Photon detectors in Medical Imaging

Gabriela Llosá

Instituto de Física Corpuscular - IFIC (CSIC-UV), Valencia, Spain

IRIS group **http://ific.uv.es/iris**

RD51 Academia-Industry Matching Event

Special Workshop on Photon Detection with MPGDs

CERN, Geneva, 10-11 June 2015

Outline

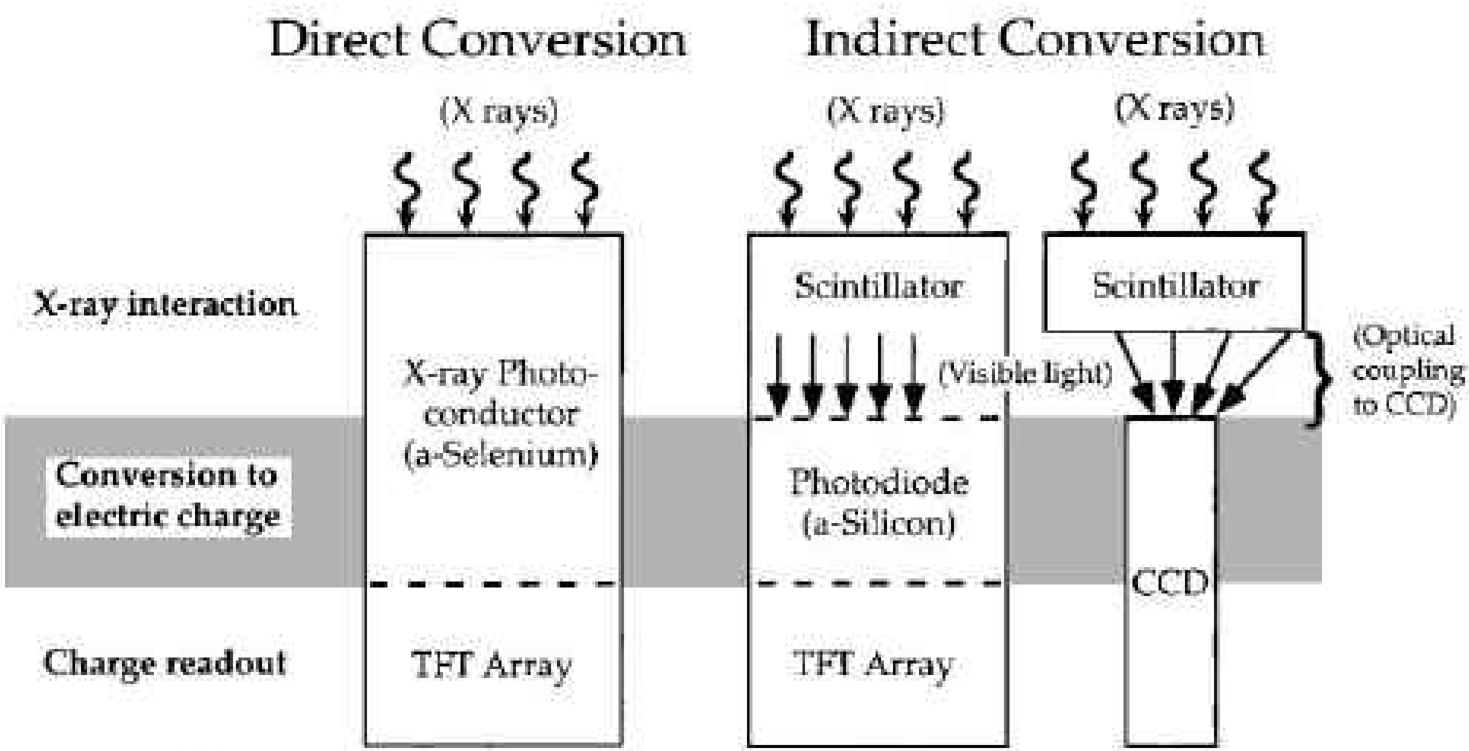
- Detectors for medical imaging:
  - X-rays. CT.
  - Positron Emission Tomography (PET)
  - SPECT
- Detectors in radiotherapy and hadron therapy:
  - Dosimetry in conventional radiotherapy → Talk by G. Claps.
  - Monitoring dose deposition in conventional radiotherapy.
  - Beam monitoring in hadron therapy.
  - Treatment monitoring in hadron therapy.

Detectors for medical applications

- Scintillators + photodetectors:
  - Very good performance at affordable cost.
  - Easy to use. Improved performance with SiPMs.
  - Dominate the market, in particular for clinical devices.
- Solid state detectors: CZT, CdTe → Dedicated systems
  - Excellent performance in some aspects (efficiency, energy and spatial resolution), at high cost.
  - Still not perfect uniformity. Worse timing resolution.
  - Small detectors: portable gamma cameras, small animal PET.
- Gaseous (liquid) detectors:
  - Lower efficiency. Timing?
  - Low cost. Good for large areas (whole body)?
  - Difficult segmentation for very high resolution.

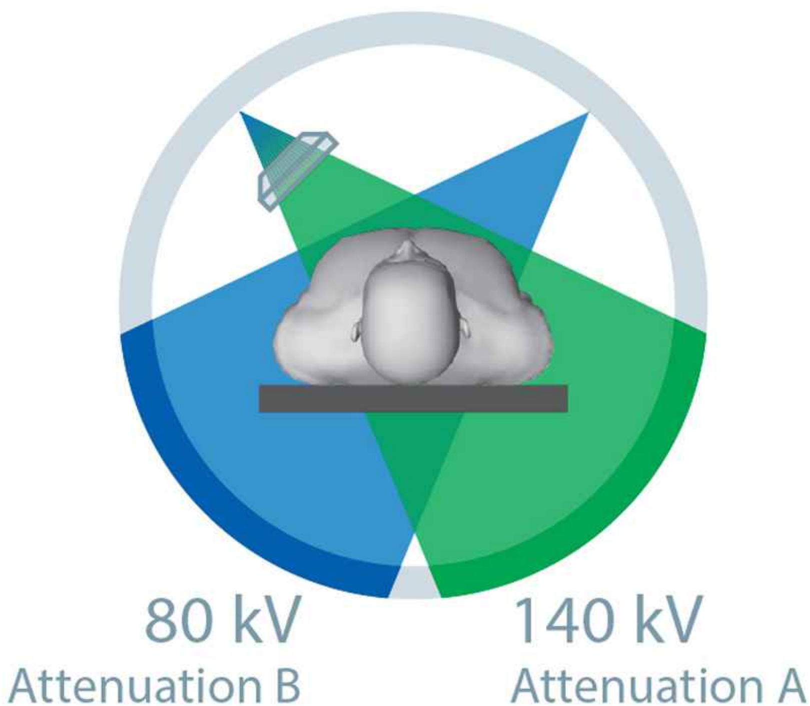
X-rays

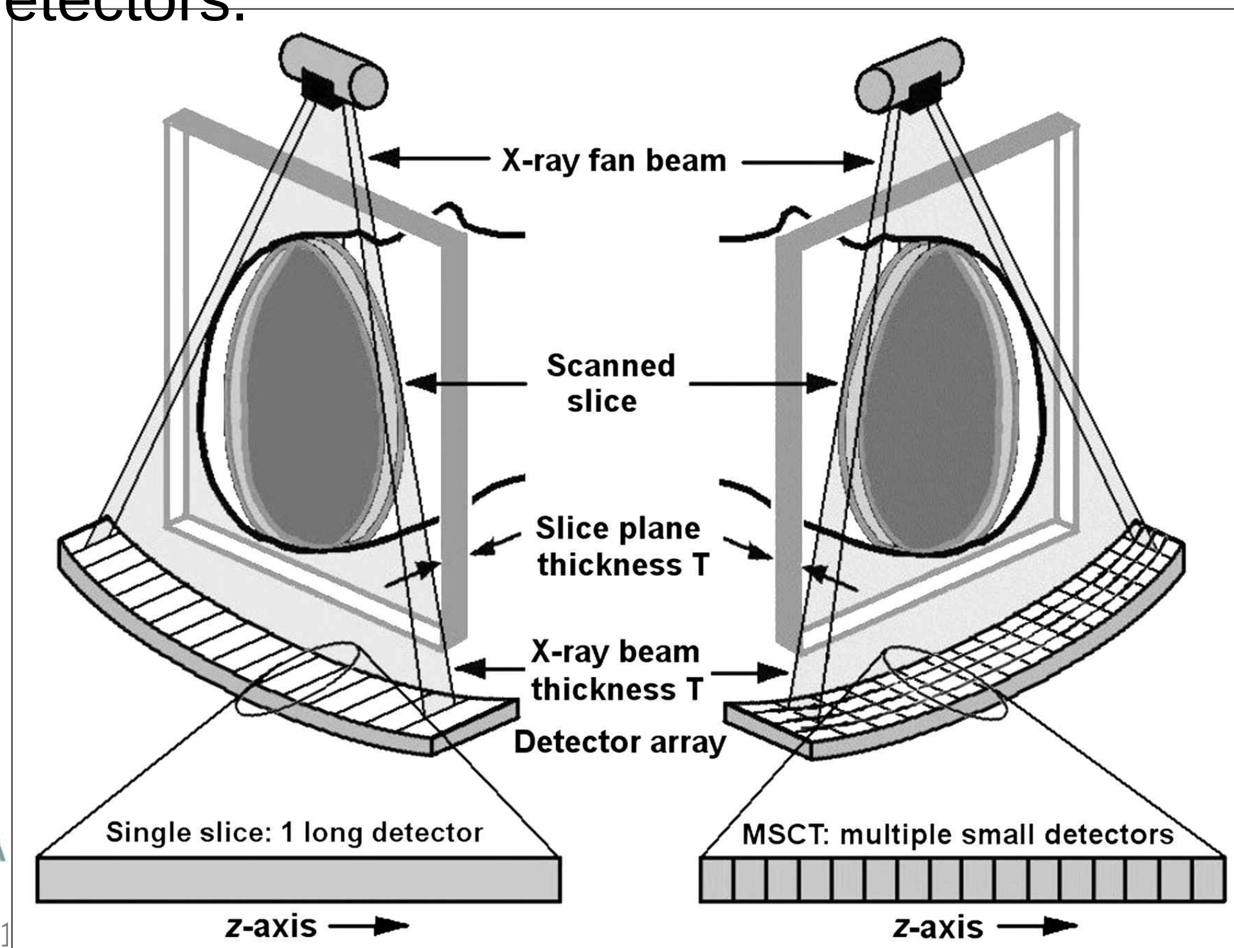
- Radiography. Film-> Flat panel better efficiency.
- High resolution, low noise, large dynamic range and fast processing.
  - scint+photodetector: CsI,Gd_2O_2S + aSi-TFT or CCD.
  - Direct semiconductor: a-Selenium



Computed Tomography

- Cone beam, helical acquisition.
- Fast (fraction of a second).
- Dual X-ray source,
- Wide, multislice detectors.
- Dose





Computed Tomography

- Ionization chambers → scintillator detectors

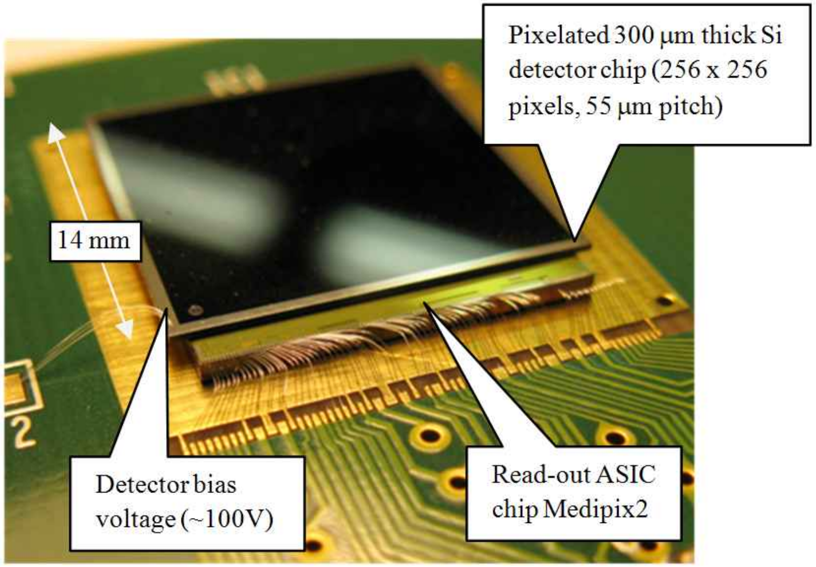
High pressure Xe ionization chambers	scintillator crystals (CsI or $CdWO_4$) or UFC Ultra-fast ceramics (Gd_2O_2S)
• Lower efficiency but low dead area • Simple construction • Uniform response • Difficult for multi-row	• UFC decay time ~ 10^{-6}. • Better performance than Xe. • Multi-row

Computed Tomography

- Preclinical: longer acquisition times > 30 s
  - Direct conversion detectors can be appropriate.
  - CdTe, CZT, HgI2, best candidates.
- Single photon counting (instead of current integrating mode) + energy discrimination.
  - Measures each x-rays and bins by energy
  - Larger dynamic range + additional info in data
- Lower dose (or higher speed) and better soft tissue contrast.

Medipix

- CMOS pixel detector readout chip designed to be connected to a segmented semiconductor sensor.
- X-ray imaging is the primary application field.
- Higher dynamic range and energy sensitivity



"Medipix 2 assembly" by IEAP-CTU in Prague, Czech Republic.

"Ground beetle" by IEAP-CTU in Prague and Centre of Excellence Telč, Czech Republic

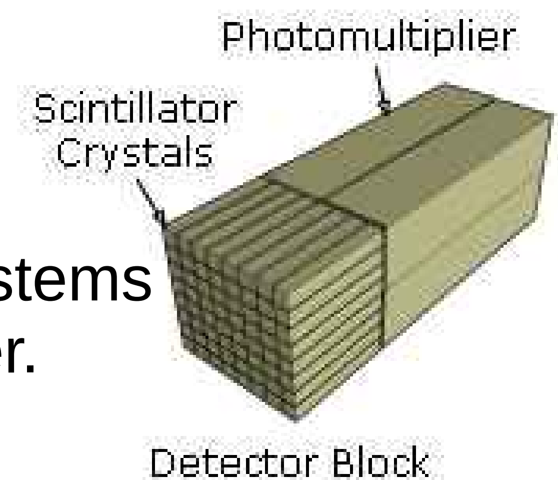
http://medipix.web.cern.ch/medipix/

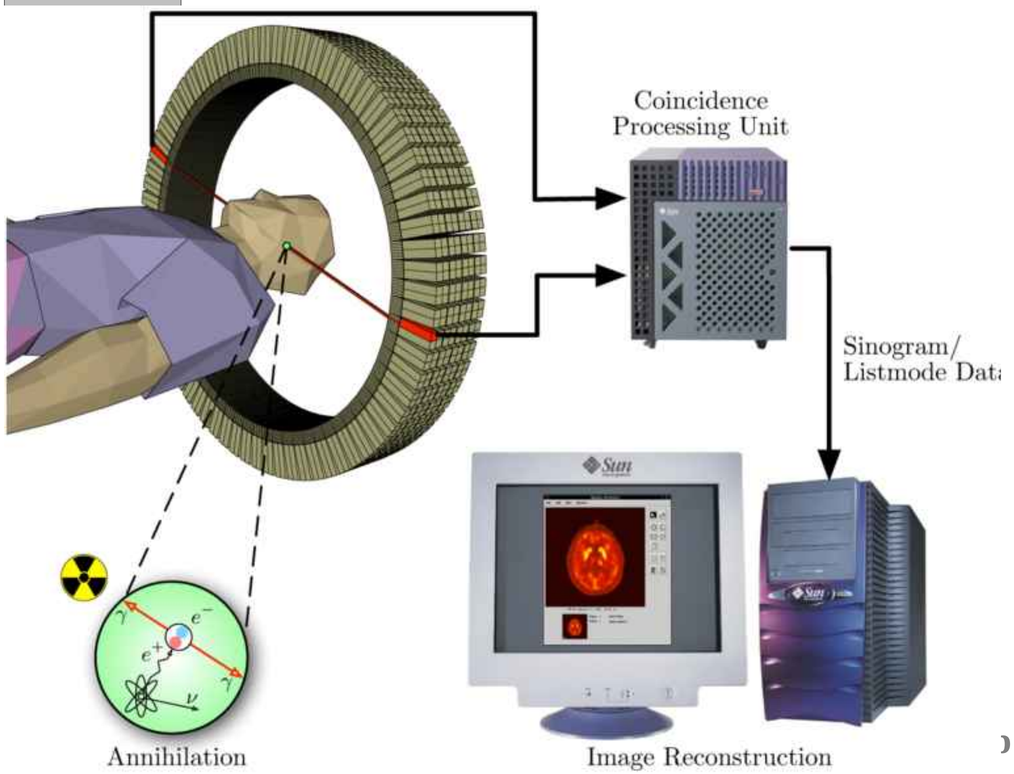
Positron Emission Tomography

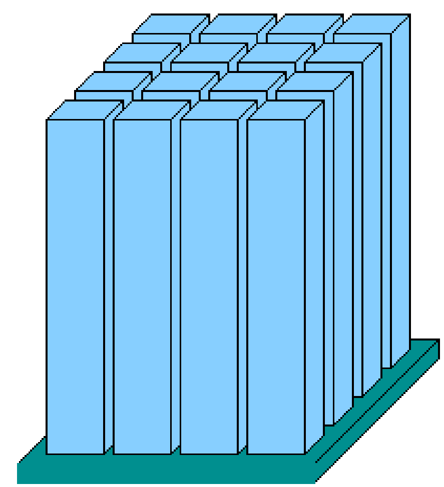
- Depth Of Interaction (DOI)
- Time-Of-Flight
- PET-MR

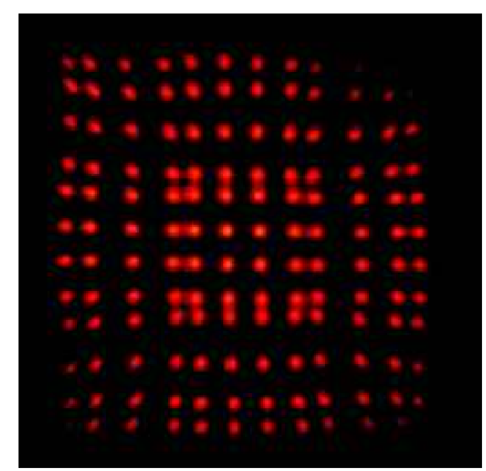
  SiPMs!!
- Dedicated/animal systems with solid state / other.

