASIC, stopping power differences of air (IC) and Ar:CO_2:CF_4 (GEMPix)



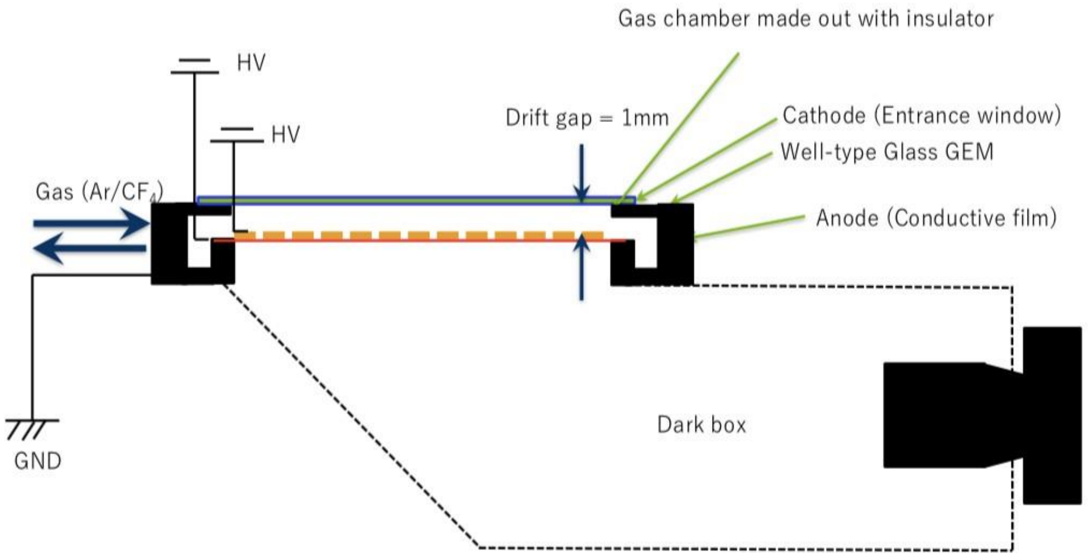


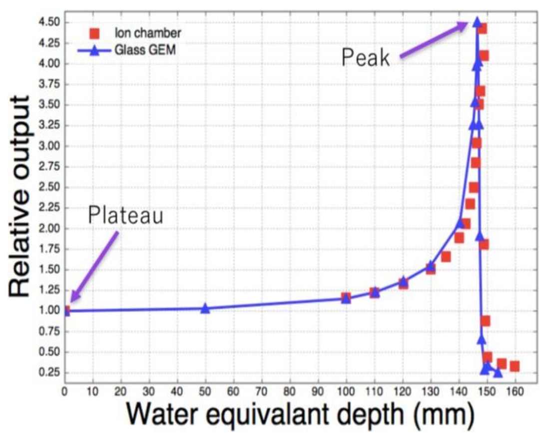


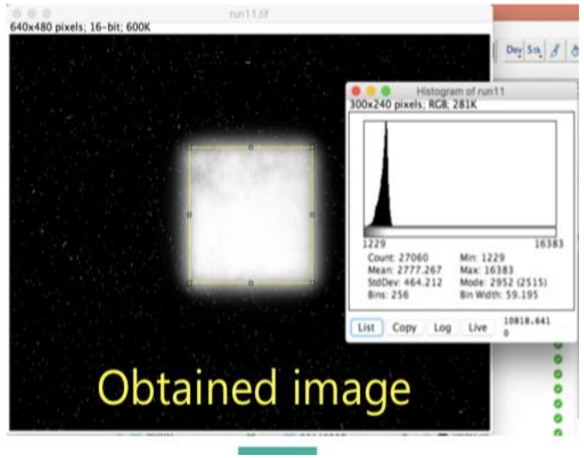
Medical Applications of the GEMPix
Johannes Leidner (CERN), Fabrizio Murtas (CERN and LNF, Dafne Light), Marco Silari (CERN)
DOI: 10.3390/app11010440
Published in: Appl.Sciences 11 (2021) 1,440

Hadron Therapy Monitoring

Optically read out GEMs can be used online monitoring in hadron therapy.
Low material budget of gaseous detector minimises beam attenuation and multiple scattering
Optical readout permits placement of camera outside of beam path (lower material budget, lower radiation exposure of sensor) .
This van provide **high spatial resolution** images of scanning pencil beams for beam characterisation and treatment plan verification
Optically read out **glass GEM** well suited for dose imaging and dose depth curve measurement.
Peak to Plateau ratio of dose depth curve of carbon beams accurately reproduced.
Scanning pencil beams imaged with high spatial resolution and short exposure time (10 ms).







