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Radiation Detectors for Medical Physics

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INFN Bari
Istituto Nazionale di Fisica Nucleare
Sezione di Bari

References

Dr Barbara Camanzi Oxford
“Imaging and detectors for medical physics” series of lectures
The Cockcroft Institute

Edited by M A Flower
Webb’s Physics of Medical Imaging
CRC Press

A Del Guerra
Ionizing Radiation Detectors for Medical Imaging
World Scientific

https://cds.cern.ch/record/2737317/files/
Lecoq2020_Chapter_DetectorsInMedicineAndBiology.pdf

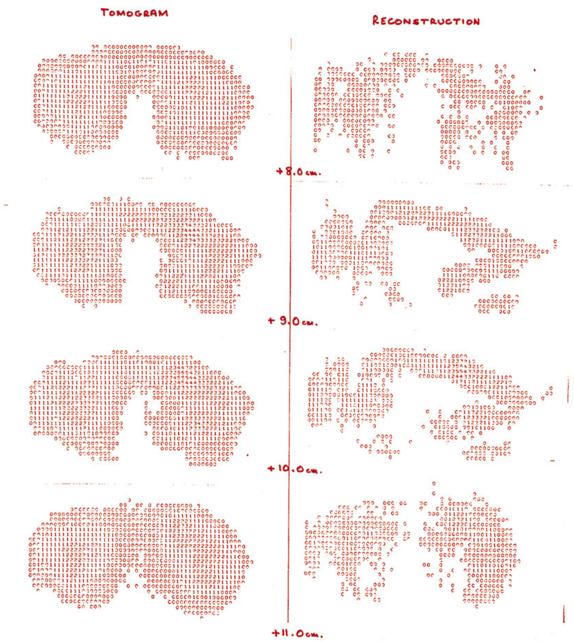
From particle physics to medicine

- There is a long history of successful applications of particle physics technologies to medicine.
- CERN develops cutting-edge technologies in a wide range of domains and has significant experience in applying this know-how to medical applications:
    - Over 50 years of experience in development of PET technologies.
    - Design and characterization of **high spatial resolution, fast timing detectors, uses in hadron therapy and medical imaging**.
    - Hybrid pixel detector technology was developed for particle tracking at CERN and has enabled high resolution, color X-ray CT imaging

[https://kt.cern/competences/general-medical-applications]

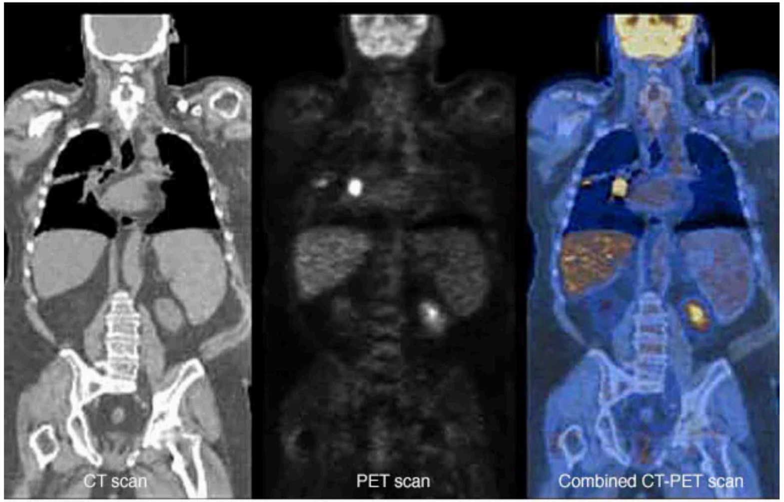
Positron Emission Tomography

First PET image of a mouse taken in 1977 at CERN using high-density avalanche chambers



https://cerncourier.com/a/pet-and-ct-a-perfect-fit/

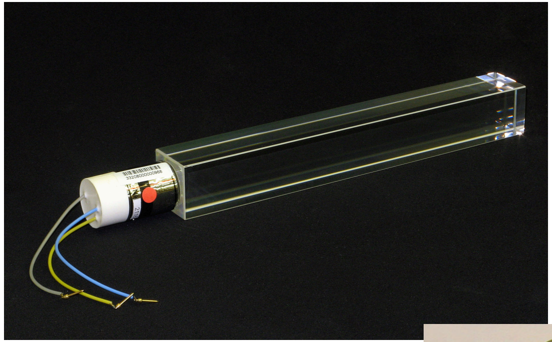
Multi modality imaging PET + CT

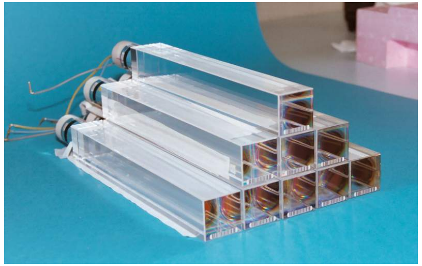


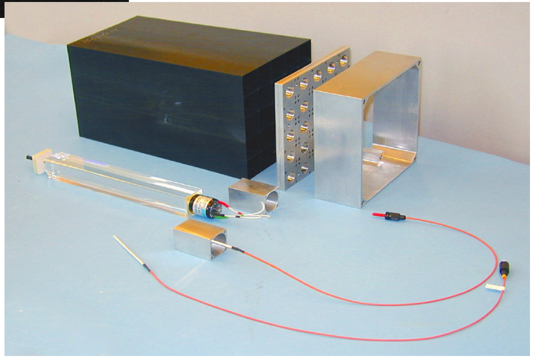
https://www.mayoclinic.org/tests-procedures/pet-scan/about/pac-20385078

Radiation Detectors in Medicine

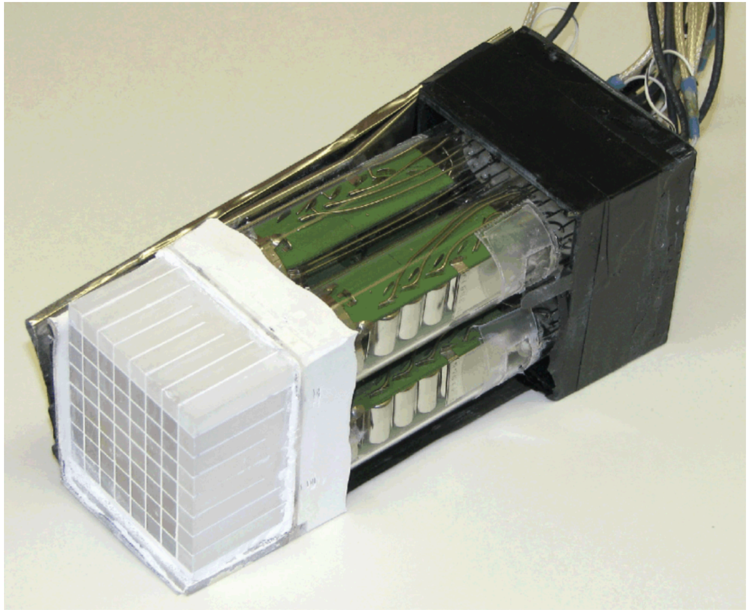
CMS ECAL module







PET scanner module



Which detectors ?

Particle physics

- Solid state detectors (Si, diamond)
  (Beam location and abort, vertex reconstruction, tracking)
- Gas detectors
  (Tracking, calorimetry, muon detectors)
- Scintillating materials + photon detectors
  (Calorimetry)

Medical physics

- Detectors for particle physics and medicine have different requirements:
  - Developments in radiation detectors won’t be driven by advances in technology alone, but a medical reason is needed!
  - **Detector for medical application needs custom design** → it’s not a technology looking for an application, but a problem looking for a solution

Specific requirements

Detection range	– Low energies: 18 keV for mammograms for ex.
Read-out	– No trigger (no bunch crossing) → self-triggering electronics or free running – High acquisition rates > GHz – Manageable number of read-out channels
Event size	– Can be small 1 bit ÷ 10 bytes
Geometry	– Large area often required – Almost no dead space
Patient's requirements	– Meet stringent ethical requirements and regulation – Ensure patient's comfort
Market	– Can be large: $10^3 \div 10^6$ units

Which applications?