Conventional PET detector



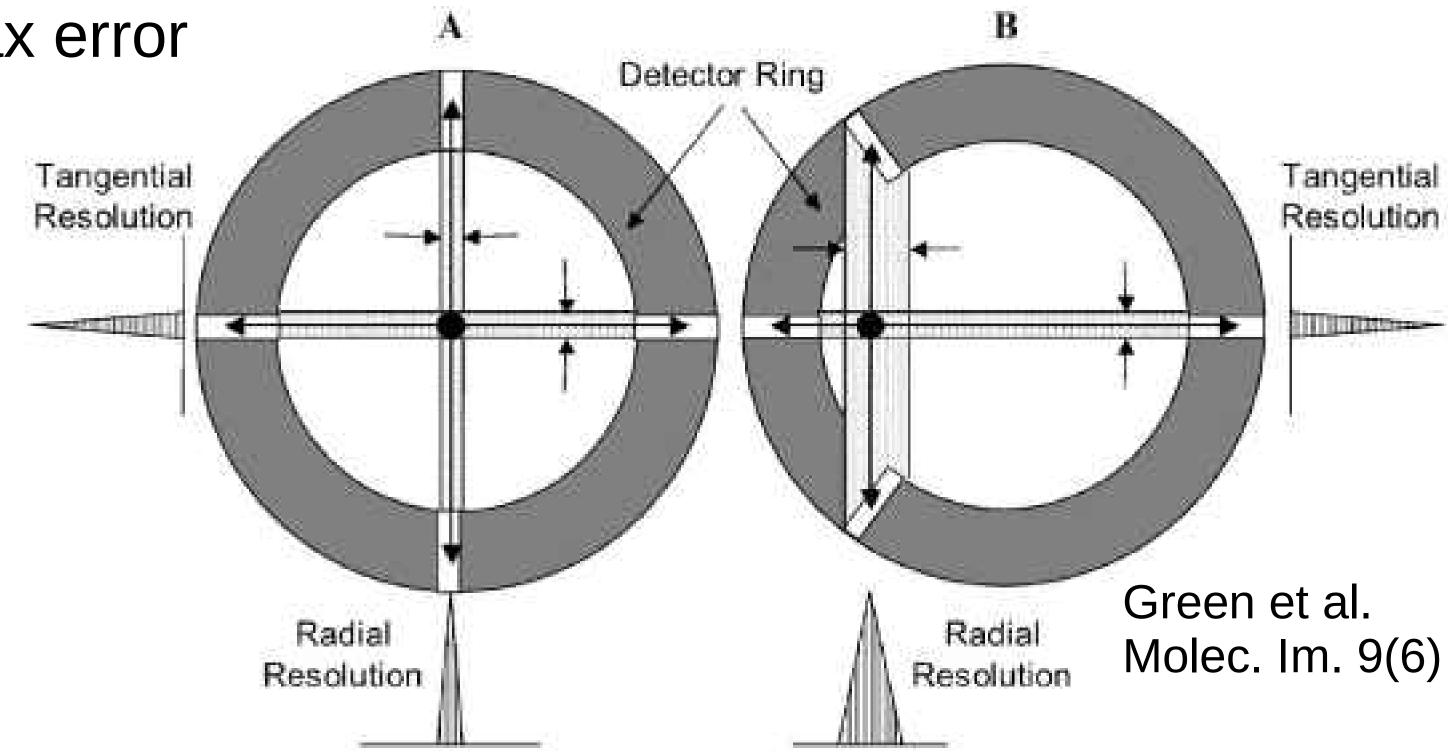




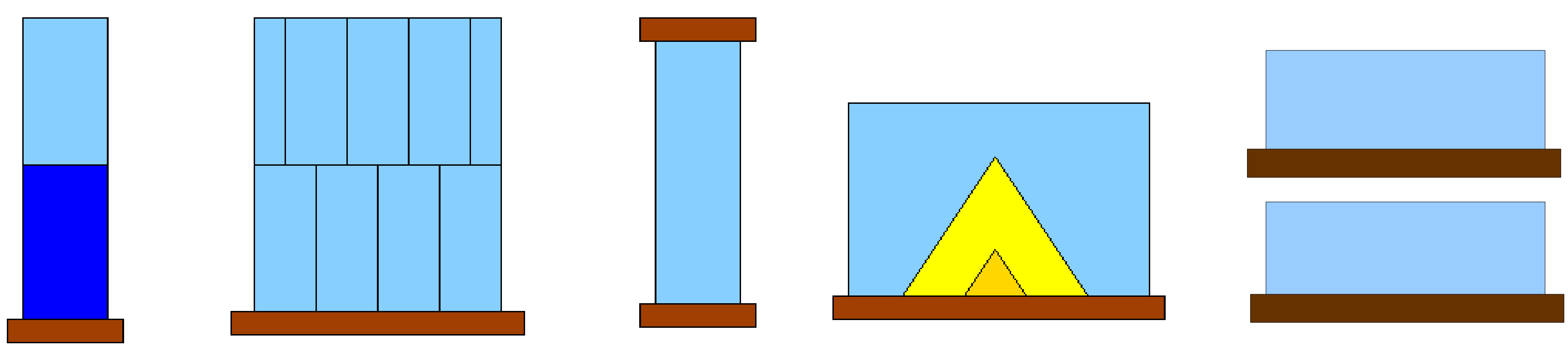


Depth Of Interaction (DOI) determination

Parallax error

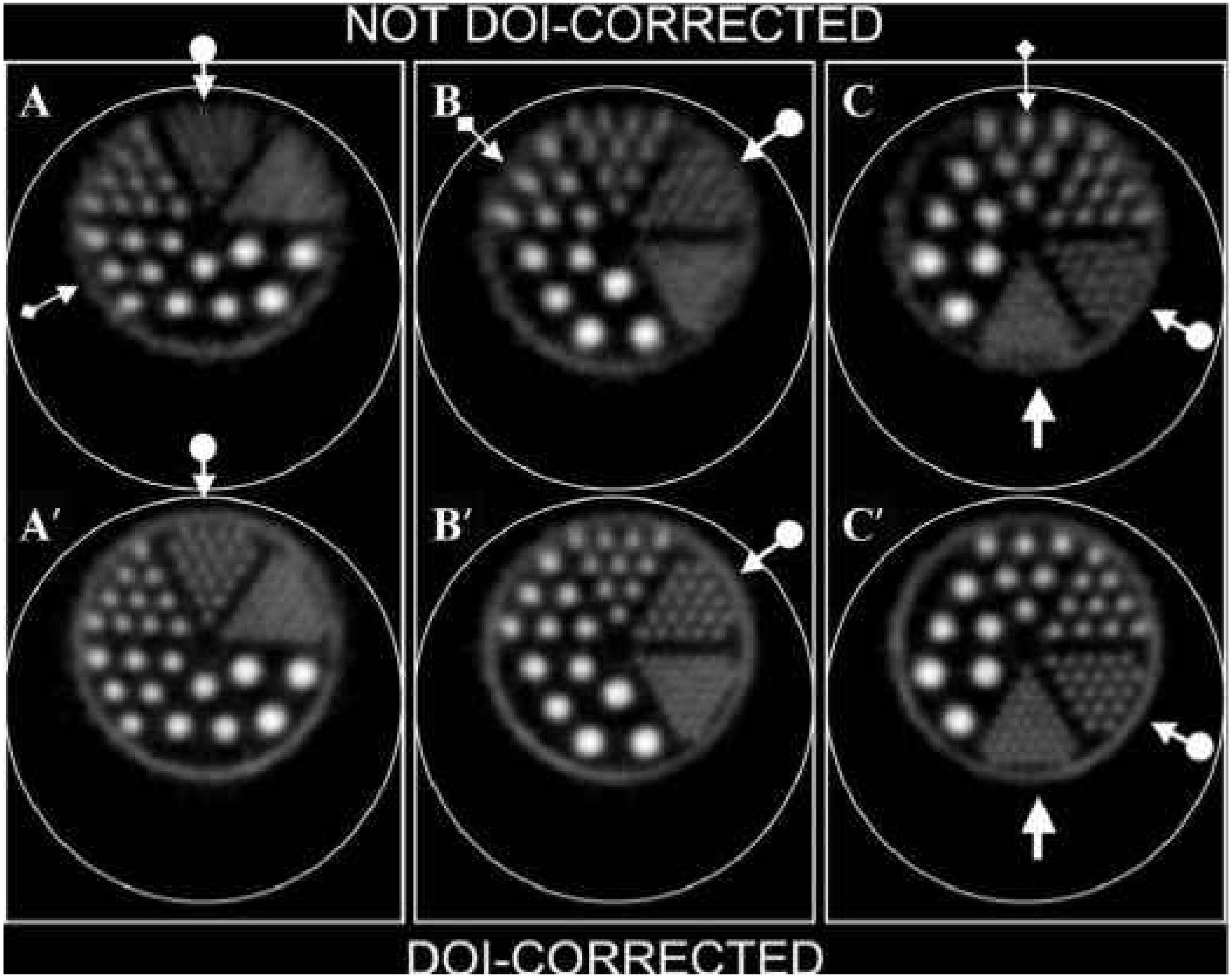


Green et al.
Molec. Im. 9(6) 2010

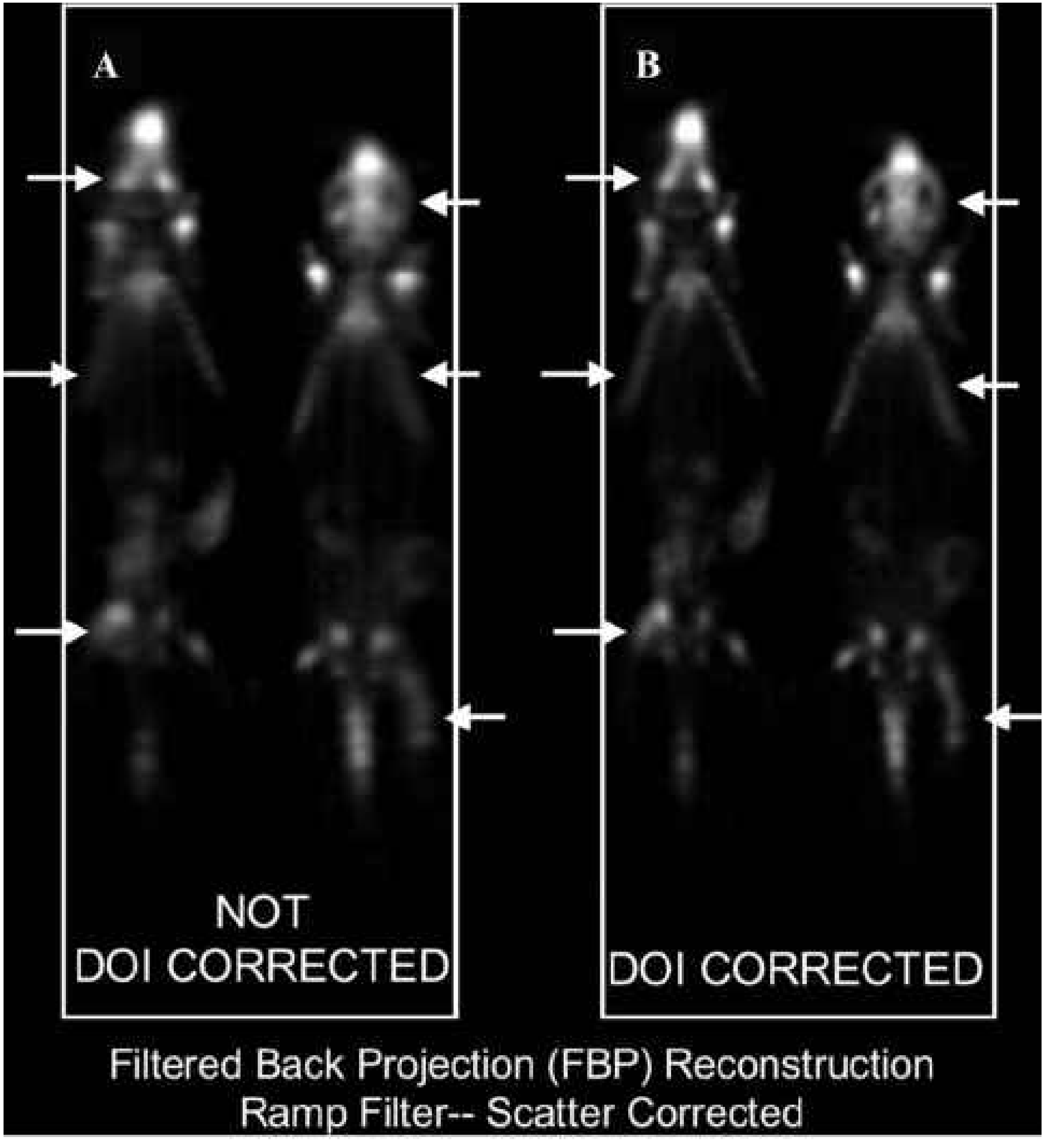


DOI determination

Green et al.Molec. Im. 9(6) 2010



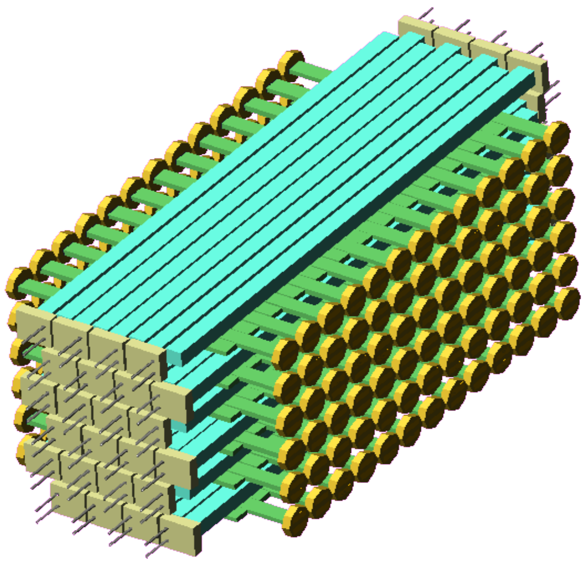
DOI determination



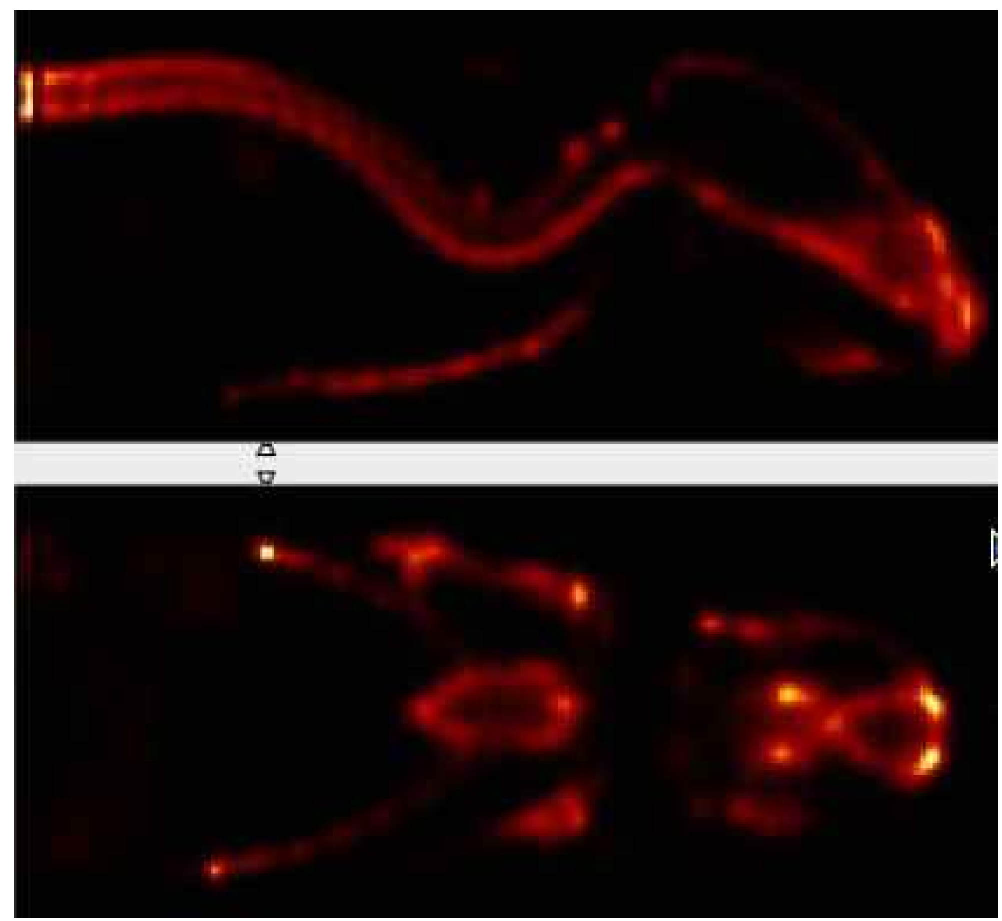
Green et al.
Molec. Im. 9(6) 2010

DOI determination

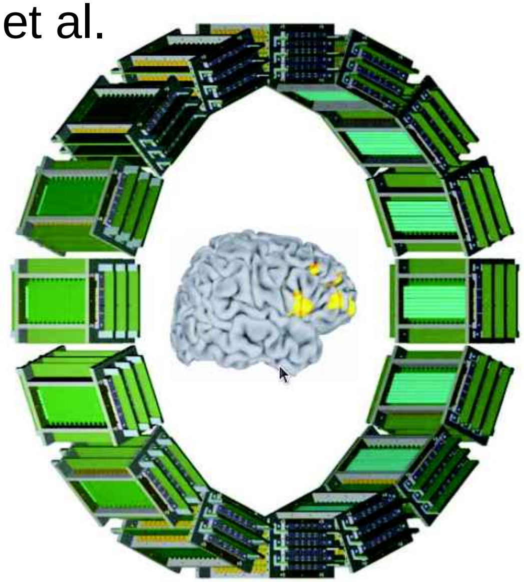
- AX-PET working prototype



E. Bolle et al. 2013 IEEE
NSS MIC Conf Rec. M03-2.



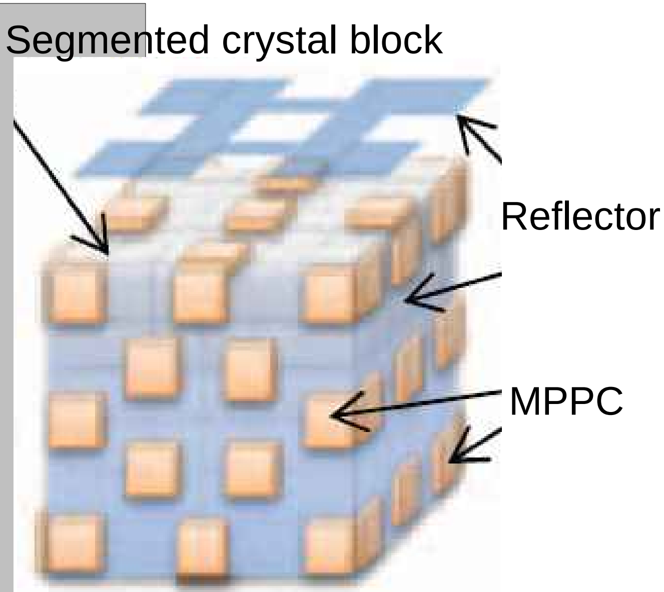
P. Beltrame et al.
NIMA 2011