Portal Imaging in Radiotherapy

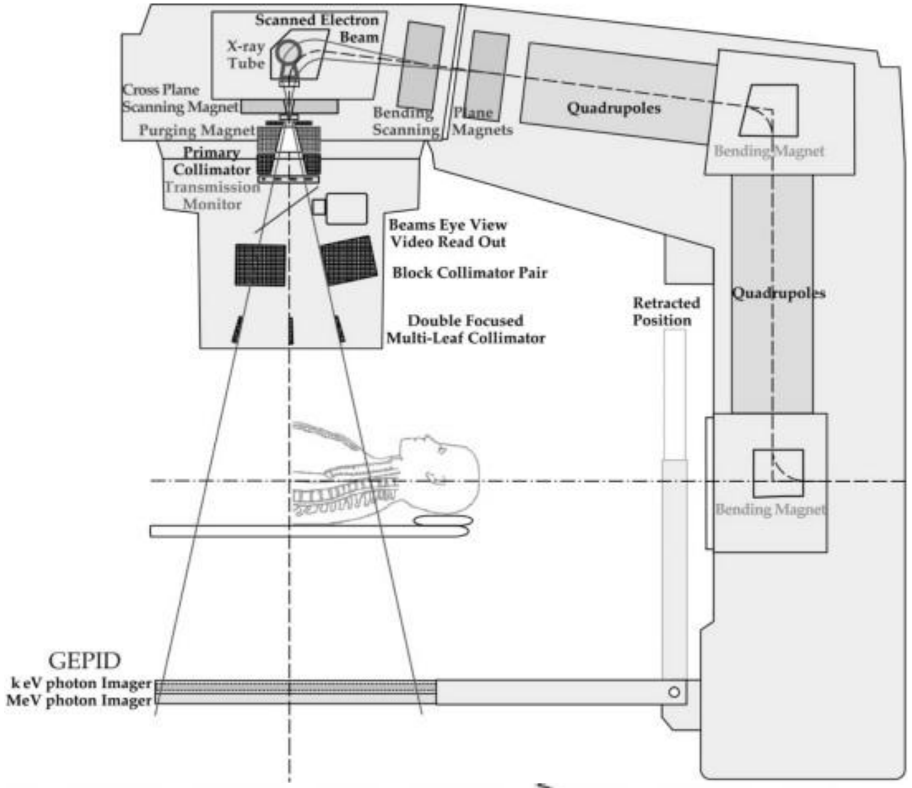
Electronic portal imaging devices (EPIDs) are used for advanced beam monitoring and alignment of treatment beams with respect to tumour location.

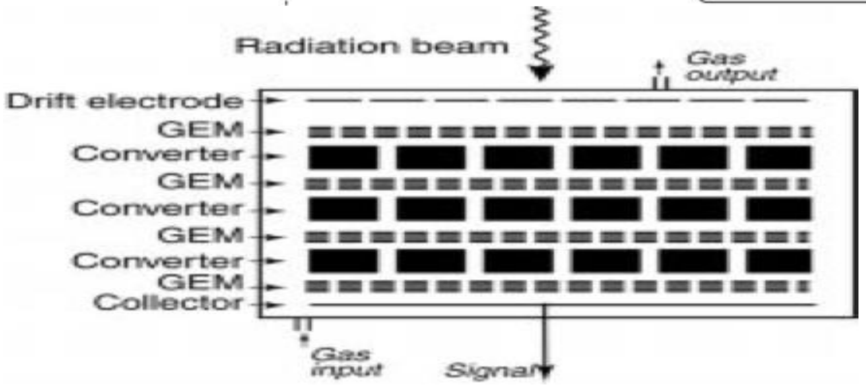
Detectors are required to be compatible with
high particle fluxes
wide-range of photon
energies moderate active areas

Realiability and radiation hardness are key requirements of EPIDs.