The patient journey

- Diagnosis
- Treatment
- Post-treatment

Diagnosis

Diagnostics

Imaging:

- Planar X-ray imaging
- Computed Tomography
- Positron Emission Tomography
- Single Photon Emission CT
- MRI
- Ultrasound

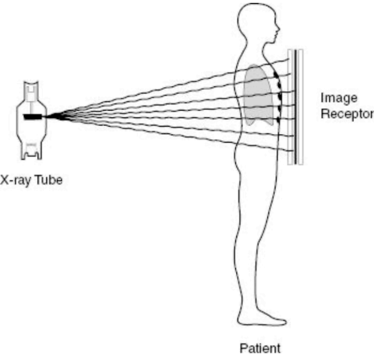
Endoscopy

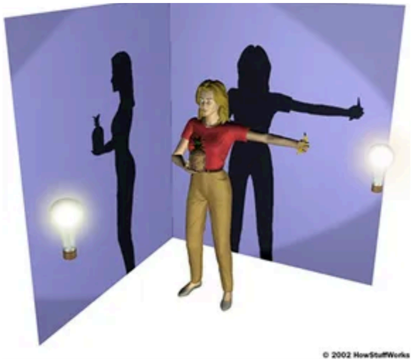
Tests on samples:

- Tissue (biopsy)
- Blood
- Body fluids

X-ray imaging

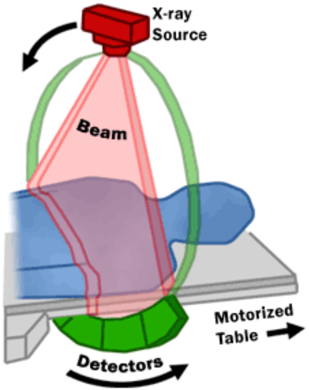
Planar radiography

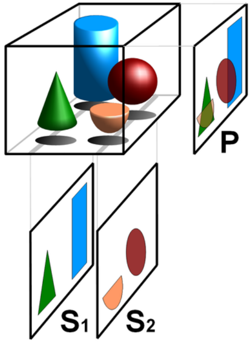




- X-ray source and detector fixed
- 2D projection of all tissues between Xray source and detector

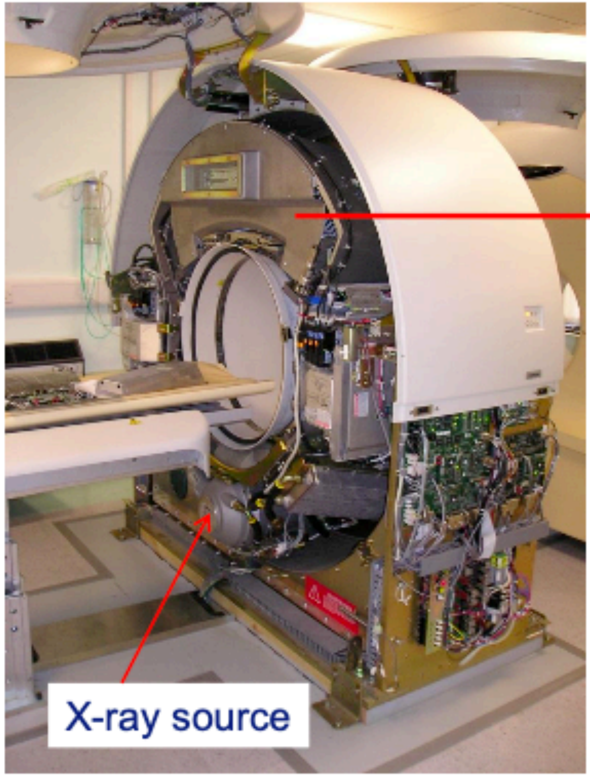
Computed Tomography

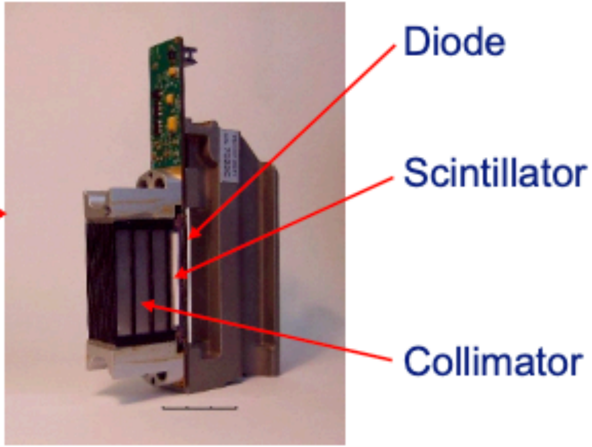




- Xray source and detector rotate at high speed around patient + patient moved in third direction
- 3D image of body region
- much higher dose wrt to planar radiography

Scintillators and photon detectors





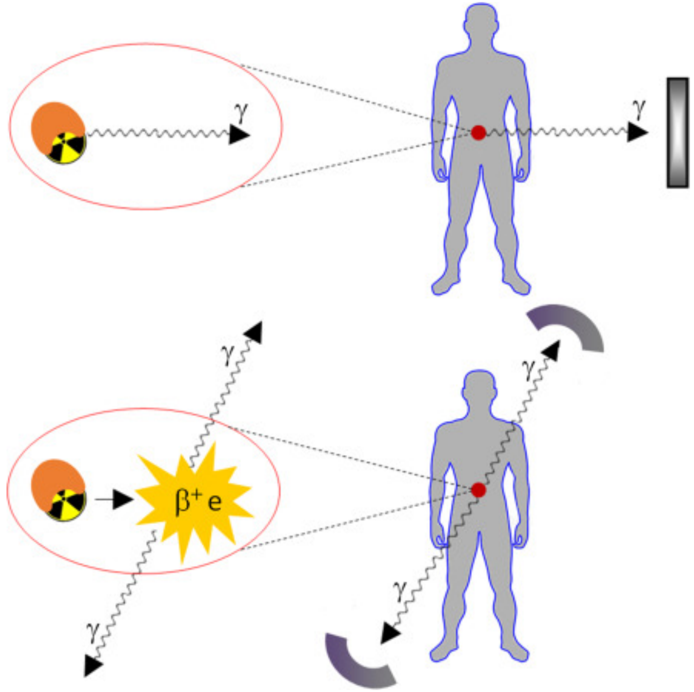
CT scanner:

- 120 keV X-rays rotating source
- Diametrically opposite detector unit
- 30k scanners worldwide

Nuclear medicine imaging

Imaging of radioactive decay products of a radiopharmaceutical (radiotracer) introduced into the body → emission imaging (as opposed to X-ray imaging = transmission imaging)

Spatial distribution depends on how radiopharmaceutical interacts with tissues in the body



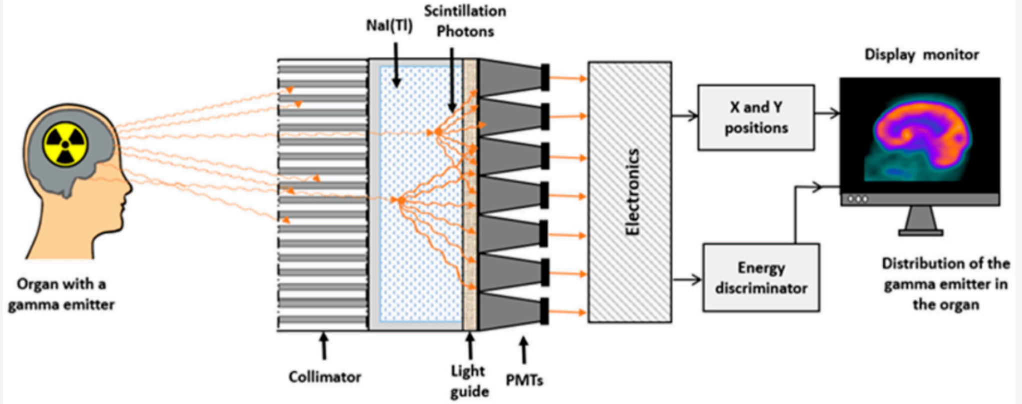
Choice of radionuclides for imaging

1. Produces γ rays with high photon yield (good counting statistics) and suitable $E\gamma$
   - High enough so that Photon is able to efficiently escape the body
   - Photopeak is easily separated from scattered radiation
   - Low enough so that Detection efficiency is still good Photons are not too difficult to shield and to handle
2. Absence of particulate emission (α or β particles) → no unnecessary dose to patients