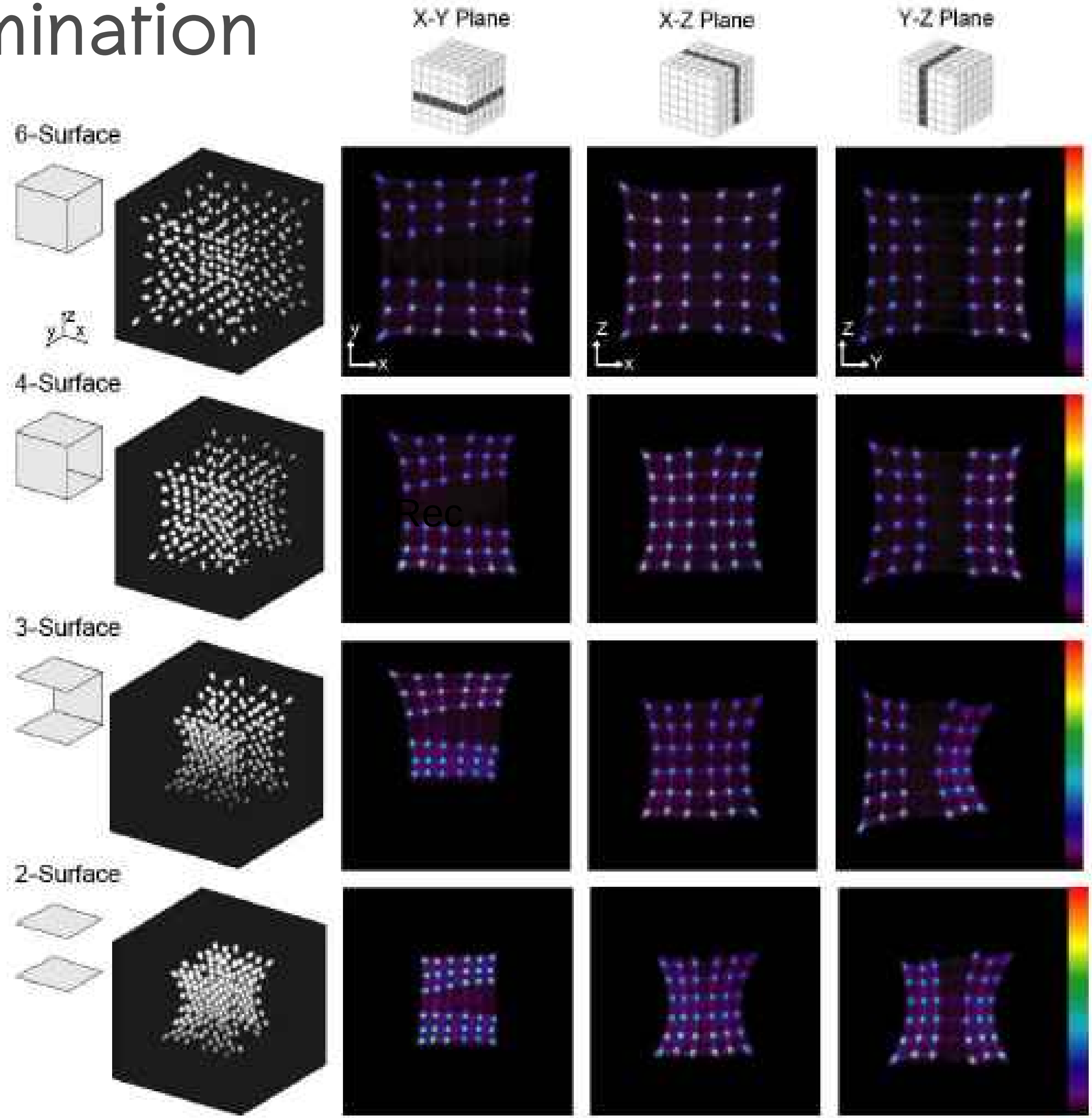


DOI determination

X'tal cube

3D position determination



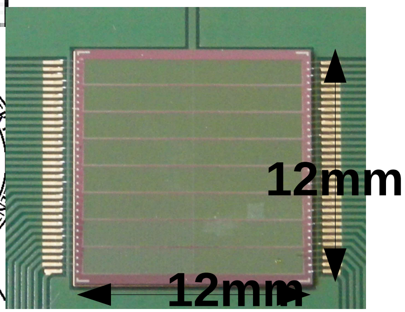


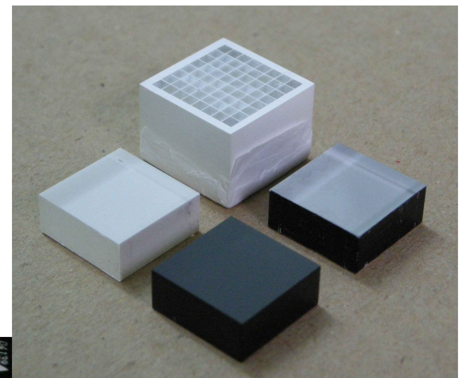
Y. Yazaki et al. 2009 IEEE NSS MIC Conf Rec

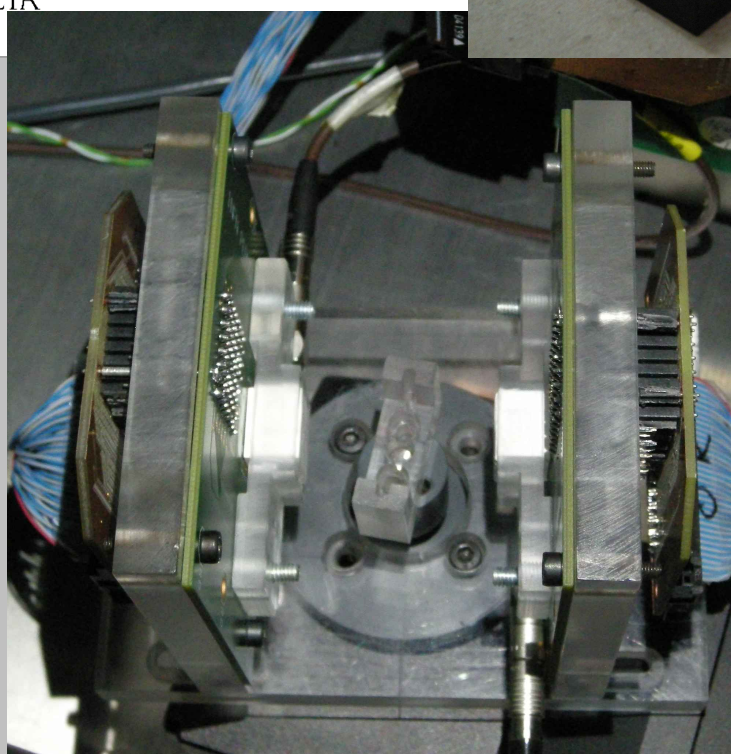
3D in continuous crystals

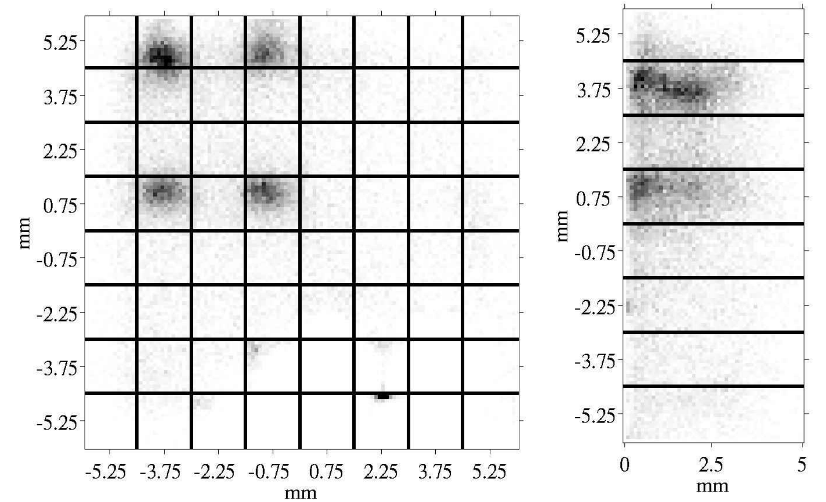
Continuous LYSO crystals 12 x 12 x 5/10 mm^3

SiPM arrays 1.4 x 1.5 mm pitch

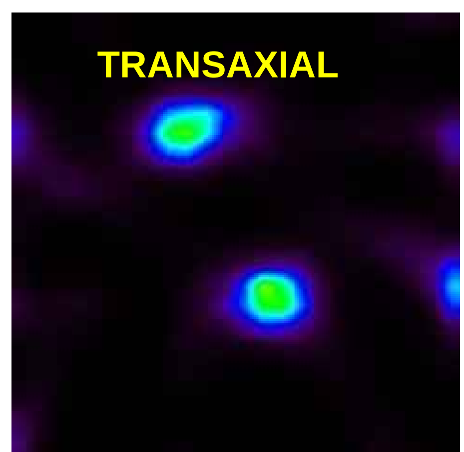








Intrinsic resolution
0.7 mm FWHM in X-Y
2 mm in DOI.

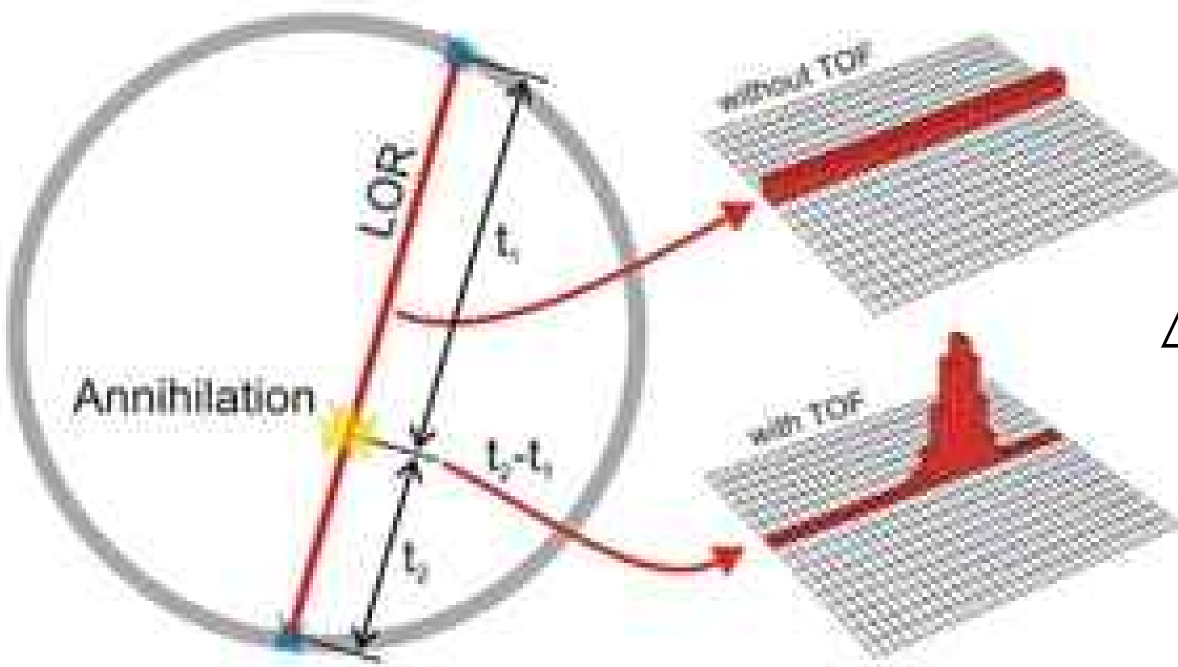


Images FWHM better than 1 mm

Llosá et al. NIM A 2012

Time of Flight PET

- Good timing resol. allows to reject accidental coincidences
- Very good: TOF-PET.