Hybrid detector: Gaseous electron multiplier portal imaging device

keV photon detector: diagnostic tool, converter (photoeffect) + GEM
MeV photon detector: perforated metal converter (Compton electrons) + GEM

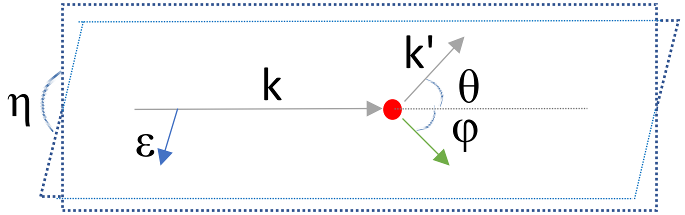




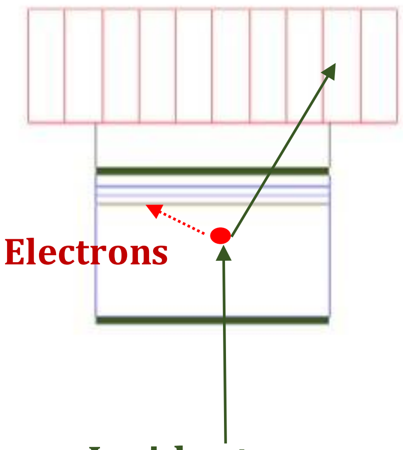
C. Iacobaeus et al., "A novel portal imaging device for advanced radiation therapy," in IEEE Transactions on Nuclear Science, vol. 48, no. 4, pp. 1496-1502, Aug. 2001, doi: 10.1109/23.958386.

PET Event Selection Technique

- Q-PET works on Compton Scattering.
- Look for Compton Scattered events, photon scattered by sensitive material of chamber towards the Calorimeter.
- GEM Chamber works as electron tracker I.e. gives the direction of recoil electron. Provide the point of Compton-interaction.
- Back end Calorimeter absorbs the scattered gamma-ray. Provide the point of interaction of scattered gamma-ray.



k = incident photon momenta
k'= scattered photon momenta
η = angle between plane of scattering & plane of polarization
ε = polarization vector
θ = angle of scattering
φ = angle of recoil



Klein-Nishina cross section

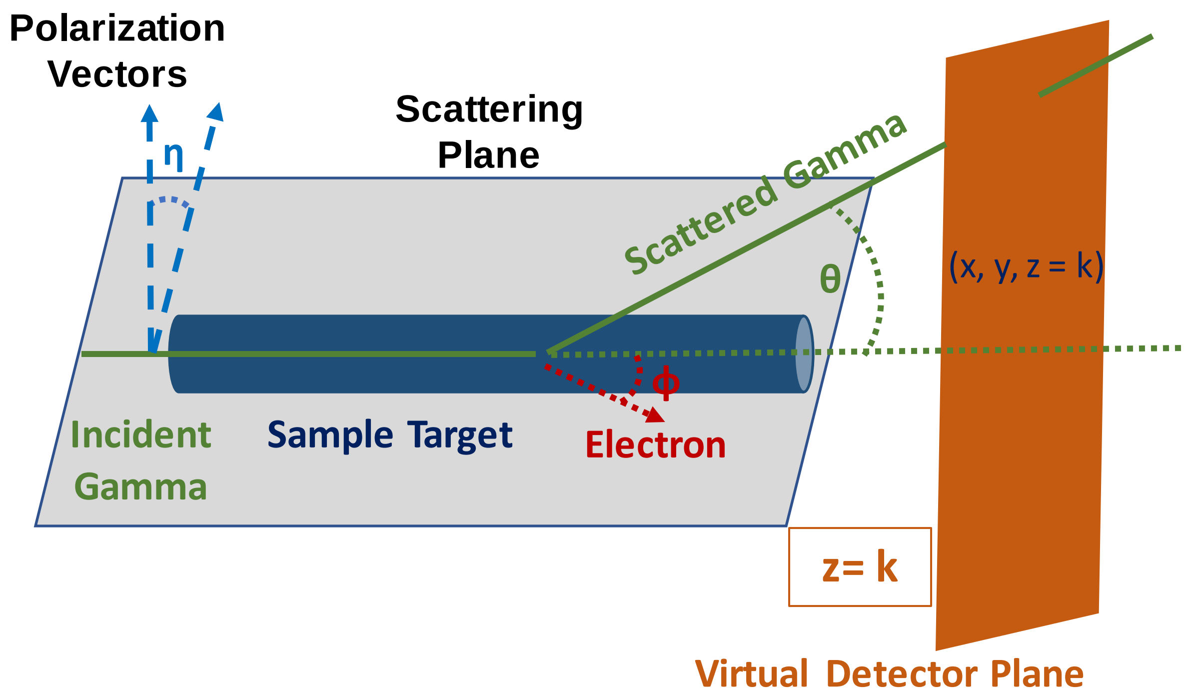
$$d\sigma/d\Omega = (r_0^2/2)\,(E`/E)^2\,(E/E` + E`/E - 2 + \cos^2\eta)$$