Single Photon Emission CT

Detects γ-rays and for each γ-ray records x-y position, energy and time

- $^{99}Tc^{m}$ injected into body → one 141 keV gamma
- two or three rotating detector head
- each **detector head made of gamma camera**:
  - capable of withstanding γ-ray detection rates up to tens to thousands events per second
  - reject γ-rays scattered in the body → no useful spatial information
  - as high sensitivity as possible → high quality images

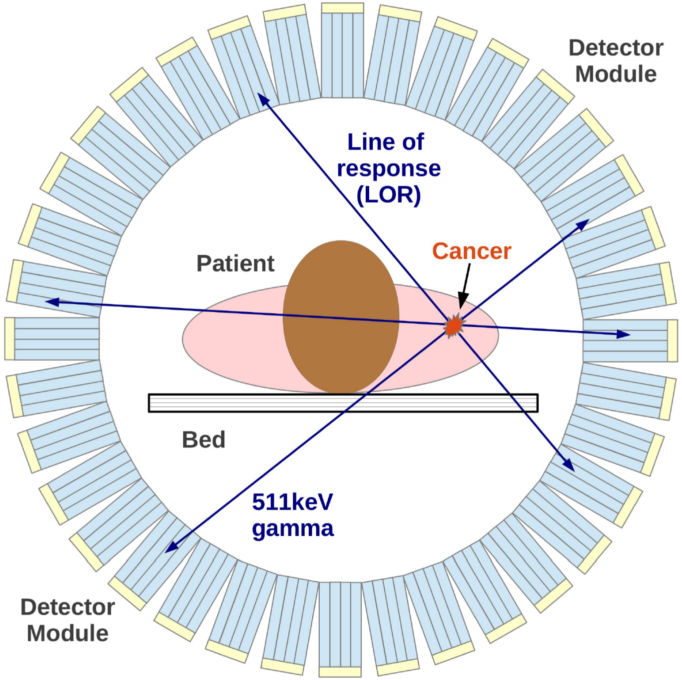


Diagnostics 2024, *14*(13), 1431; https://doi.org/10.3390/diagnostics14131431

Positron Emission Tomography

Basic principle:

1. Radiotracers used undergo β+ decay → emit e+
2. e+ travels on average 0.1÷3 mm in tissue depending on radiotracer → scatters → loses energy → comes to rest
3. e+ at rest combines with atomic e− to form positronium
4. Positronium decays emitting two back-to-back 511 keV γ

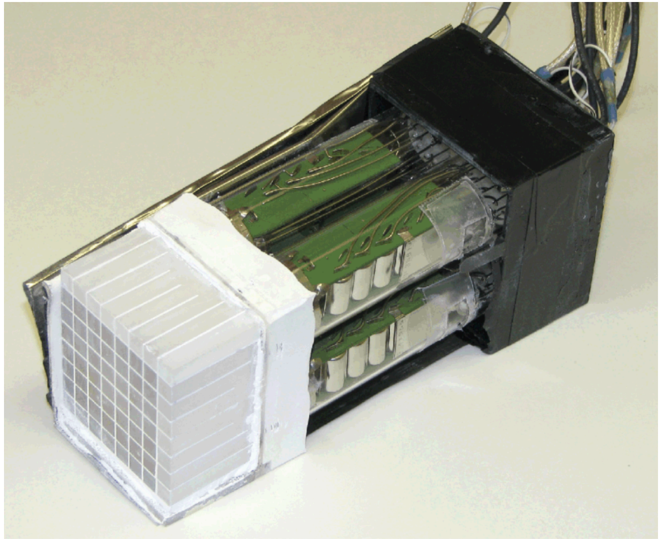


PET detection unit is made of a full ring of scintillating detectors surrounding the patient to detect photons in coincidence

PET block detector

- PET module is has ‘block detector’ design
- Ideal geometry would be one crystal coupled to one PMT → better spatial resolution but too expensive
- usually arrays of crystals shares same PMT
- Ideal scintillation material for use in PET has:
  - High detection efficiency for 511 keV γ-rays
  - Short decay time to allow for short coincidence resolving time
  - High light yield and optical transparency at emission wavelength to minimise reabsorption

PET scanner module



Scintillators for PET

	Decay time (ns)	Relative light yield[1]	Efficiency	Emission wavelength (nm)	Refractive index
BGO	300	0.15	0.72	480	2.15
$LSO(Ce)$	40	0.75	0.69	420	1.82
BaF_2	0.8 prim 600 sec	0.12	0.34	$220, 310$	1.49
$GSO(Ce)$	60 prim 600 sec	0.3	0.57	430	1.85
$NaI(Tl)$	230 prim 10^4 sec	1.0	0.24	410	1.85

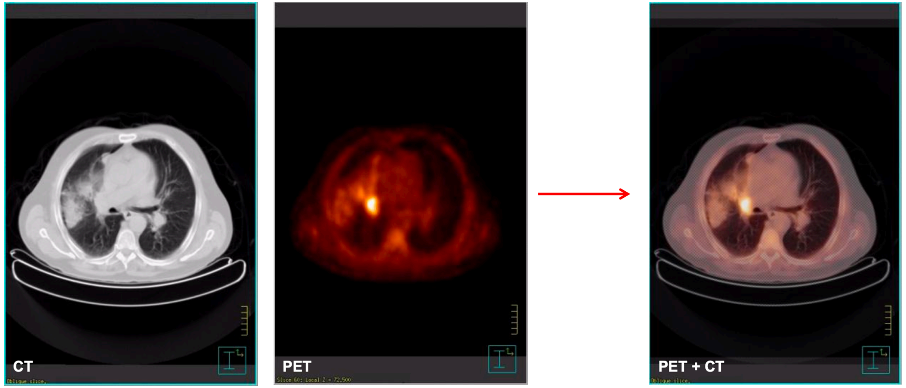
[1]Relative to $NaI(Tl)$

- Scintillator must be 2 cm or more in thickness for high sensitivity
- $NaI(Tl)$ =low efficiency for 511 keV γ-rays $\rightarrow$ not used in PET
- LSO/LYSO crystal (Lutetium (yttrium) Oxyorthosilicate) is the best option

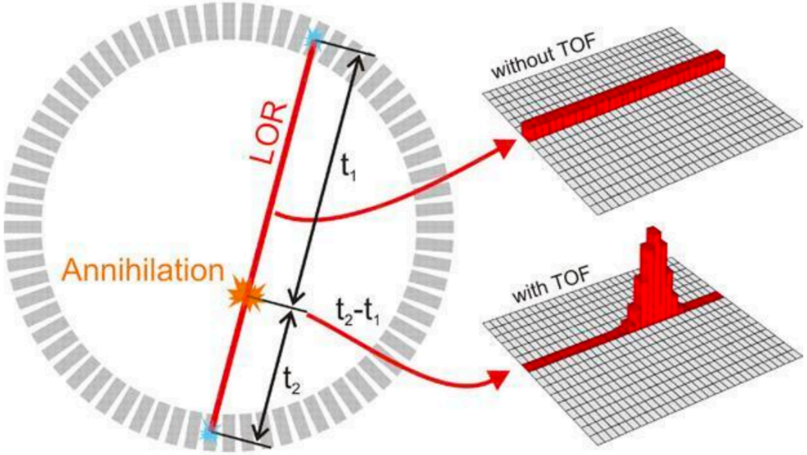
Hybrid PET/CT

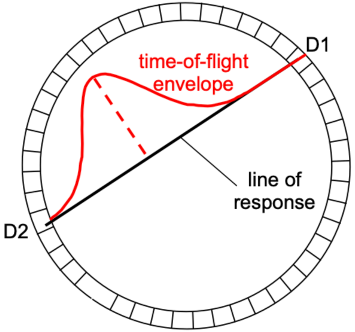
Stand-alone PET scanner almost entirely replaced by **hybrid PET/CT scanners**:

- Two separate systems one next to the other
- Bed that slides between two systems
- Improved attenuation correction
- Ability to fuse anatomical (morphological) and functional information



Time of Flight PET

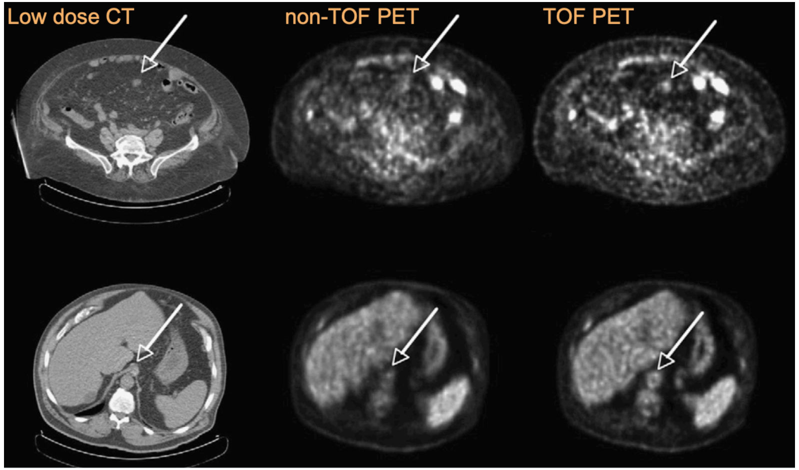




Accurate measurement of arrival time of γ-ray allow localizing the annihilation point along the line of response (LOR)

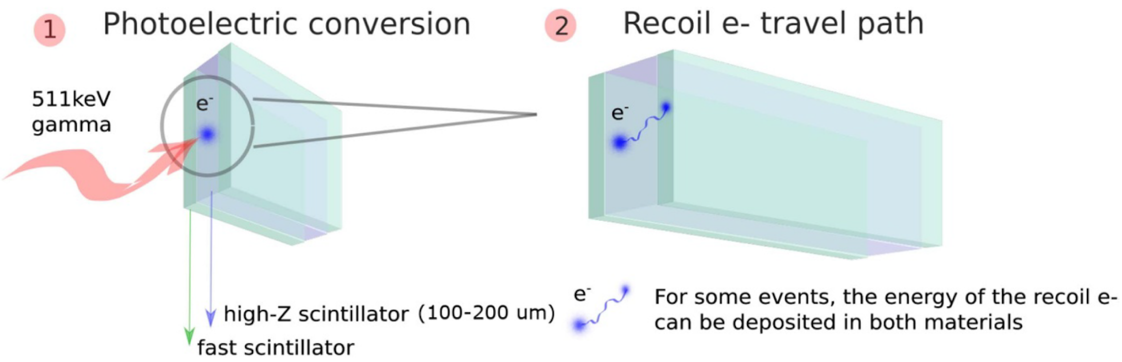
– Fast scintillating materials needed for TOF-PET

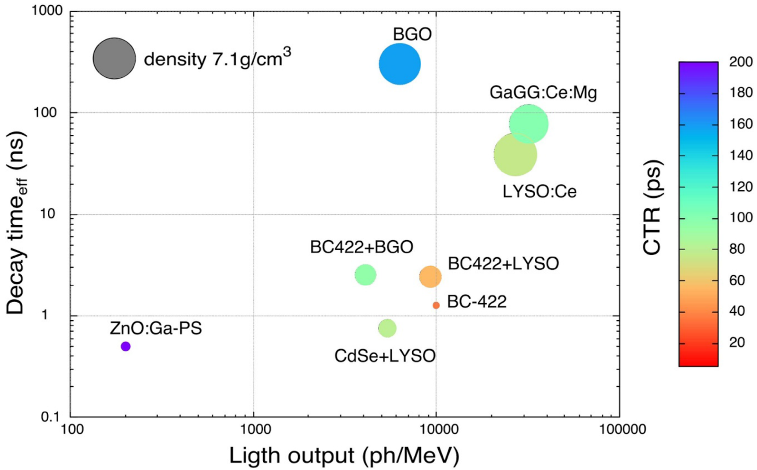
– Fast photon detectors



Heterostructures

Hybrid structures in which high-Z inorganic scintillator is layered with fast scintillators (organic/nano-crystals) for time tagging





ONGOING R&D

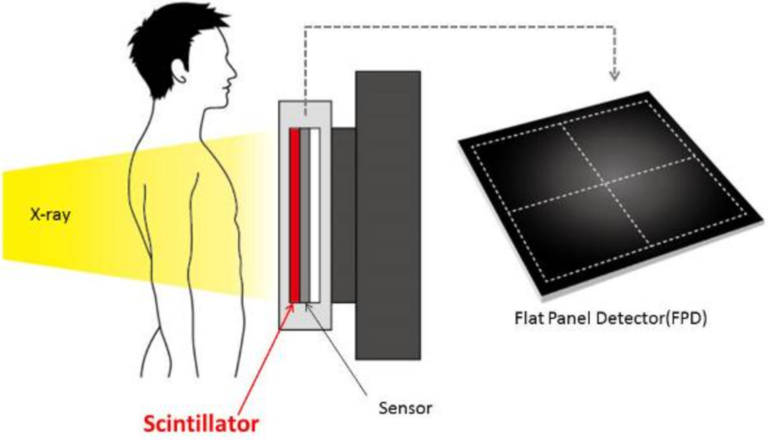
- ultra-fast scintillators for medical applications and HEP (Crystal Clear Collaboration)
- doped plastic scintillators (AidaInnova)

P. Lecoq et al 2020 Phys. Med. Biol. 65 21RM01

Other examples

- **Gas detectors have limited application in medical imaging** because of the higher energy threshold for producing ionisation than other detectors → less ionisation produced for same incident energy → lower energy resolution and lower stopping power

- **Semiconductors detectors** need only few eV to create e–h pair → for given energy greater ionisation produced than in gas → higher energy resolution
    - Small sensitive area limited by engineering
    - ChargeCoupled device (CCDs) have low detection efficiency for photons with E > 30 keV and charged particles → used coupled with scintillators
    - flat panel are used as imaging systems for X-ray radiotherapy



Treatment

Treating cancer with radiation

External beam radiotherapy:

- X-ray beam
- Electron beam
- Proton/light ion beam

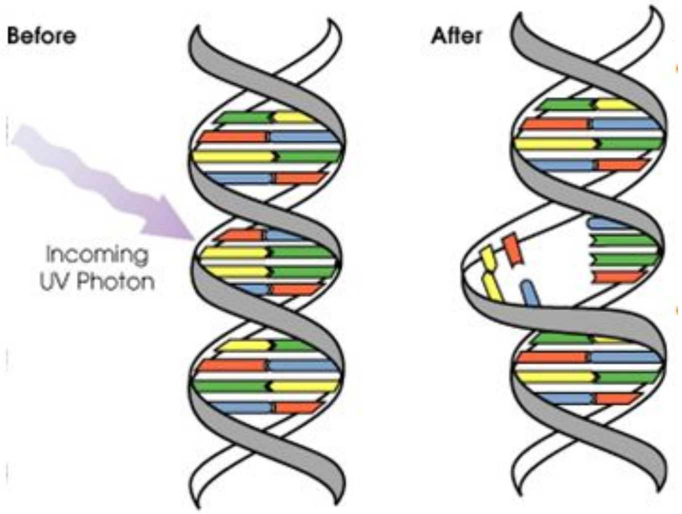
Internal radiotherapy:

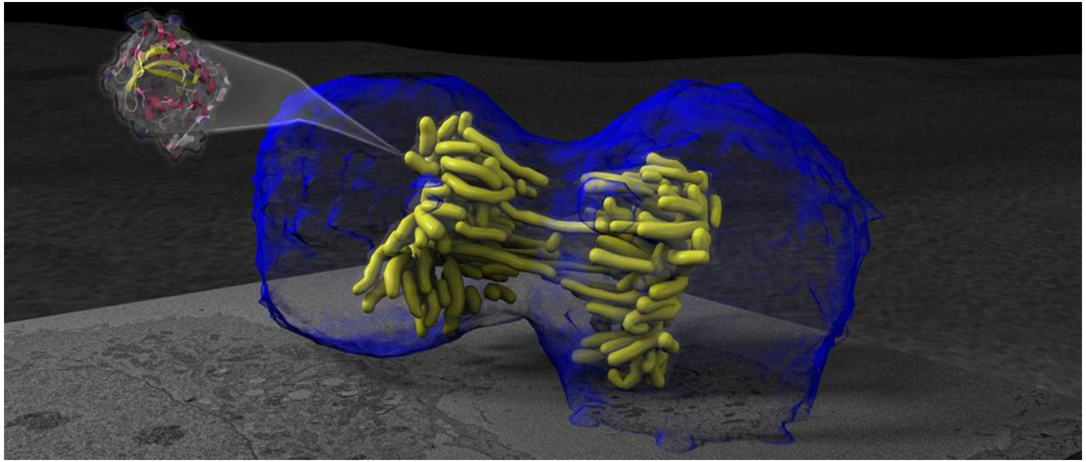
- Sealed sources (brachytherapy)
- Radiopharmaceuticals

Binary radiotherapy:

- Boron Neutron Capture Therapy (BNCT)
- Photon Capture Therapy (PCT)

Killing Cancer via DNA Damage





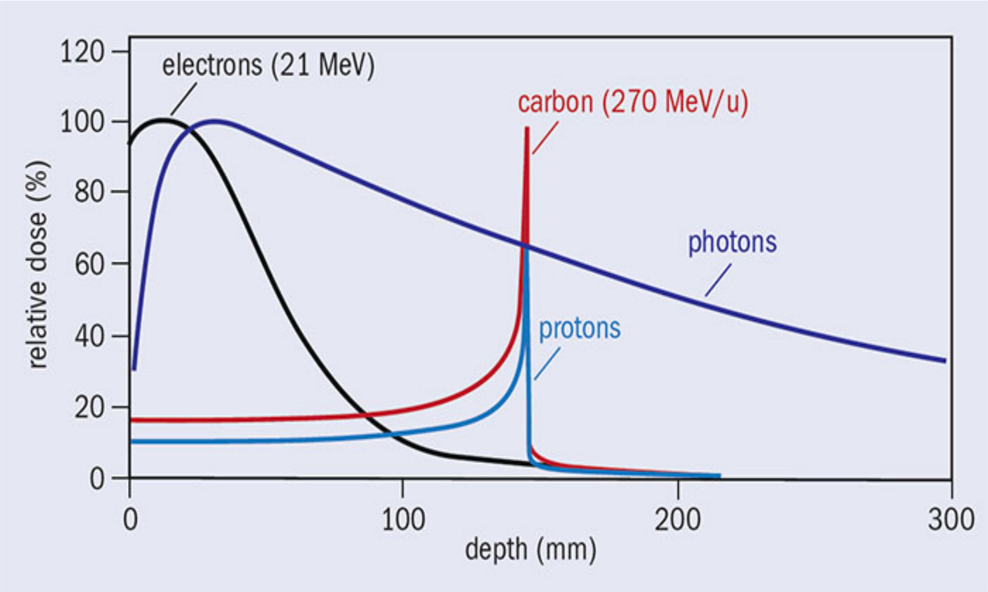
External beam radiotherapy

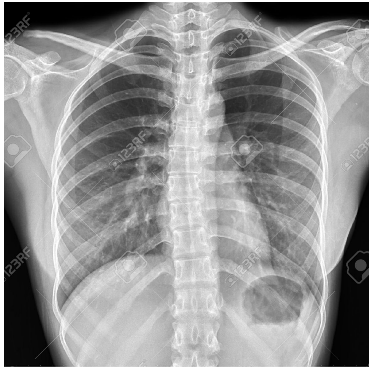
Unlike X-rays, charged particles stop!

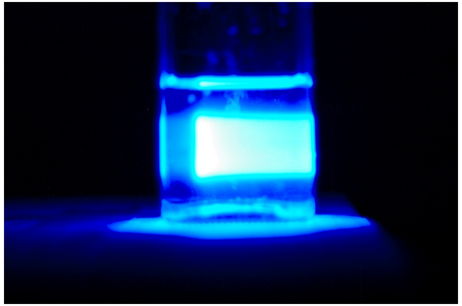
Electrons, being lighter, scatter and spread out.

Protons deposit most dose at the *end* of their path: the ***Bragg Peak*.**

Protons stop, but you need to know where…

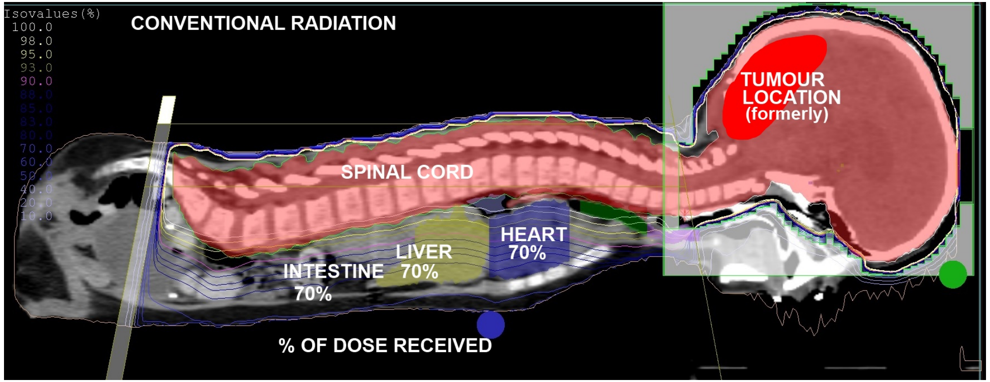




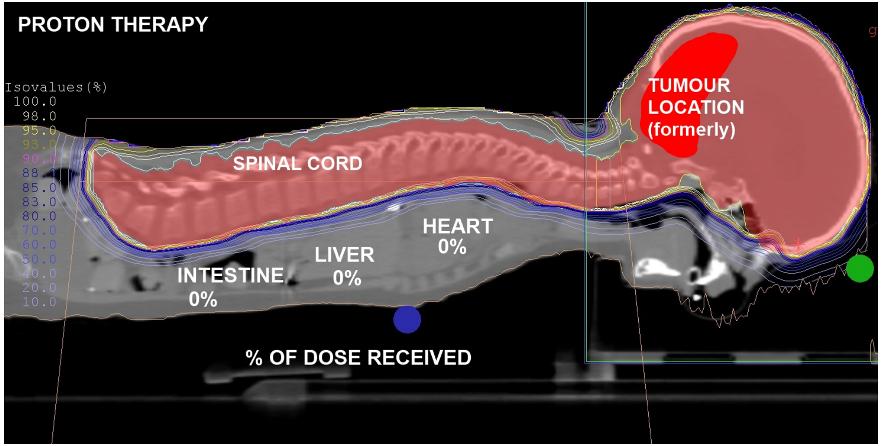


Medulloblastoma Comparison

X-rays



Protons



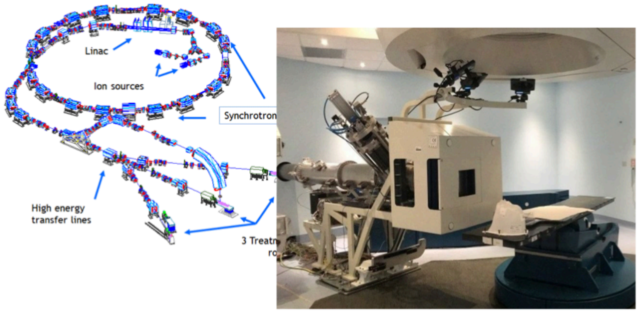
https://www.itnonline.com/content/pediatric-brain-tumor-patient-uk-undergoes-first-treatment-proton-therapy