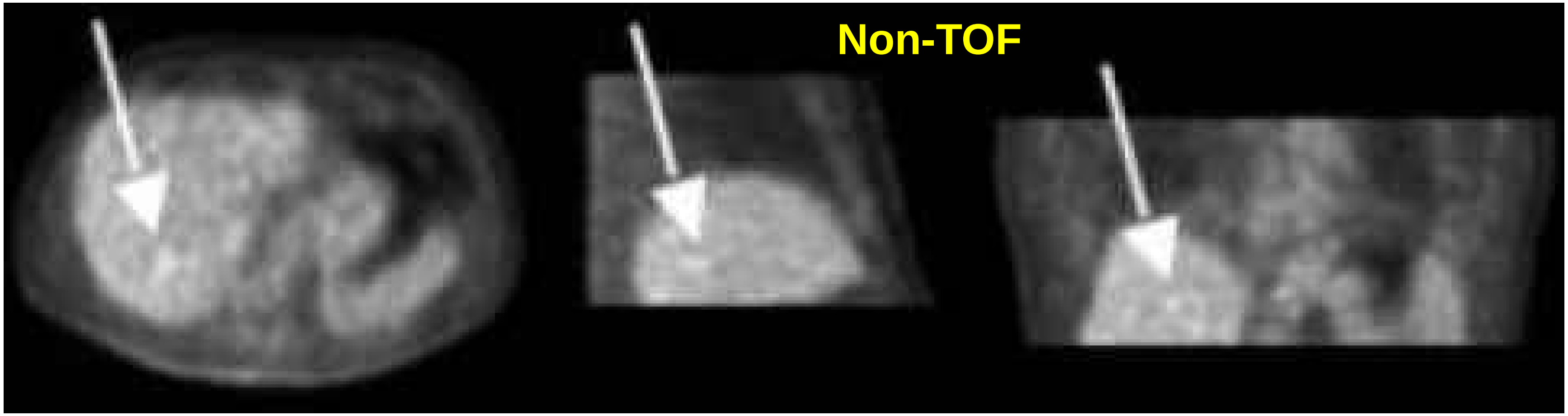
$$\Delta d = \Delta t \times \frac{c}{2}$$

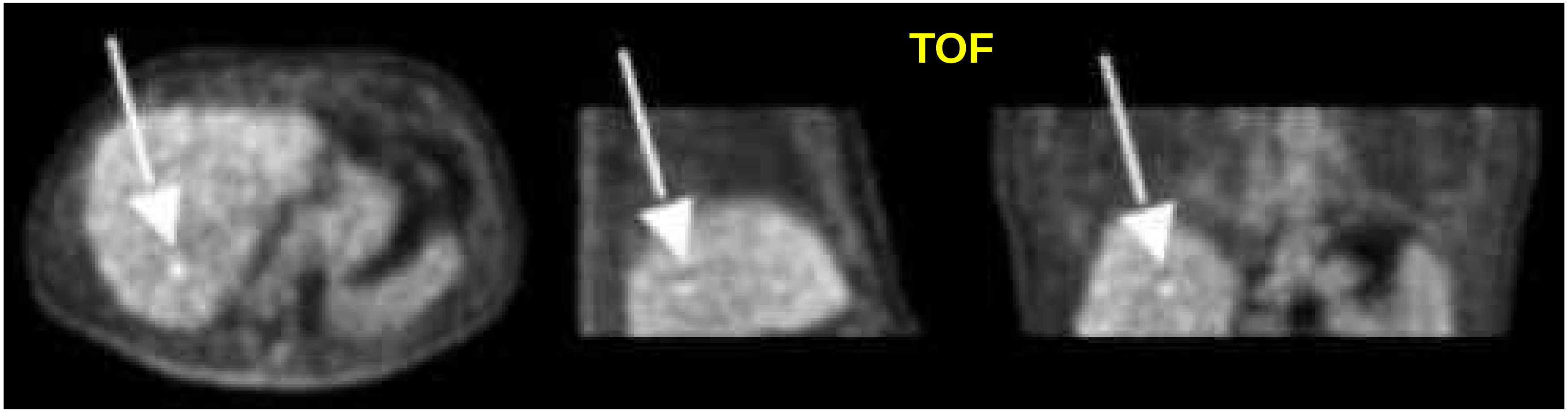
Commercial systems: coincidence timing resolution
~ 500 ps FWHM

TOF-PET

Surti et al.
J Nucl Med 52(5). 2011

- Liver lesion





- Photodetectors: PMTs, MCPs, SiPMs, DSiPMs

TOF-PET

- Research results beter than 200 ps with small crystals

101 ps FWHM with

- $LaBr_3$:Ce crystals
  3 x 3 x 5 mm^3
- Hamamatsu MPPCs $3x3mm^3$, 50 x 50μm^3 microcells
- Own electronics

D. Schaart et al, PMB 2010

170 ps FWHM with

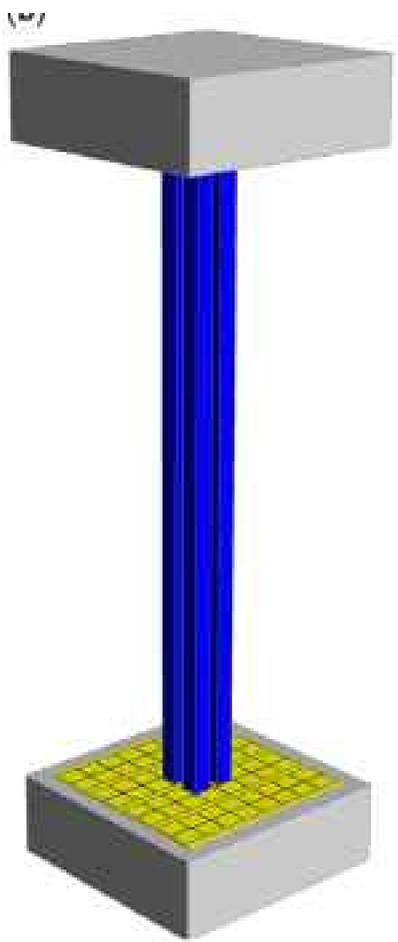
- LSO_3:CeCa crystals 2 x 2 x 20 mm^3
- Hamamatsu MPPCs $3x3mm^3$, 50 x 50μm^3 microcells
- NINO ASIC

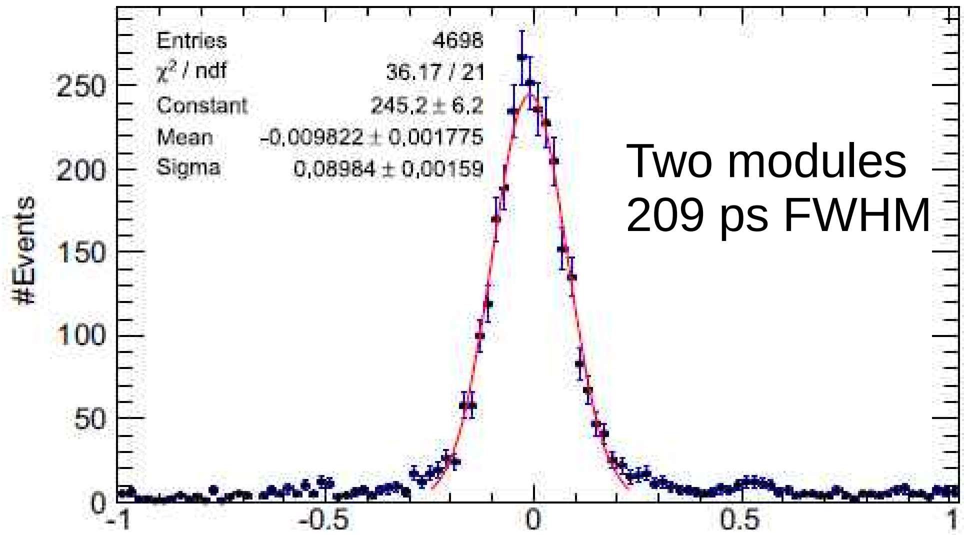
E. Auffray et al, 2011 IEEE NSS MIC CR

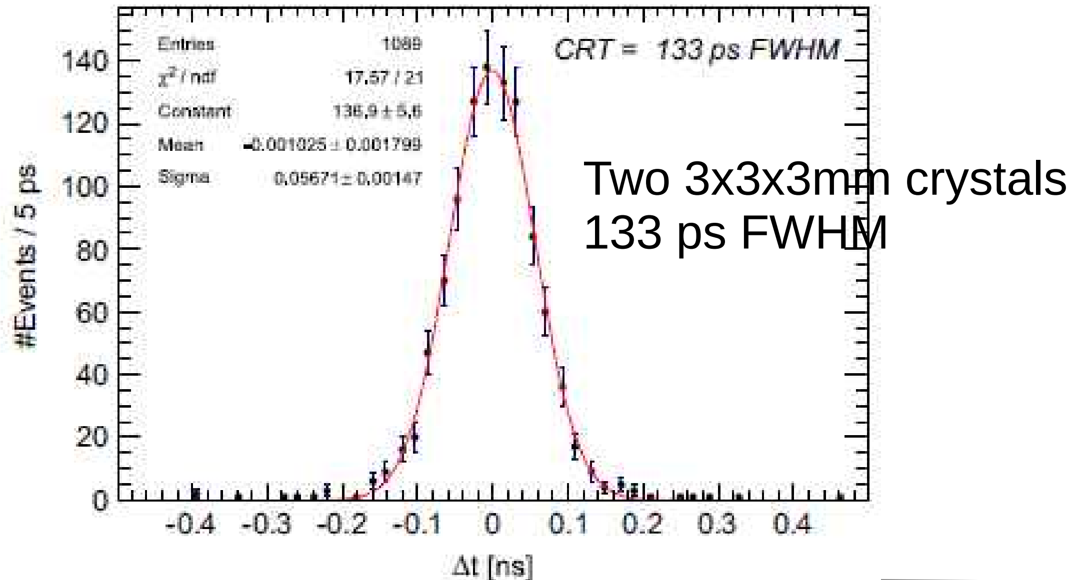
TOF-PET

Casella et al. NIMA 736, 2014

- Module: four 100 mm LYSO crystals coupled to dSiPMs on both sides

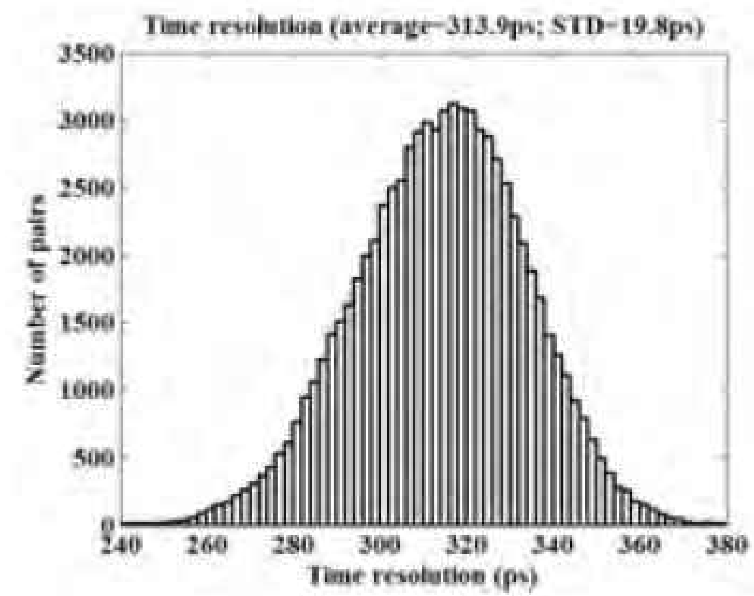




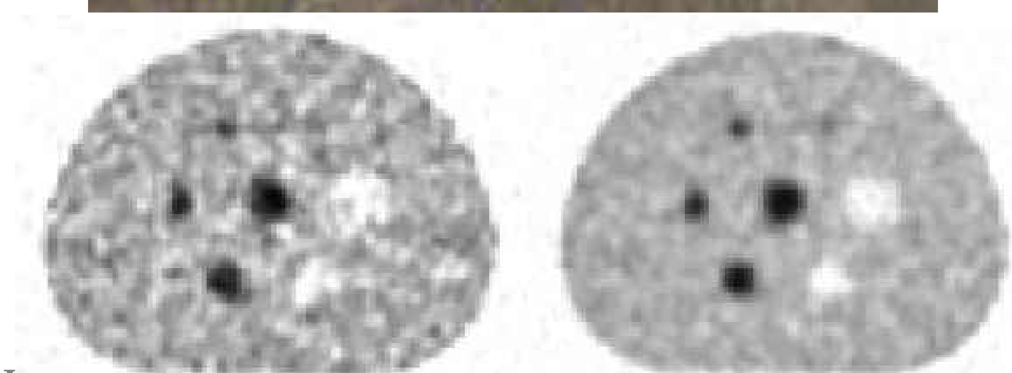


TOF-PET

- Full ring with PMTs. 76.6 cm diameter. 192 detector modules, 384 scintillator crystals.



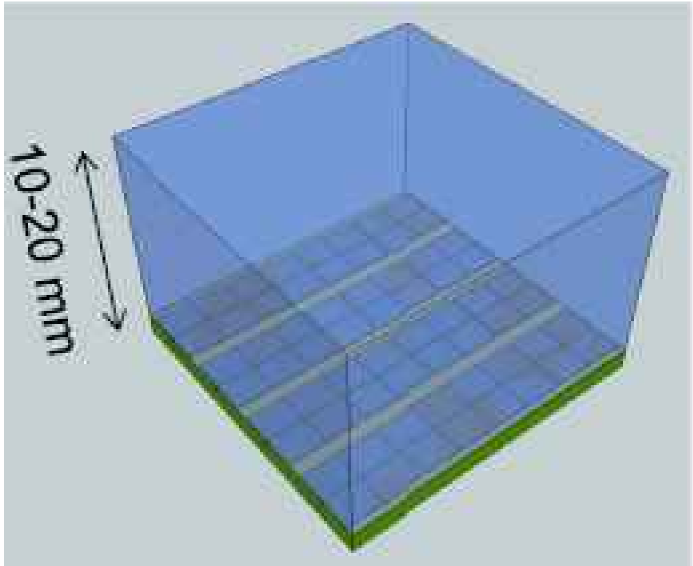
System timing resolution
314 ± 20 ps FWHM



Q. Peng et al.
2103 IEEE NSS MIC M11-1

TOF-PET

- Monolithic LYSO crystals + dSiPMs

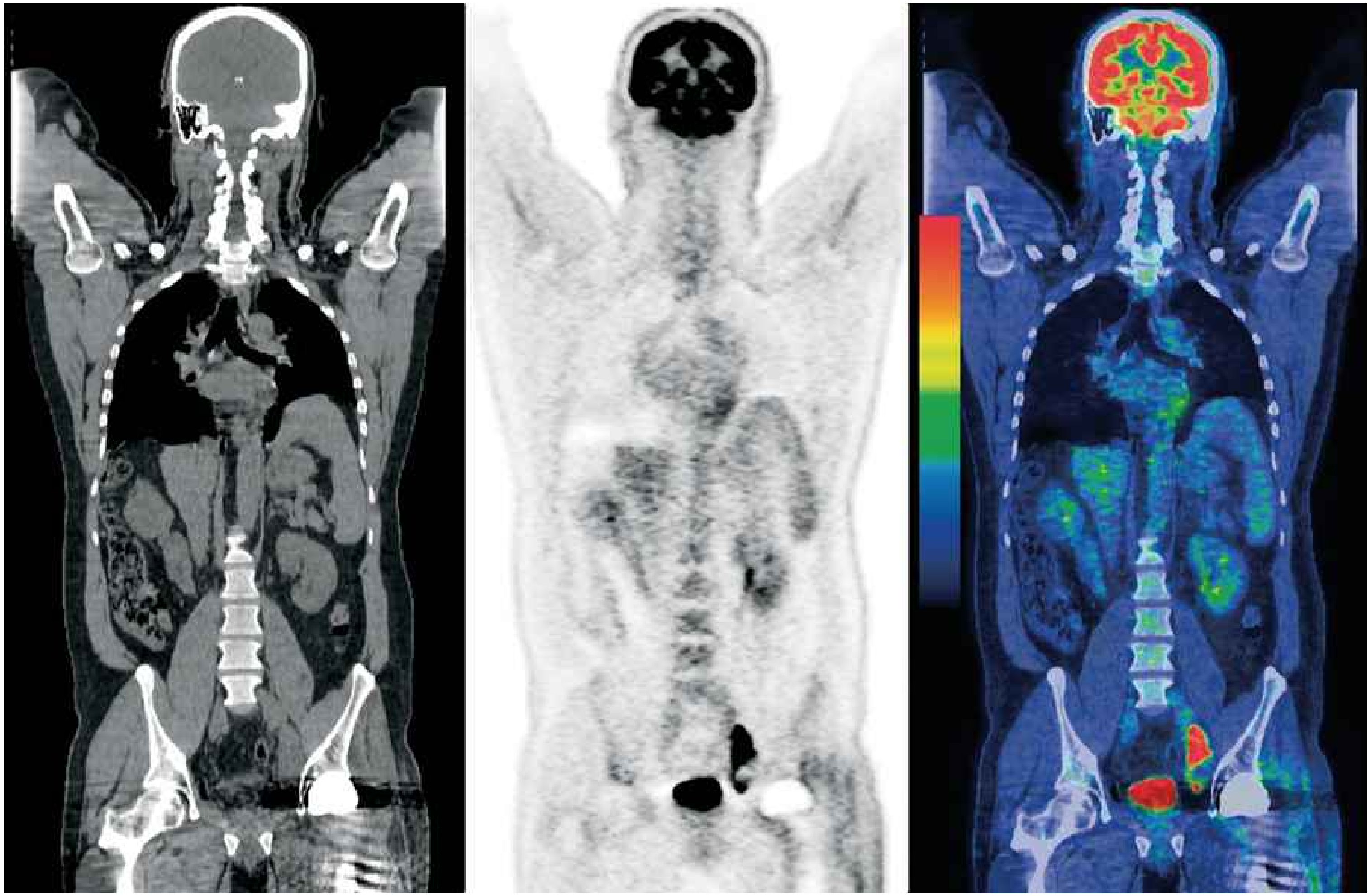


D. Schaart.
ICTR-PHE 2014

Performance parameter		Monolithic	State of the art
Energy resolution	(% FWHM)	**11 - 12**	~12
Spatial resolution	(mm FWHM)	**1.0 - 1.6**	4 - 6
DOI resolution	(mm FWHM)	**3 - 5 mm**	None
CRT	(ps FWHM)	**160 - 185**	500 - 650