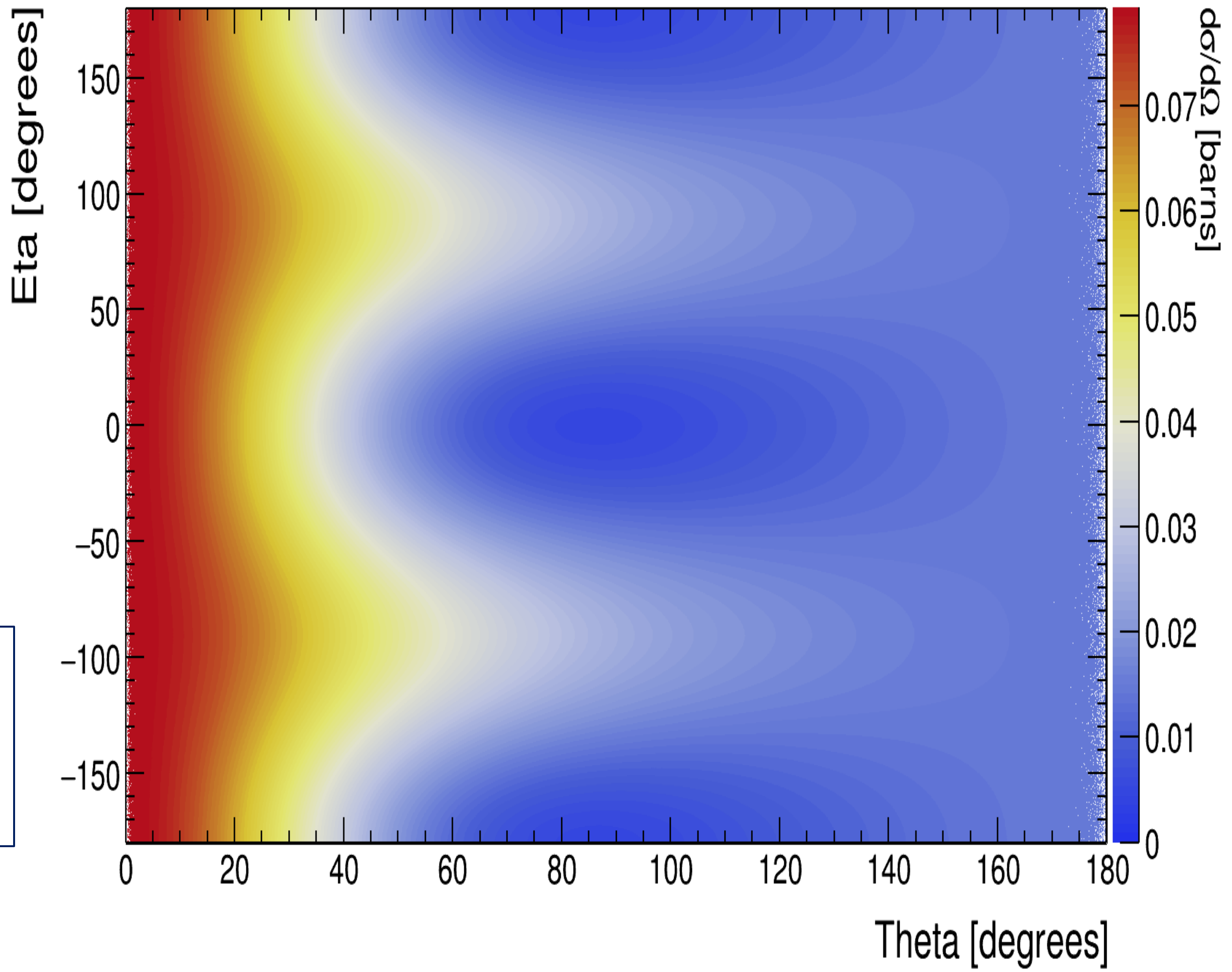
where $E` = E/(1 + E/m_ec^2\,(1 - \cos\theta))$

Both photons in para-positronium are linearly polarized & polarization vectors are orthogonal to each other