Radiation detectors for radiotherapy

- **Beam commissioning**
  - Before facility startup
- **Beam monitoring**
  - Online to guide and control the beam delivery
- **Quality Assurance**
  - daily/weekly/monthly
- **Dosimetry**
  - daily
- **Microdosimetry**
- **Radiobiology**

Radiotherapy with external beams

Cyclotron for protons and
Synchrotron for protons&light ions



- Protons (60-250 MeV/u)
- Carbon ions (115-400 MeV/u)

LINAC for radiotherapy

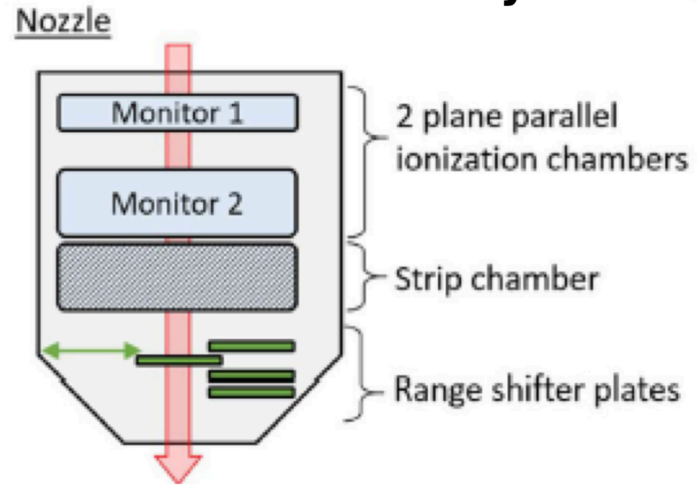
- Photons (6 - 18 MV)
- Electrons (6 - 18 MeV)

https://agenda.infn.it/event/39042 /contributions/222751/attachments/116477/167889/
SiliconDetectorsForMedicalPhysics-Last-spare.pdf

Beam monitors in the nozzle

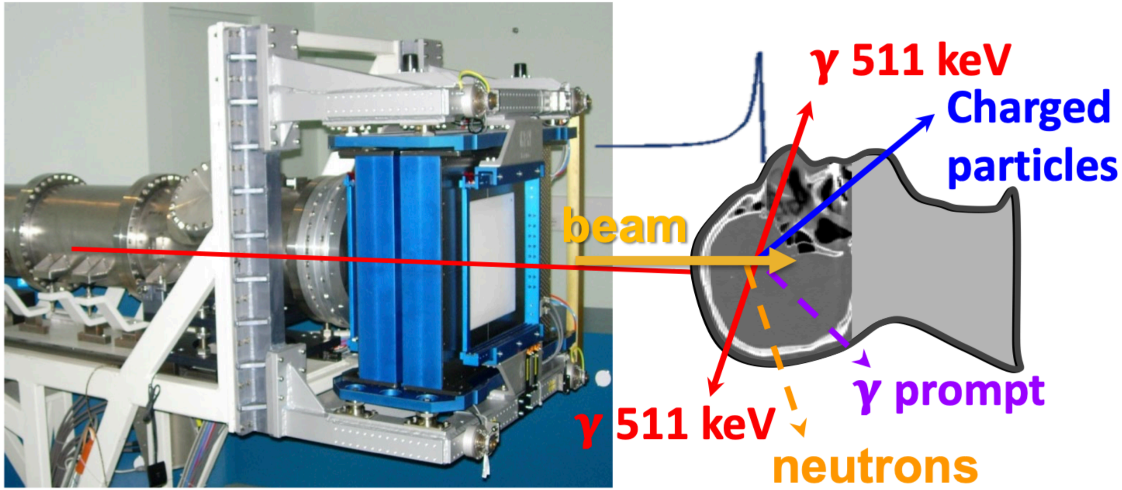
Nozzle equipped with particle detectors integrated with the accelerator control system to **guide and control** the beam in real time.

PSI – Gantry 1



Phys. Med. Biol. 68 (2023) 105013

CNAO horizontal beam line



Nucl. Instr. Met. A 698 (2013) 202

https://agenda.infn.it/event/39042 /contributions/222751/attachments/116477/167889/SiliconDetectorsForMedicalPhysics-Last-spare.pdf

Beam monitor state of the art

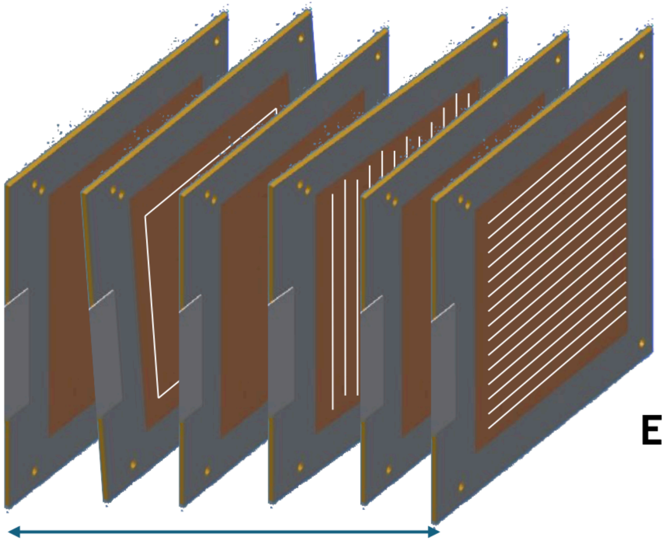
ADVANTAGES

- ✓ Reliability & long term (years) stability
- ✓ Large (up to 40x40 cm^2) sensitive area
- ✓ Simple to use
- ✓ Deeply studied manufacture
- ✓ A few mm water equivalent thickness
- ✓ Radiation resistant

Roadmap: proton therapy physics and biology
Paganetti et al. Phys. Med. Biol. 66 (2021) 05RM01

*"Currently ionization chambers(IC) are predominately used (in fact they **are legally required in most countries**). "*

Sequence of Parallel Plate ICs:
→ single **large** electrode for **FLUENCE**
→ electrodes segmented in strips for **BEAM POSITION and SHAPE**



Gas used:
- Air
- N_2,
- Ar-CO_2

E = 1 kV/cm

Thickness ~ 1 mm of water

https://agenda.infn.it/event/39042 /contributions/222751/attachments/116477/167889/SiliconDetectorsForMedicalPhysics-Last-spare.pdf

Beam monitor state of the art

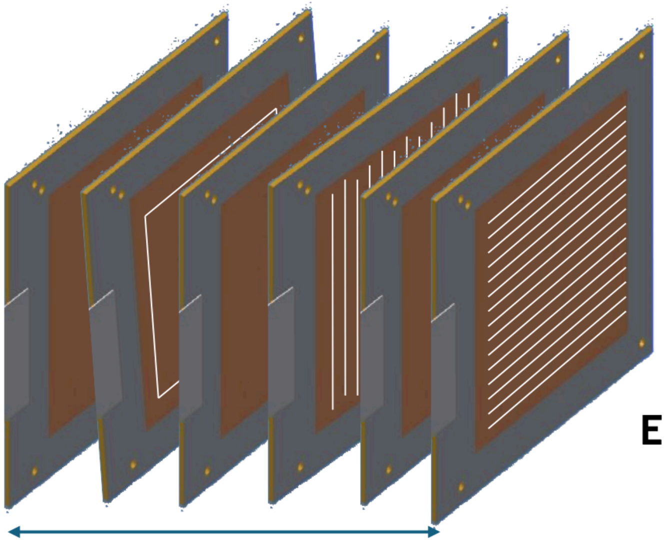
LIMITATIONS

- ✓ **Long collection times ~ 100 μs**
- ✓ **Low Sensitivity ~ 10^4 protons**
- ✓ **Poor time resolution ~ no/poor**
- ✓ **Deviation from linearity @ high dose rates**

Not suitable for
- fast scanning modalities
- timing applications
- high dose rates (FLASH)

required in most countries).