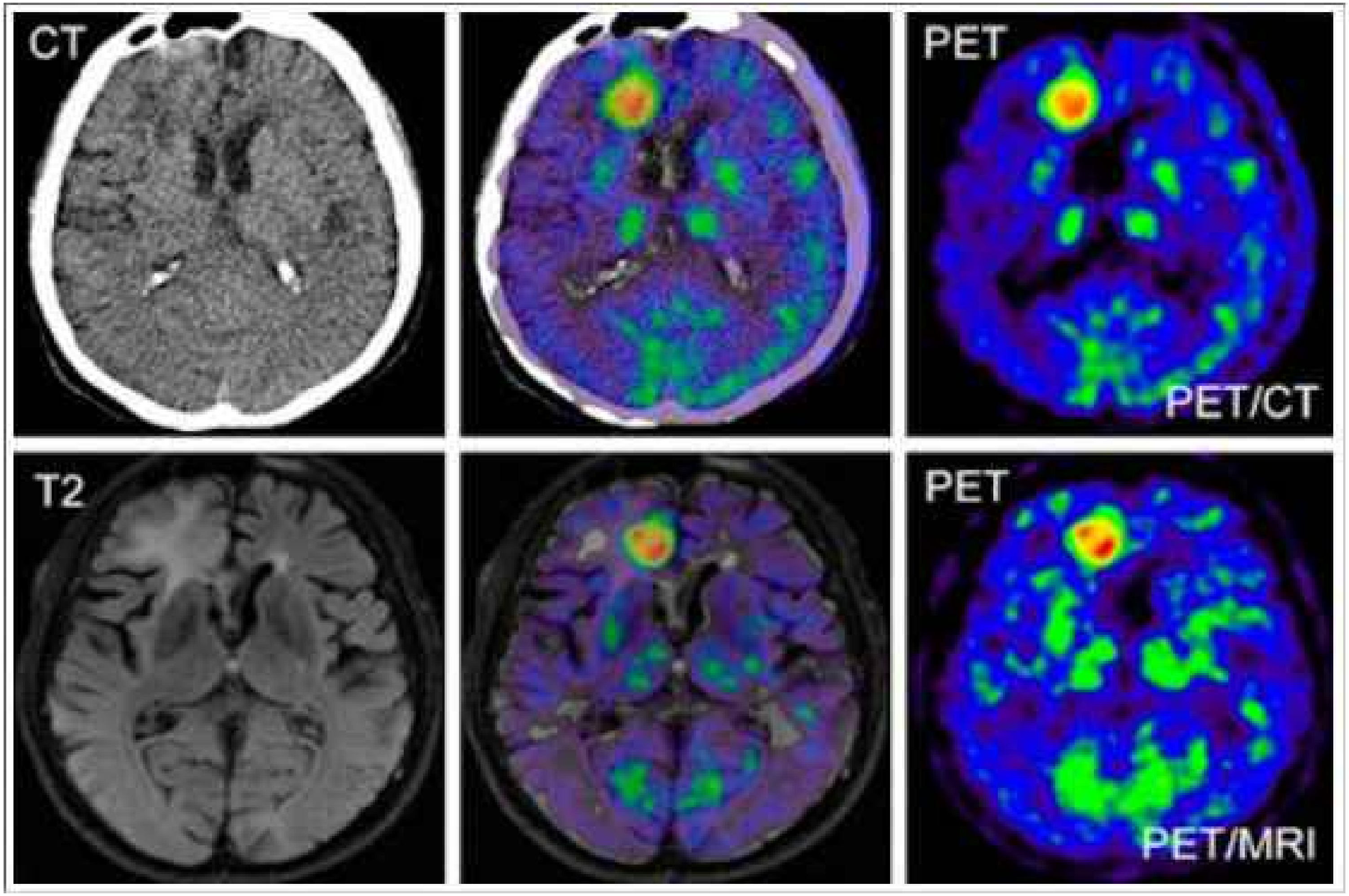
PET-MR

- Combining anatomical and functional images increases diagnostic accuracy
- PET-CT is now the standard.



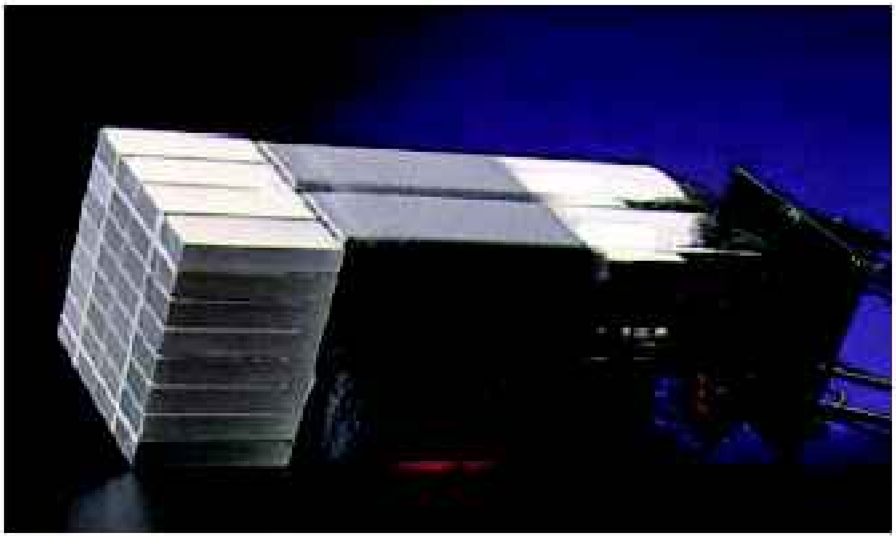
PET-MR

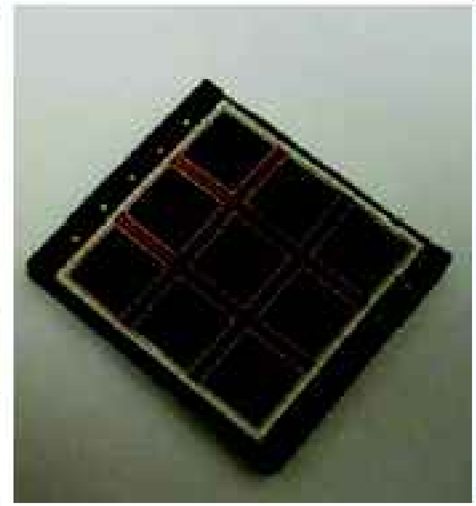
- PET-CT vs PET-MR.

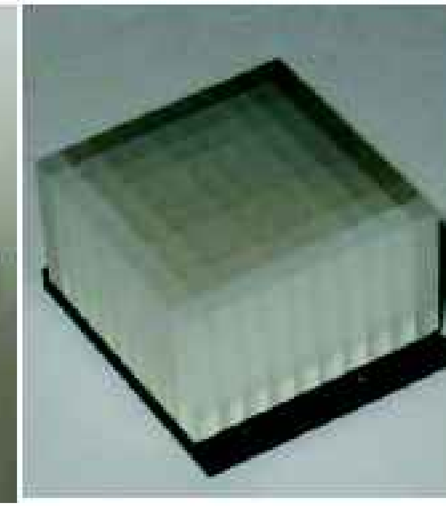


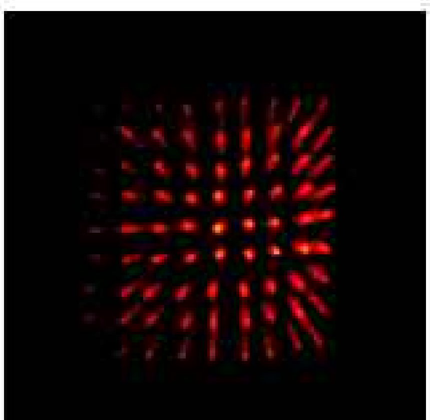
PET-MR

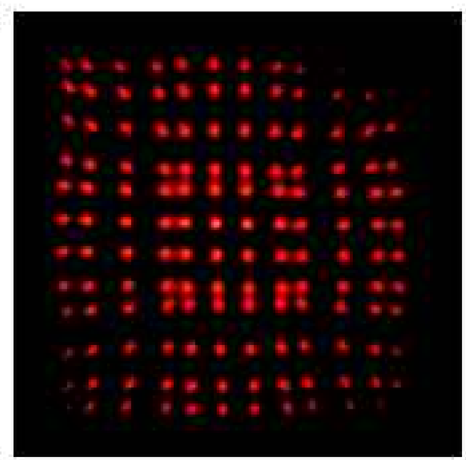
- PET-MR: problems due to PMT sensibility to magnetic fields

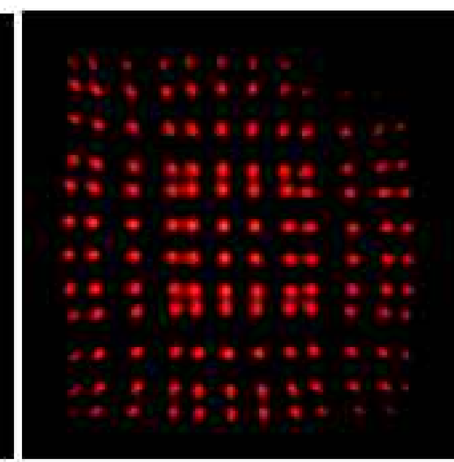










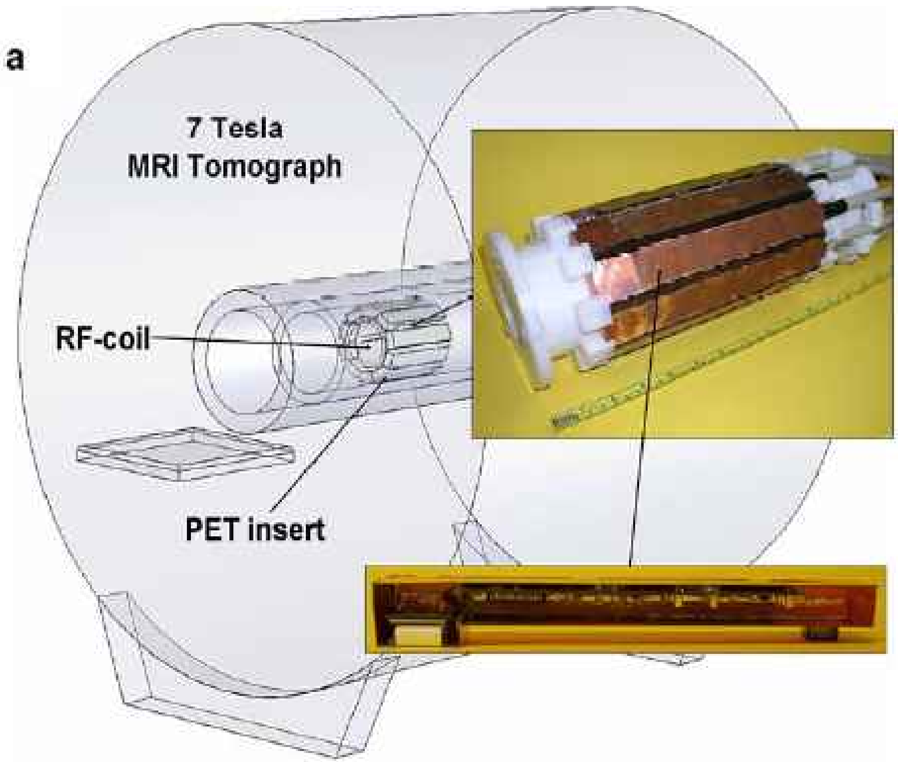


$B=0$ $B\neq 0$ $B=0$ $B\neq 0$

PET-MR

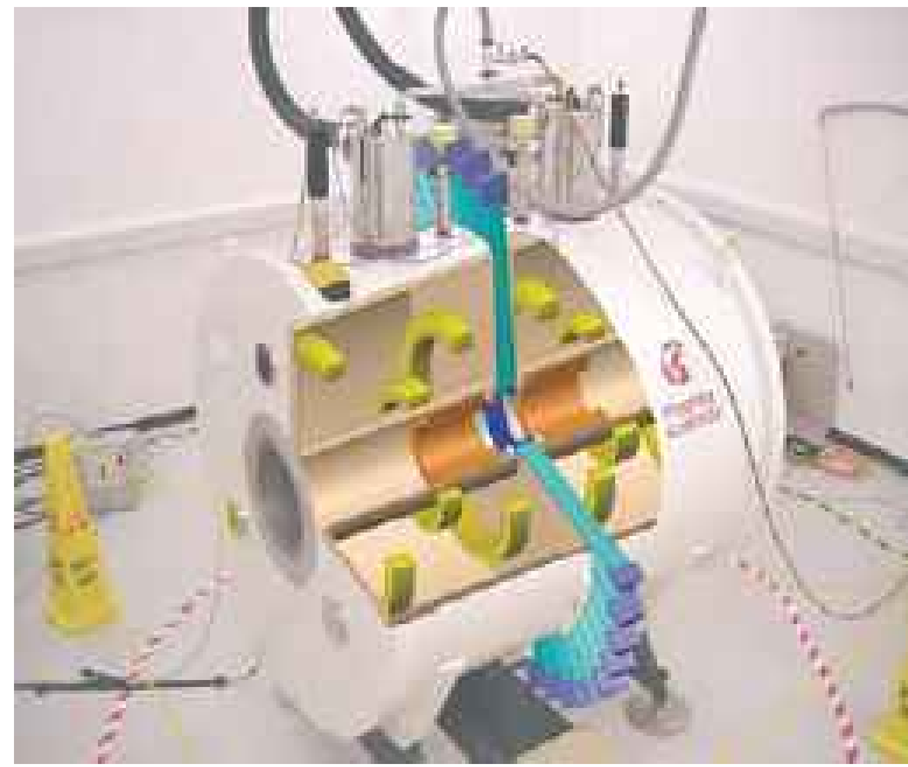
- First, small animal systems.

APDs



B.J. Pichler et al.J. Nucl Med
2006 Apr;47(4):639-47.

PMTs+ light guides

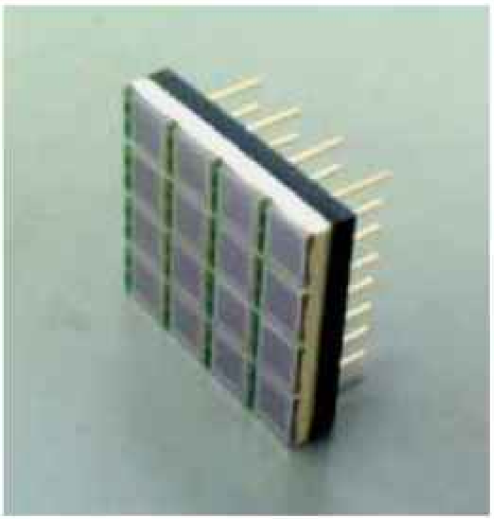
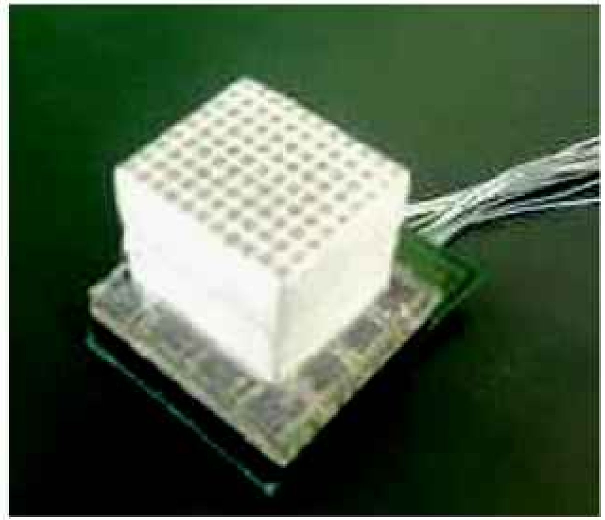


R.C. Hawkes et al.
Tech. Cand. Res. Treat. 9 (1) 2010.