$\sigma_{3\gamma}/\sigma_{2\gamma} = 1/372$

Compton PET Simulation





- *Sample of cylindrical dimensions (**Radius = 0.5 cm & Length = 10 cm)***
- *Photons of energy **511 keV** are used to irradiate the sample.*
- *A set **polarization (0, 1, 0)** is used for the primary gamma.*

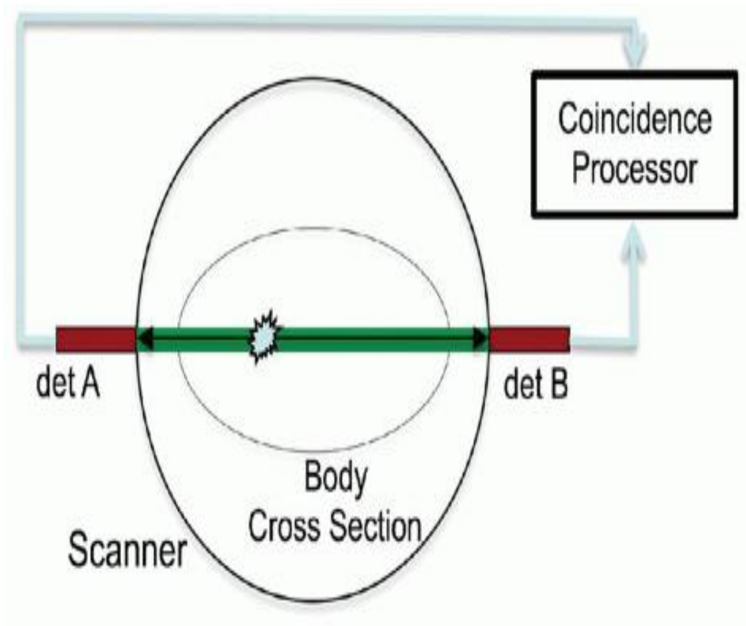
Q-PET: PET with 3rd Eye Quantum Entanglement Based Positron Emission Tomography
Sunil Kumar (Punjab U.), Sushil Singh Chauhan (Punjab U.), Vipin Bhatnagar (Punjab U.)
e-Print: 1812.06257 [physics.ins-det]
DOI: 10.1007/978-981-33-4408-2_136
Published in: Springer Proc.Phys. 261 (2021), 949-952

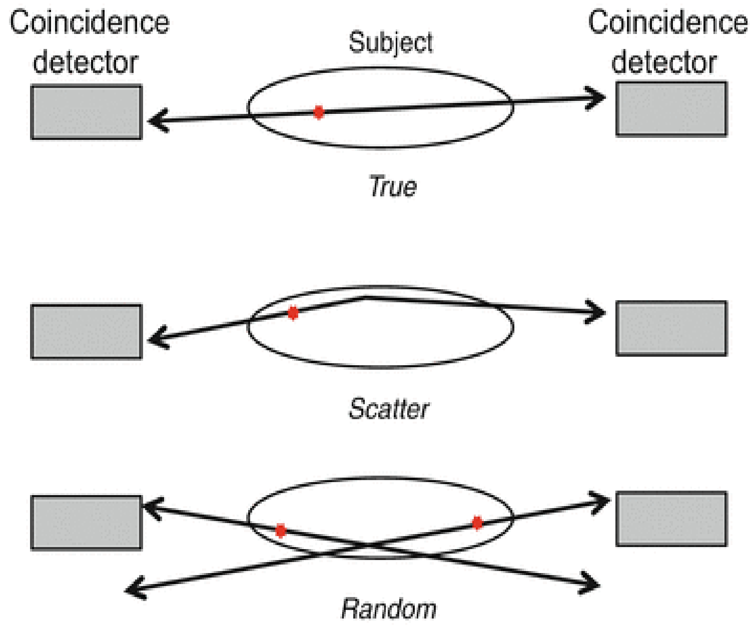
Conclusions

- GEM are very useful in many fields and research is going on for the uses to explore the other fields.
- THGEM, GEM with converter material are under development for the Gamma and Neutron Imaging.
- Definitely used for the low enrgy X-ray or Gamma imaging.
- Their role in the radiotherapy is under development and expected to be prominent with use of Hadron Therapy worldwide

Back-up

A New Selection Window





Both the photons get interacted in the opposite detectors within a time difference due to position of annihilation event.