Sequence of Parallel Plate ICs:
→ single **large** electrode for **FLUENCE**
→ electrodes segmented in strips for **BEAM POSITION and SHAPE**



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Proton Beam Quality Assurance

- Accelerators used for proton therapy typically produce protons with energies of 70 to 250 MeV.
- Accurate Quality Assurance is needed to check the beam parameters (dose, position, shape, range) before treatment.

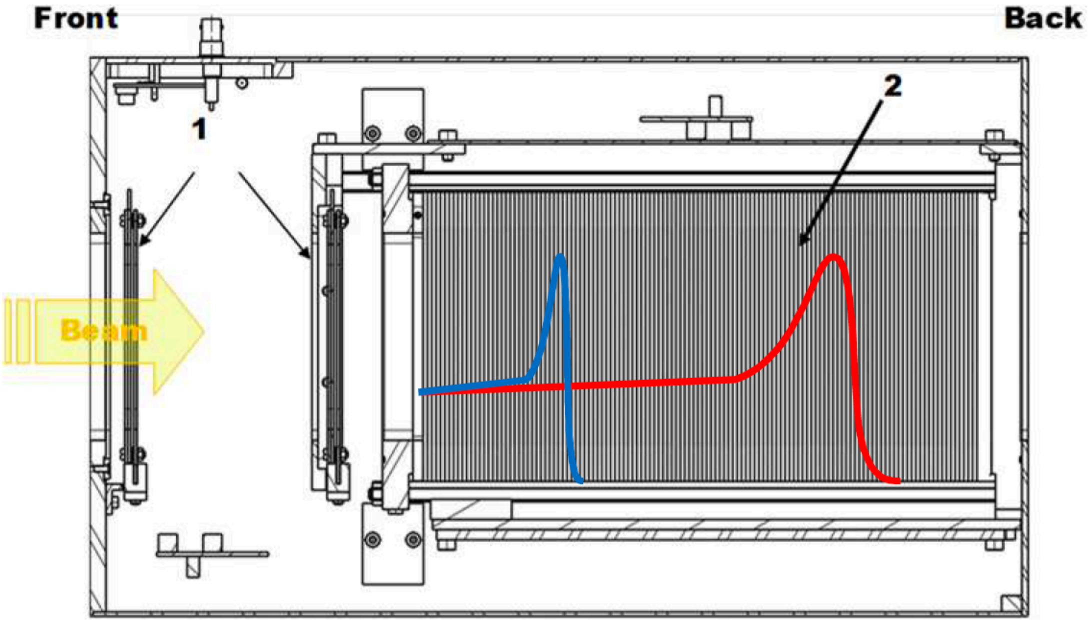
Daily QA checks	
Dosimetry	**Tolerance**
Beam constancy	±3%
Depth verification	±1mm
SOBP width	2mm
Spot position	±1mm
Spot size (monthly checked)	±10%

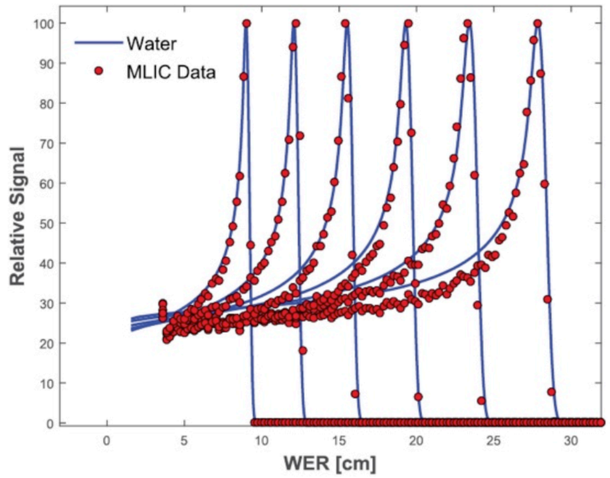
doi.org/10.1002/mp.13622

Daily Range QA @PSI: MLIC

Multilayer ionization chambers (MLICs)

- Reconstruct the Bragg peak using gas detectors
- Ionization chambers (filled with air) in a stack configuration

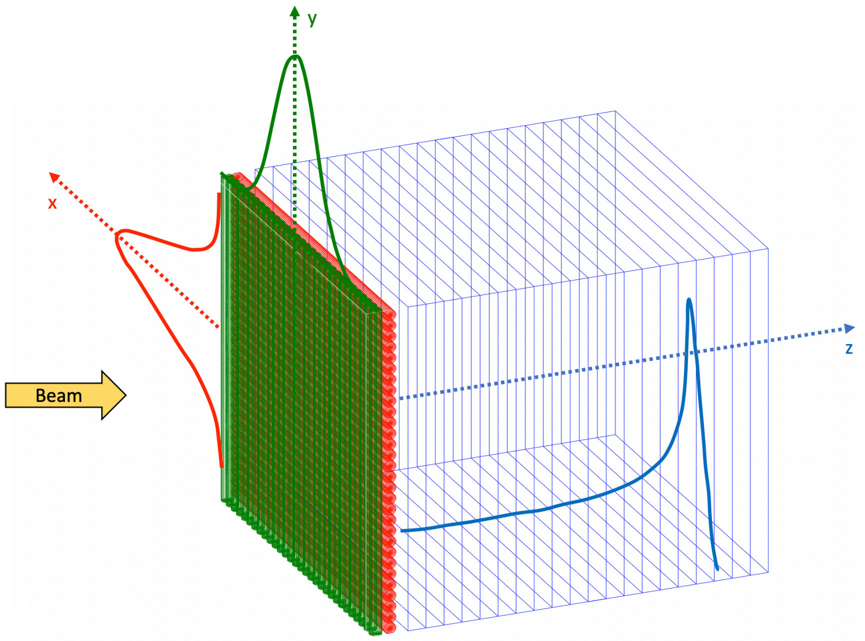




O. Actis *et al.* 2017 *Phys. Med Biol.* **62** 1661

Scintillator-based detector for clinical proton beam QA

Integrated system for range, spot position and size reconstructed with single beam delivery



RANGE MODULE

- stack of plastic scintillator sheets
- reconstruction of the depth-dose beam profile

BEAM TRACKER

- 2D scintillating fibre arrays
- Reconstruction of the transverse beam profiles at the entrance of the detector

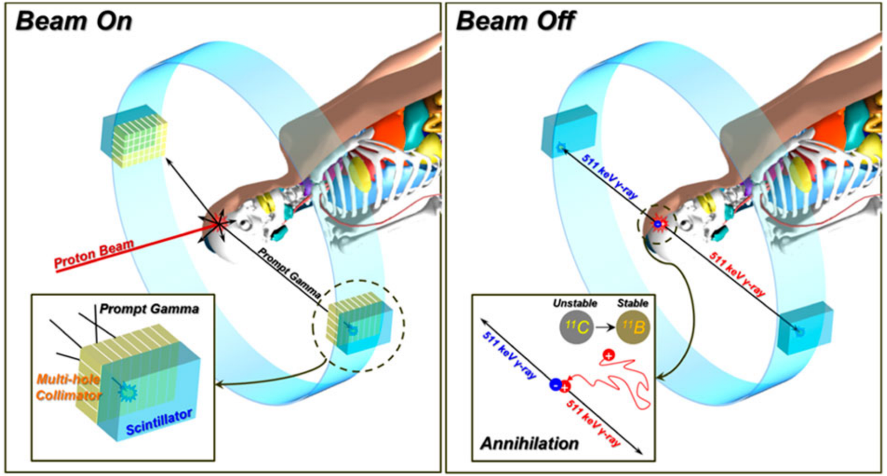
Key benefits:

- Plastic scintillator water-equivalent.
- Easy detector setup and no optical artefacts.
- Light output dose-rate independent.