- Clinical systems already exist. Sequential or APD based.
- Recents developments with SiPMs

PET-MR

Small animal PET ring

Two types of LGSO crystals (phoswich)

1.1mm x 1.2mm x 5mm

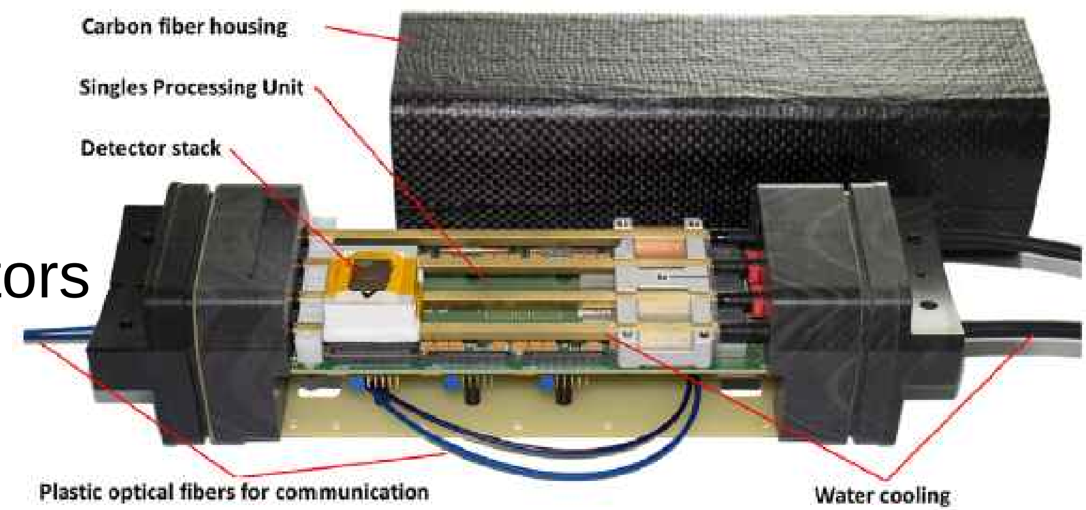
1.1mm x 1.2mm x 6mm

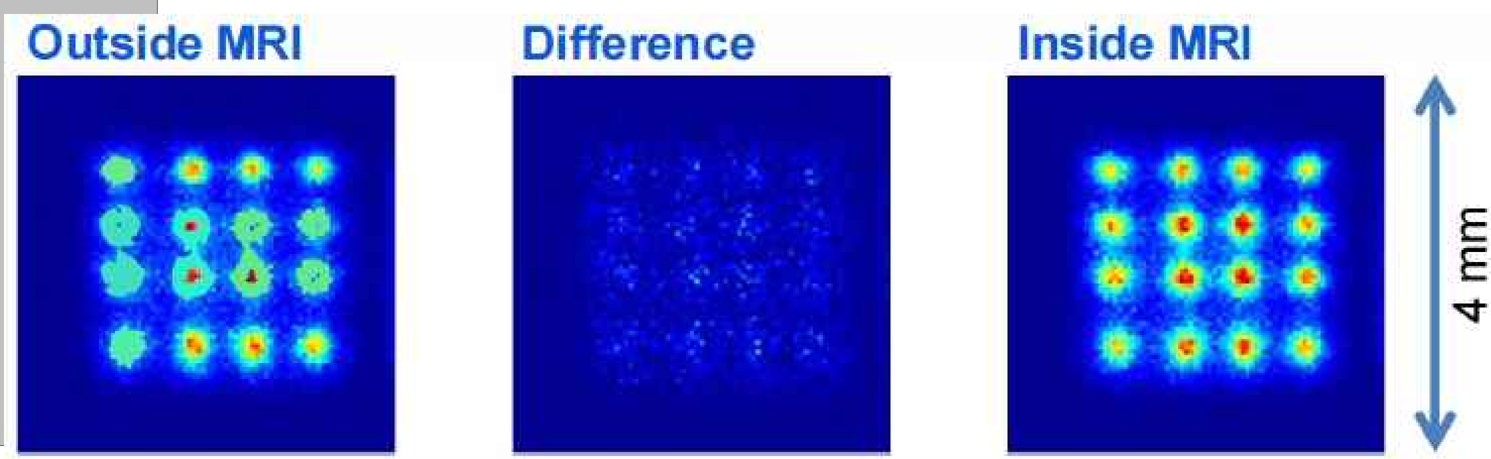

Yamamoto et al.
PMB 2010

MR-compatible

PET-MR

- Detector stack:
  - LYSO scintillator array : 30 x 30 pixels of with 1mm pitch and 12 mm length
  - DSiPM
  - cooling system
- Module: up to 6 detectors
- Ring: 10 modules. 210 mm diameter



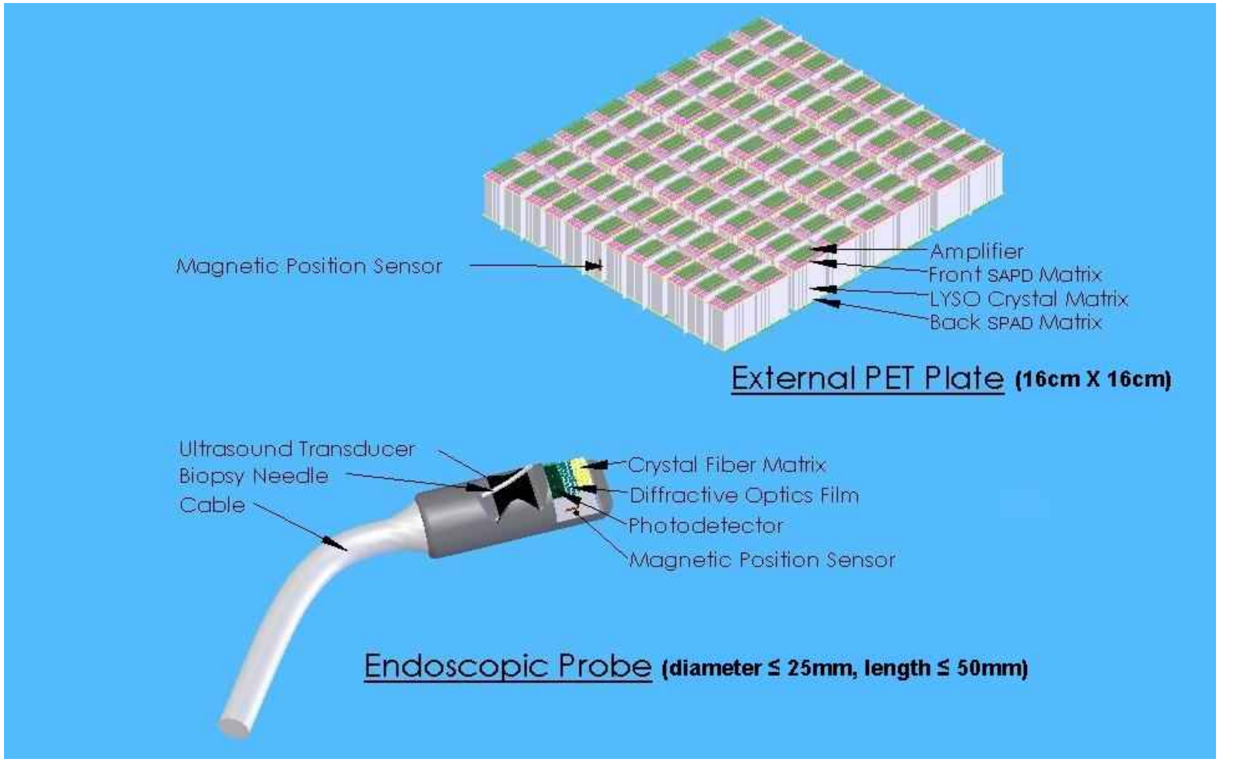


Dueppenbecker et al. 2012 IEEENSS MIC Conf Rec. M18-3

Wehner et al. NIMA 734, 2014

Compact, fast, multimodal

- ENDO TOFPET-US: endoscopic probe for pancreatic and prostatic cancer
- PET probe in coincidence with an external system. Aims:
  - 1mm spatial resolution
  - High sensitivity
  - Coincidence timing resolution 200 ps.



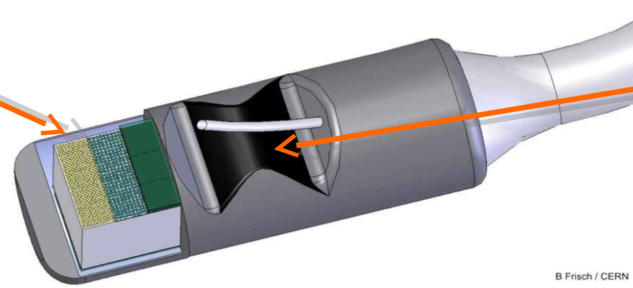
Pictures courtesy of Paul Lecoq

https://endotofpet-us.web.cern.ch/endotofpet-us/

Compact, fast, multimodal

- Probe:
  - Pixellated crystals 0.75x0.75x10mm^3
  - DSiPMs Dev at TU Delft
  - US system
  - Tracking sensor.
- Coincidence timing resolution better than 240 ps FWHM achieved

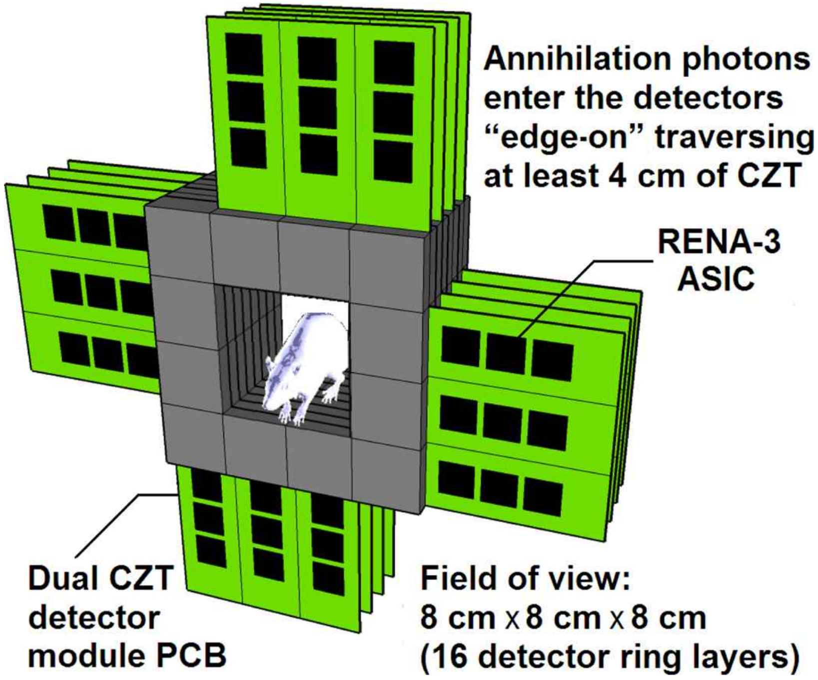
PET head

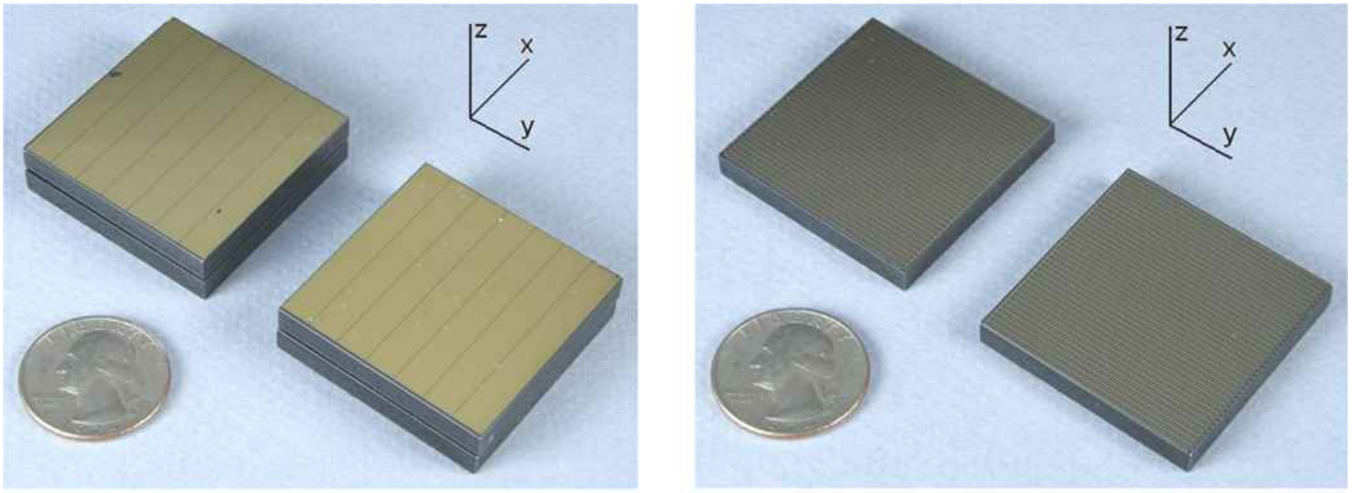


US Probe
with biopsy needle

CZT PET - small animal

- 40 mm × 40 mm × 5 mm monolithic CZT crystal detector
- Excellent (1 mm^3) 3D spatial resolution, energy resolution (3.90±0.19% at 511 keV) and efficiency (86% intrinsic for single 511 keV photons; >73% for coincident pairs).
- TOF not applicable for small animals.



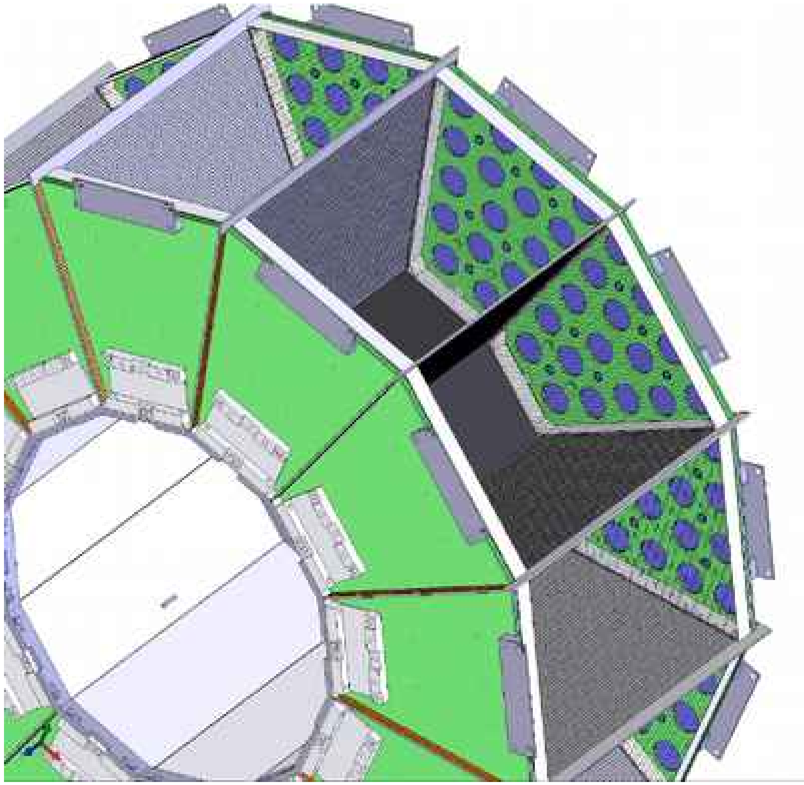


(a) (b)

Y. Gu et al. PMB 2011, 56(6) 1563-1584.

LXe PET - small animal

- 12 modules: LXe TPC with LAAPDs.
- Improved energy resolution.
- Sub-mm spatial resolution
- High sensitivity
- Compton event reconstruction.
- Timing resolution: 1 ns FWHM.