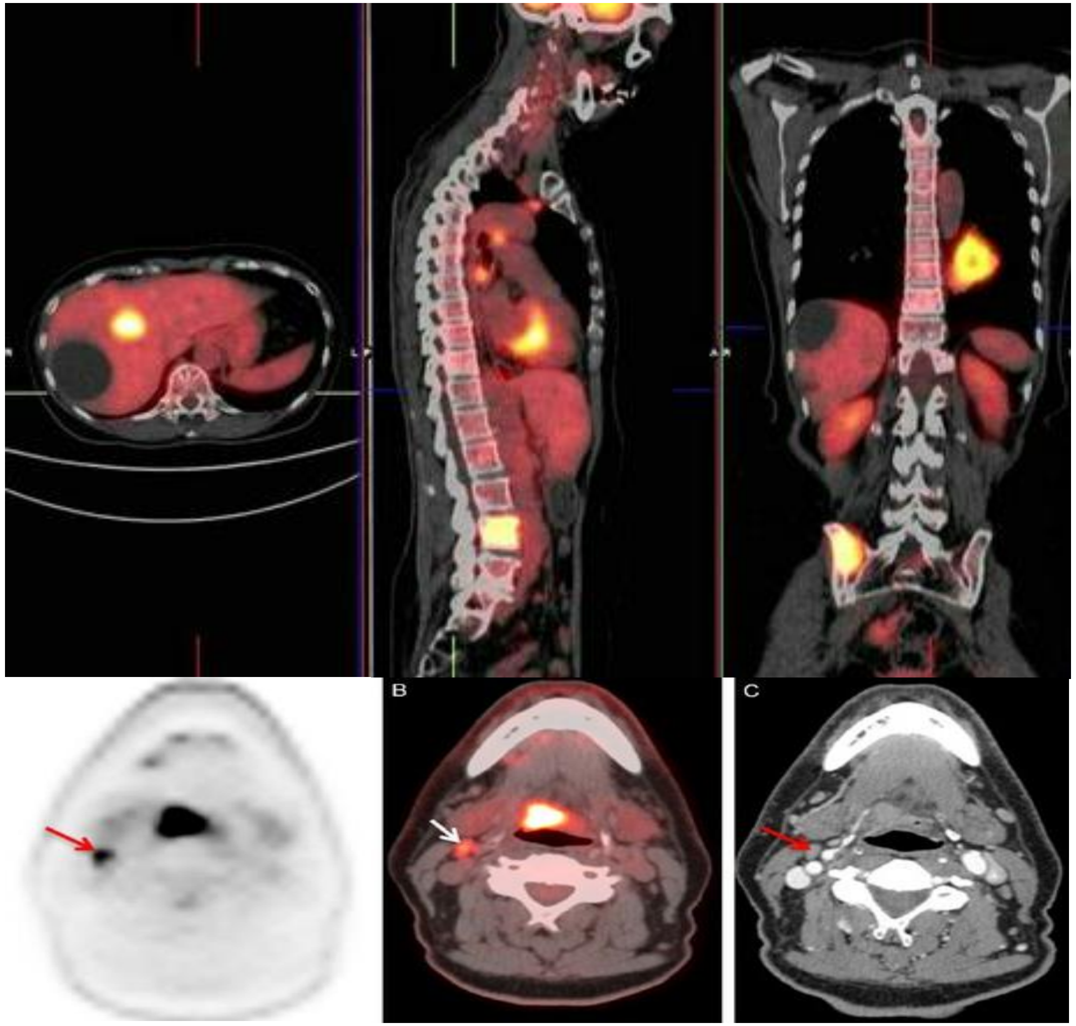
Energy and Timing window decides about the selection of the true coincidence events. Other corrections has to be done to get the true image.

To introduce an additional selection window/cut for the true coincidence on the basis of their polarization (of photon).

Positron Emission Tomography (PET)

- PET stands for Positron Emission Tomography.
- Tomography means slicing the patient body in different planes.
- A Radiopharmaceutical tagged with a positron emitting Radionuclide is introduced intravenously or by some other mean.
- PET provides the Functional/Molecular imaging and CT/MR provides the Morphological imaging for fusion.
- A calculated factor called SUV is used to estimate the therapy response, staging and restaging of particular cancer.

$$\textbf{SUV} = \frac{\textit{Decay corrected activity concentration (uCi/ml)}}{\textit{Injected dose (mCi) / Patient weight (g)}}$$



PET/CT Images