INFN-FRIDA project

Online treatment monitoring

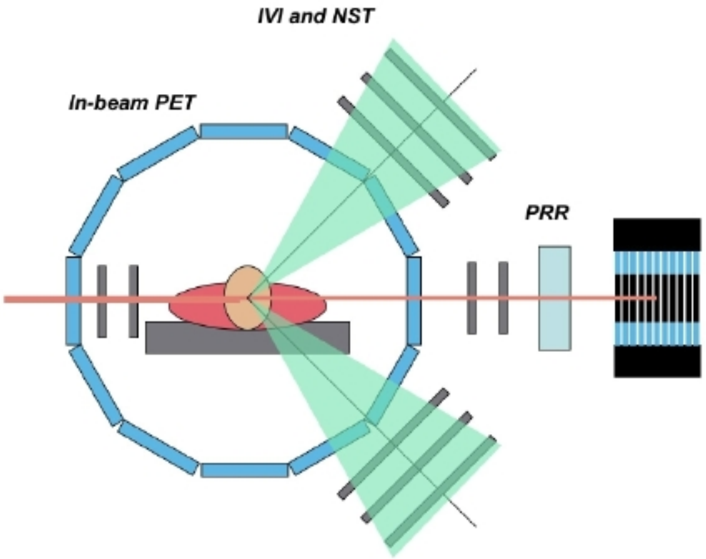
- Treatment sensitive to any source of deviation from the treatment planning.
- During treatments, high energy prompt γ-rays are naturally emitted as a result of proton-nuclear reactions with the patient's tissue.
- Online/Offline treatment monitoring is possible by detecting the secondary radiation emitted along the beam path.



https://www.frontiersin.org/journals/physics/articles/10.3389/fphy.2024.1356572/full

hydrotherapy treatment monitoring

- In-beam (open) PET system
- Proton range radiography (PRR)
- Interaction vertex imaging and nuclear scattering tomography (IVI and NST)

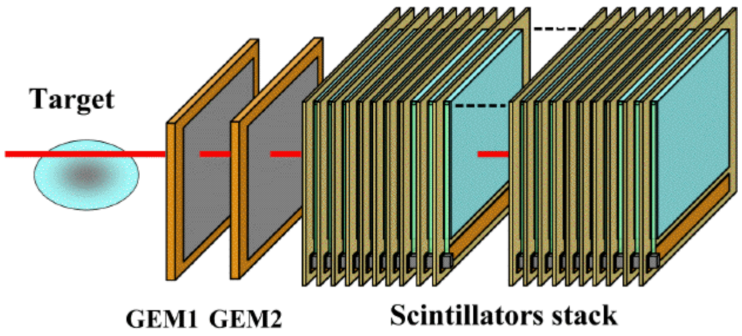


- In-beam PET needs high sensitivity because of the low induced activity when compared to nuclear imaging
- open geometry to avoid interactions with the beam
- Multi-gap Resistive Plate Chambers and multi-layered GEMs considered for superior localization properties and lower cost as alternative to scintillators.
    - low intrinsic efficiency in detecting high-energy photons as to be increased i.e. using high-Z converters (passive or as electrodes)

TERA foundation: https://project-aqua.web.cern.ch/

Proton range radiography

- Proton range telescope measures protons trajectory and residual energy (range)
- could provide a 3D-map of the relative stopping power.



An alternative to scintillators could be the usage of a high-granularity digital tracking calorimeter based on silicon/absorber sandwich

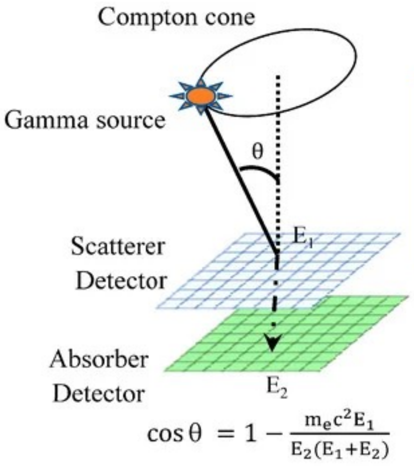
TERA foundation: https://project-aqua.web.cern.ch/
Ref NIM A 732, 564–567, 2013

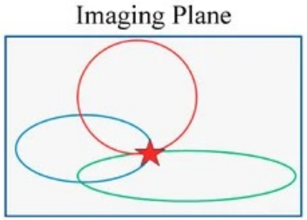
Compton Chamber

Two position- and energy-sensitive sub-detectors: scatterer and absorber

A γ undergoes a Compton scattering in the first detector and is then absorbed in the second detector

- Direction of the γ is not univocally determined (cone)
- Many γ from the same source point are needed to reconstruct the source position





Compton cones superimpose to estimate gamma source

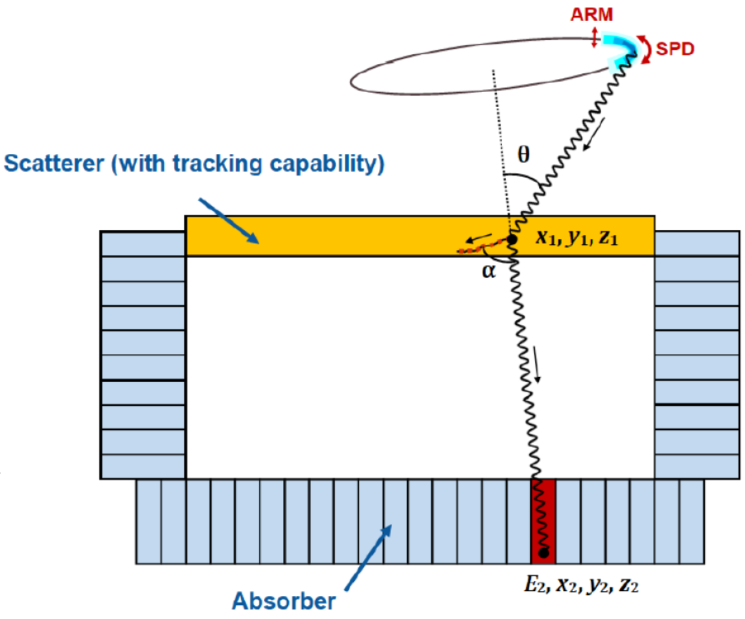
For online treatment plan verification, it is needed an high-resolution imaging of gamma sources within few seconds:

- conventional Compton chamber do not yet allow an on-line monitoring

Electron Tracking Compton Chamber

Pixel Chamber as the scatterer

- The Pixel Chamber is a stack of thin pixel detectors capable of tracking the emitted electron
- This can constrain the original direction using a single photon reducing the background, the number of gamma required for performing precise source imaging and acquisition time.



A first prototype of Pixel Chamber is proposed considering state-of-the-art monolithic active pixel sensors, the ALPIDE sensor developed for the ITS of the ALICE experiment at the CERN LHC

Conclusions

“The significant advances achieved during the last decades in material properties, detector characteristics and high-quality electronic system played an ever-expanding role in different areas of science, such as high energy, nuclear physics and astrophysics. And had a reflective impact on the development and rapid progress of radiation detector technologies used in medical imaging.”

[D. G. Darambara, “State-of-the-art radiation detectors for medical imaging: demands and trends”, Nucl. Inst. And Meth. A 569 (2006) 153-158]