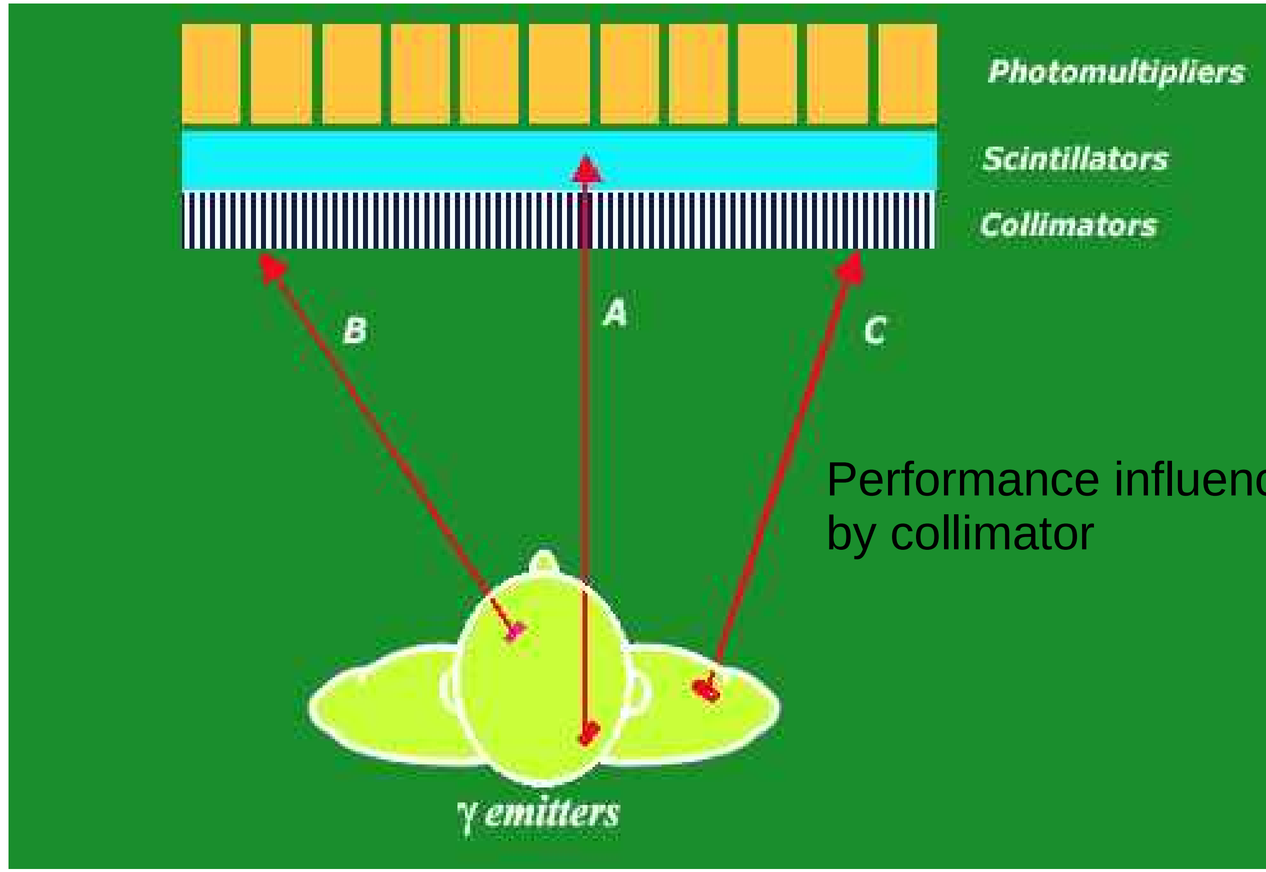


A. Miceli et al. Proc SPIE 2012.

P. Amaudruz et al.

Gamma cameras

- Principle



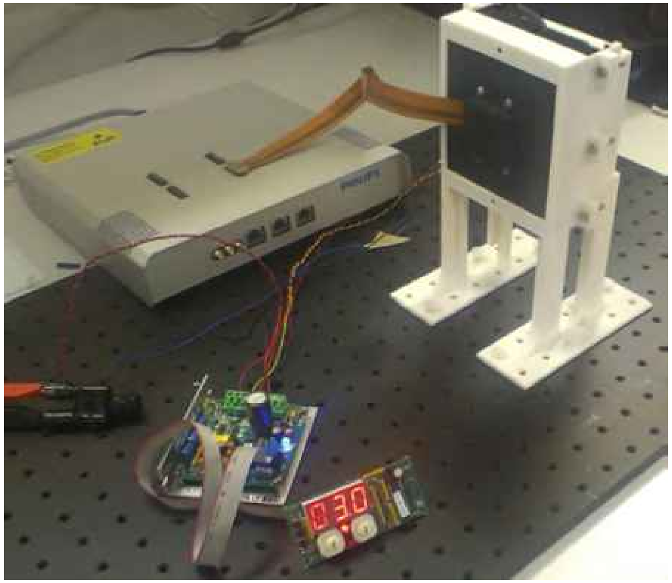
Performance influenced by collimator

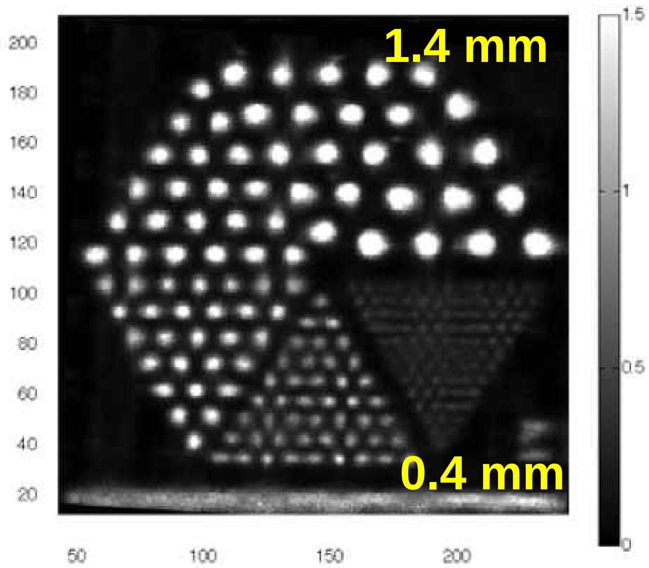
- Large systems still dominated by scintillators.
- Dedicated systems: Scintillators, solid state (e.g. CZT in cardiac or breast commercial systems), gas.

Gamma cameras

- In small systems:
  - Excellent intrinsic resolution (<0.5 mm).
  - Static ring systems → Much higher efficiency.
  - MRI compatible
  - Multi-isotope SPECT

Monolithic 32 x 32 x 2 mm3 LYSO crystal + dSiPM

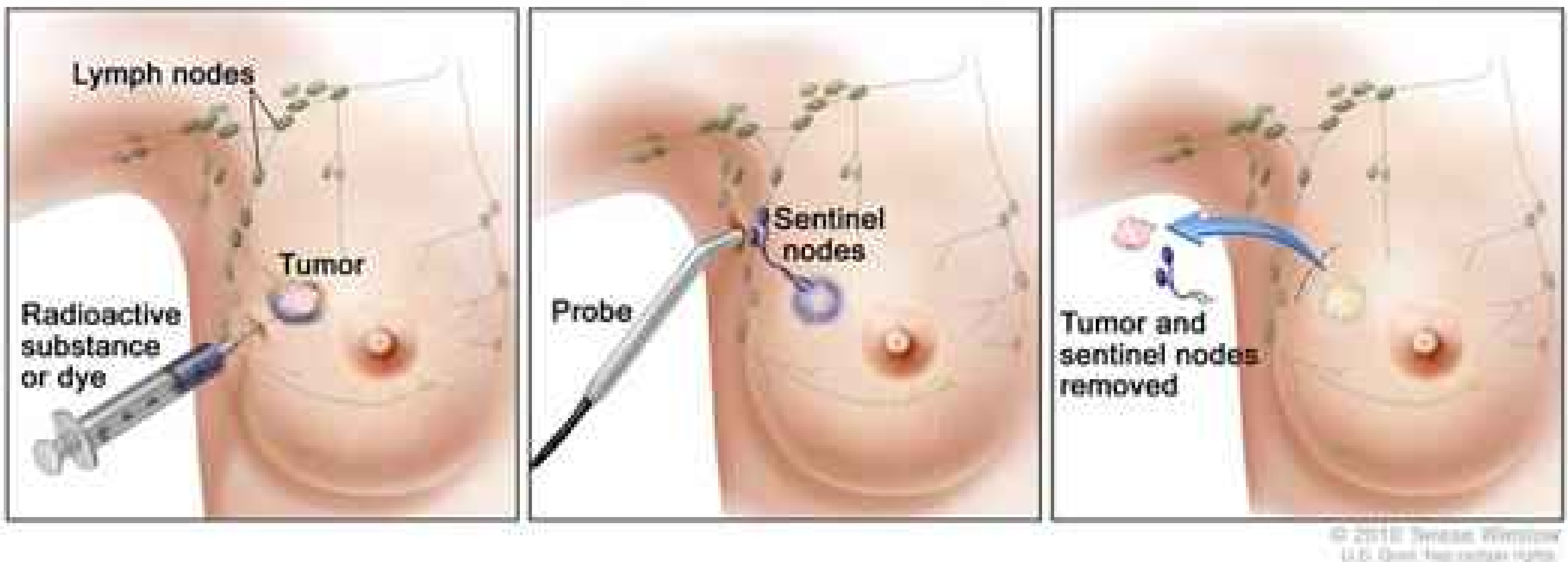




C. Bouckaert. 2013 IEEE NSS MIC. M14-7.

Intraoperative probes

- Intra-operative imaging of tumours helps the surgeon to determine precisely the tumour extension and separate from healthy tissue.
- Typical application: sentinel lymph node.



Intraoperative probes

- Beta and gamma intraoperative probes (photon counting) and mini gamma cameras (imaging).

X and γ < 511 keV

γ = 511 keV

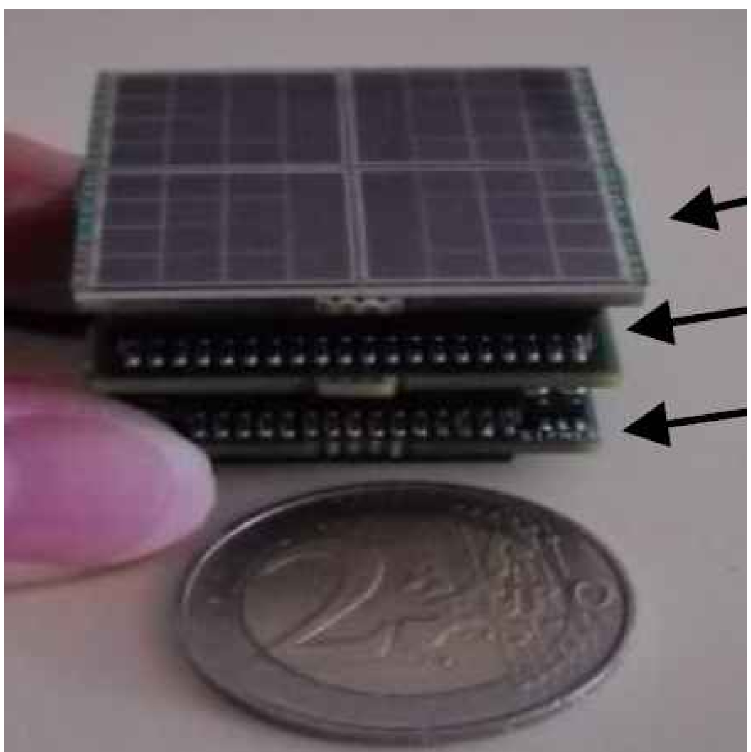
β

Heller and Zanzonico Seminars in Nuclear Medicine

- Probes have small FOV
- Need large FOV (5x5 cm^2) with excellent spatial resolution while portable and small.
- Recently solid state or scintillator + SiPMs (lower cost)

Mini gamma cameras

- SIPMED:
  - $LaBr_3$ scintillator 5.5 cm x 5.5cm
  - ~ 6 cm thick, 700 g; 256 readout channels
  - E resolution: 10.5% FWHM @ 122 keV
  - Spatial resolution: 1.23 mm FWHM @ 122 keV



SiPM board

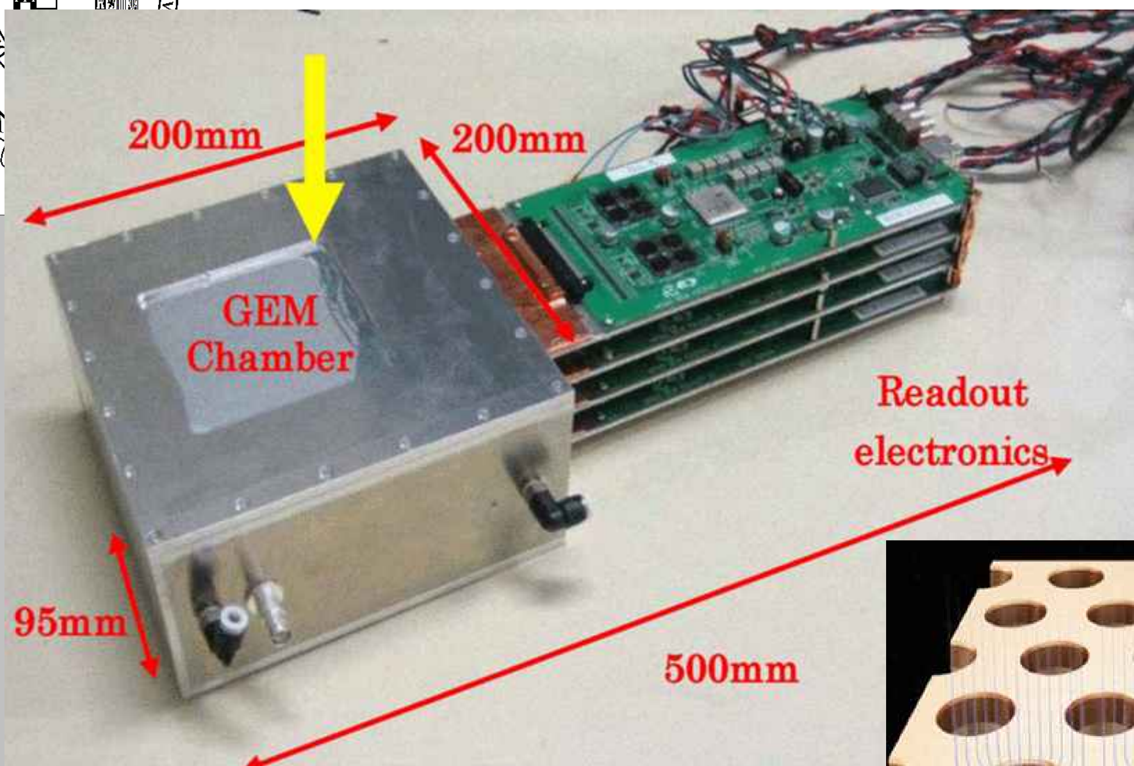
ASIC board

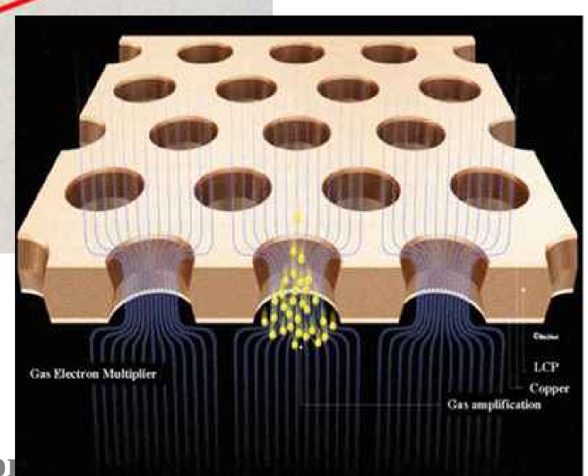
FPGA board

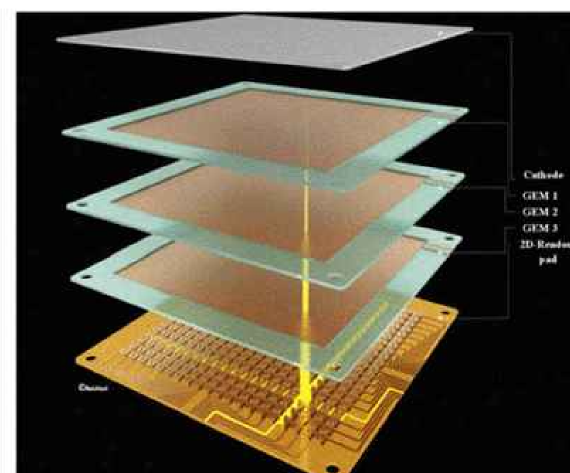
Imando et al. PoS 2012.
N. Dinu et al. NDIP 2013.

Mini gamma cameras

- CZT, I. Blevis et al. 2011 IEEE NSS MIC conf record.
- LaBr3, R. Pani et al 2015 JINST 10 C06002.
- GEM- T. Koike et al. 2011 IEEE NSS MIC conf record.



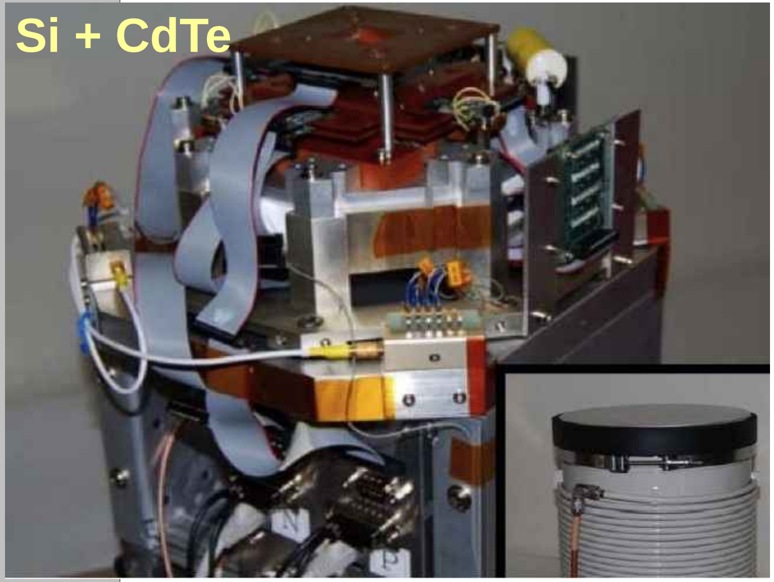


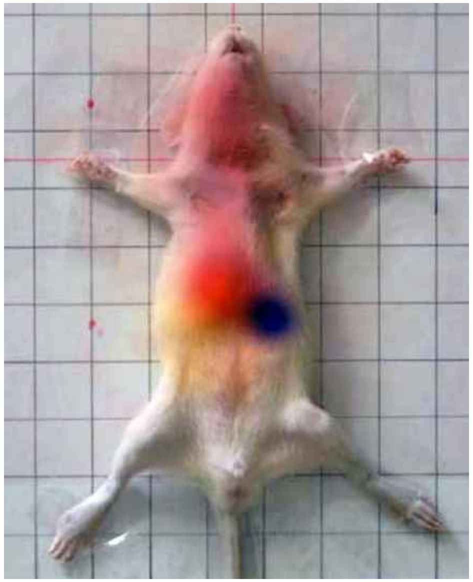


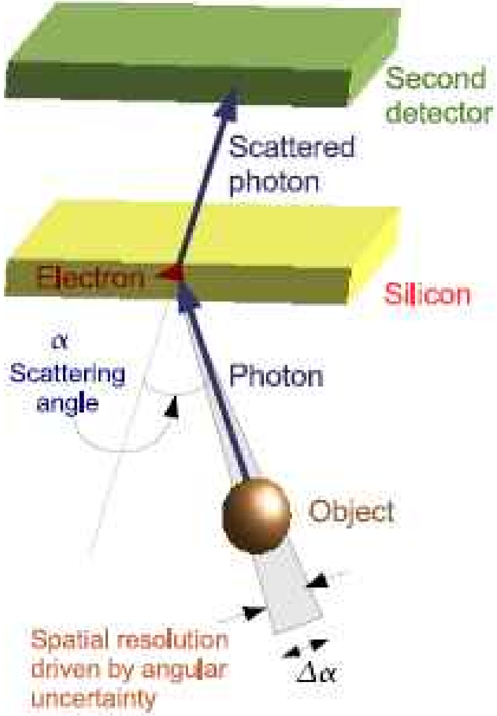
Compton Imaging

- Applied in different fields. Made of different materials. Commercial products.
- Advantages: improvement of resolution and efficiency, improvement at high energies...
- Far from being used in clinical practice.

Are they really of interest in medical imaging? Can we do better?





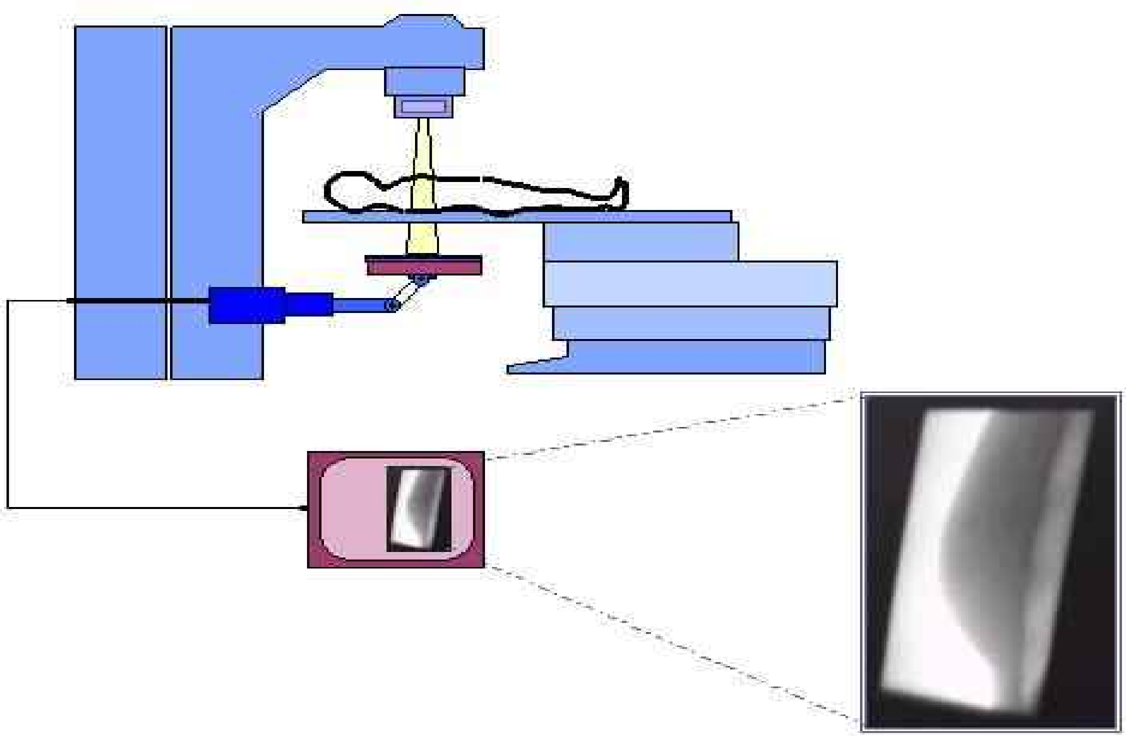


Detectors in therapy

- Detectors in radiotherapy and hadron therapy:
  - ~~Dosimetry in conventional radiotherapy~~
  - Monitoring dose deposition in conventional radiotherapy.
  - Beam monitoring in hadron therapy.
  - Treatment monitoring in hadron therapy.

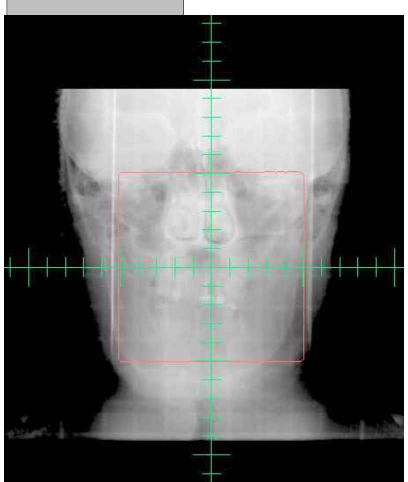
Dose deposition monitoring in radiotherapy

- Portal radiography (low quality) → EPID: electronic portal imaging devices verify patient position measuring exiting radiation.
  - Mount on the linear accelerator
  - Real time, digital feedback to user



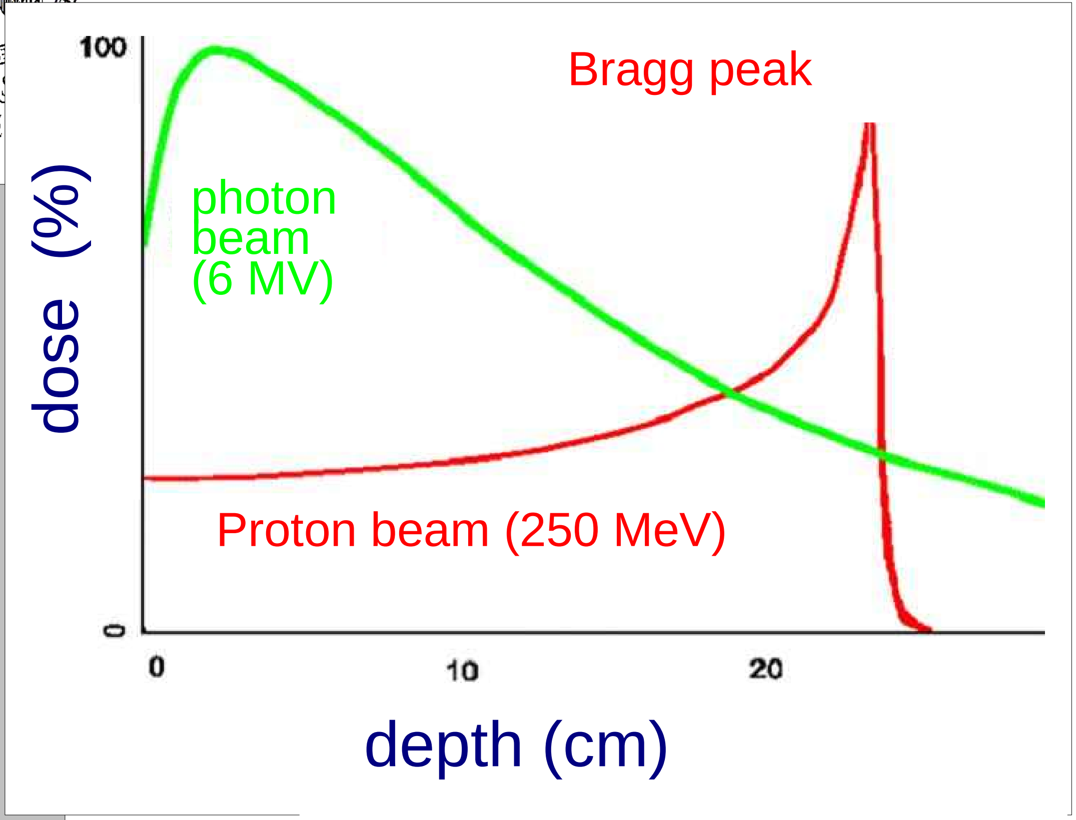
Dose deposition monitoring in radiotherapy

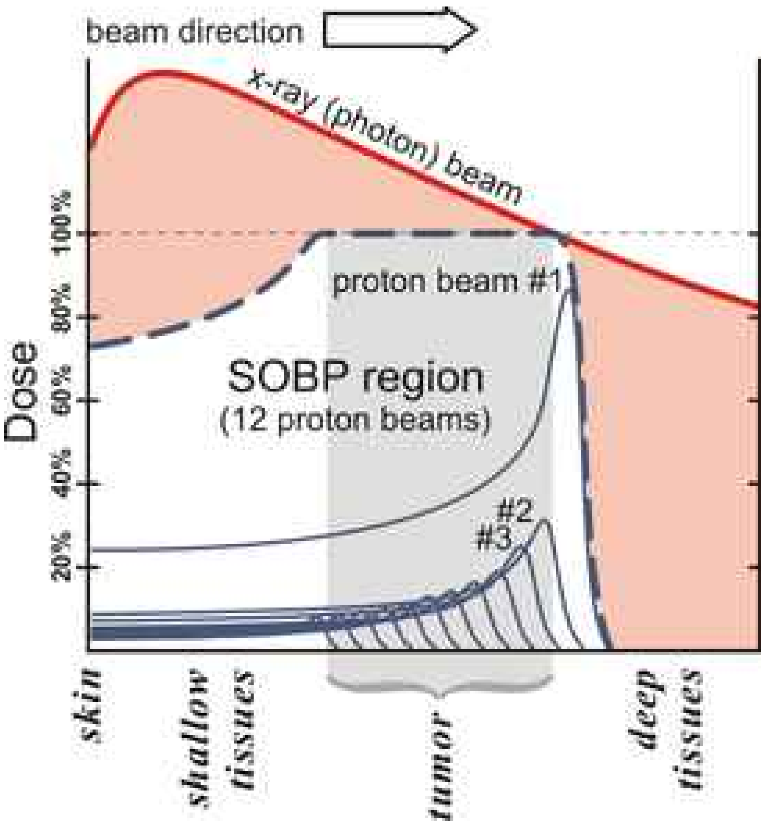
- Detectors similar to X-ray imaging (higher energies).
    - Fluoroscopy (video)
    - Ionization chamber systems
    - Flat panel- low efficiency for higher energies.
- Alternatives:
    - Direct detection with amorphous selenium and gaseous amplification.
    - Improve the efficiency of indirect detection.
        - kV imaging, CsI scintillator.
        - MV imaging, thicker scintillating BGO and CsI crystals.



Hadron therapy

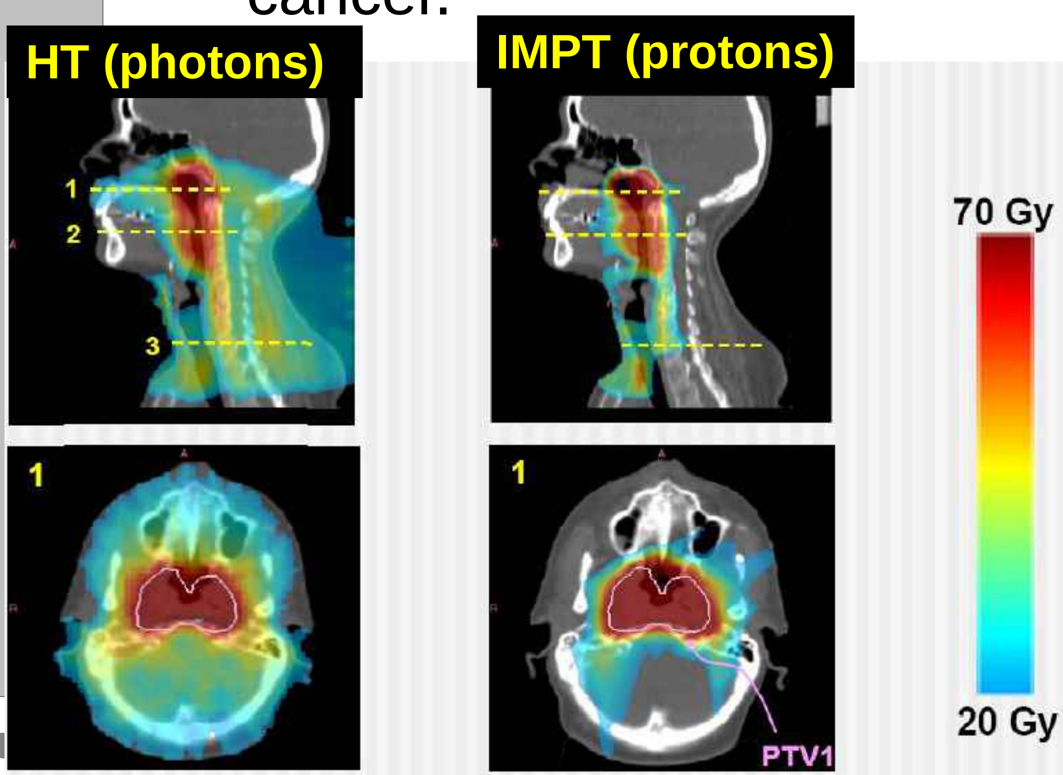
- Hadron therapy: charged particles (protons or Carbon ions), precise delivery of radiation dose (Bragg peak).
- Reduce the dose to healthy tissue.

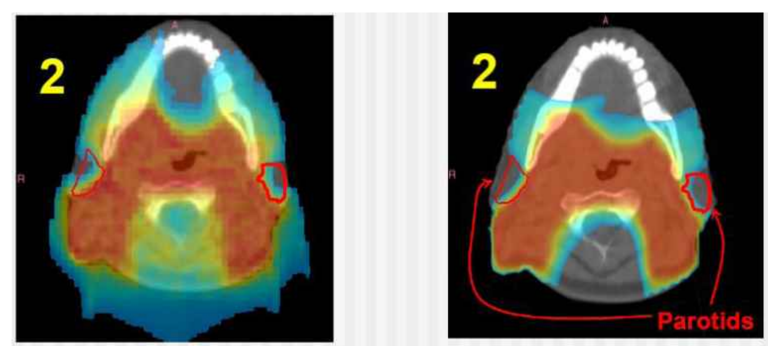




Hadron therapy

- Large benefit over conventional radiation therapies in some cases (ocular tumours, children, organs at risk, radioresistant tumours).
- Higher relative biological effectiveness (RBE) than photons
- Precise delivery to tumour area => increase of cure rates and reduction of side and long term effects and secondary cancer.

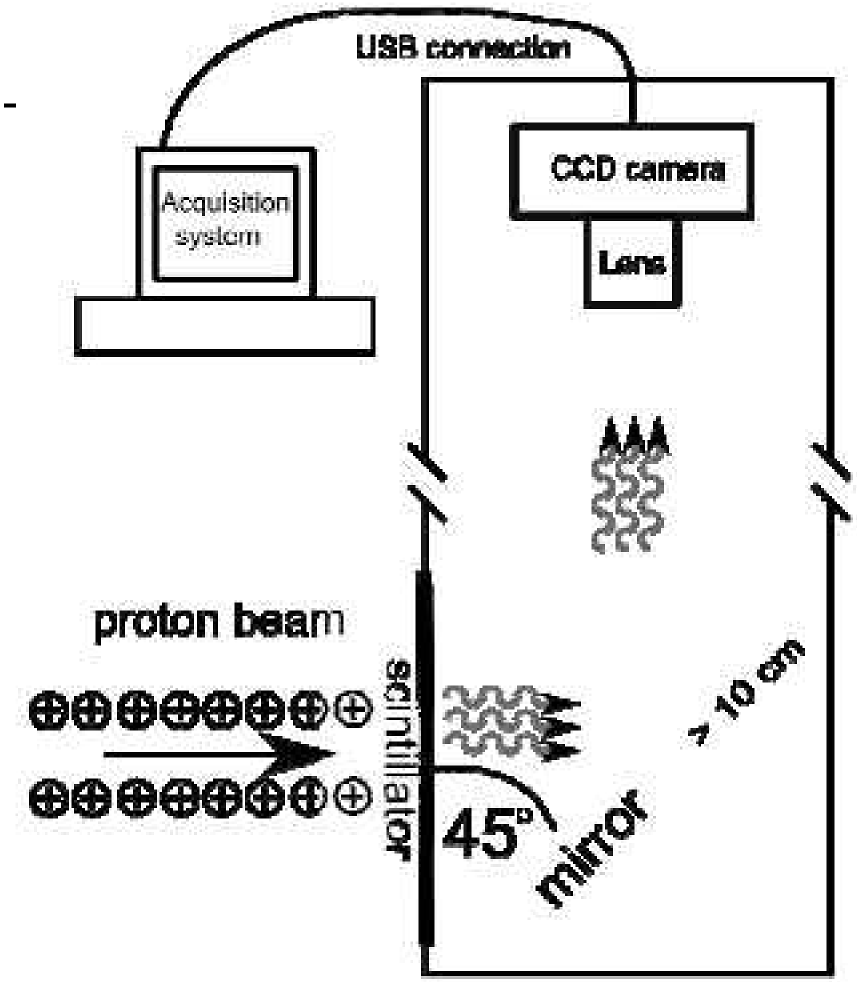




L. Widesott et al.
IJROBP 72(2):589, 2008

Beam monitoring

- Quality assurance in a proton ocular treatment facility.
- PROBIMS (PROton Beam IMaging System):
  - 2 mm thick Gd_2O_2S:Tb (Gadolinium Sulphate Oxide doped with Terbium - inorganic phosphor) convert proton beam to visible light
  - CCD camera (3362 x 2504 pixels)
  - 45º angle to avoid radiation damage

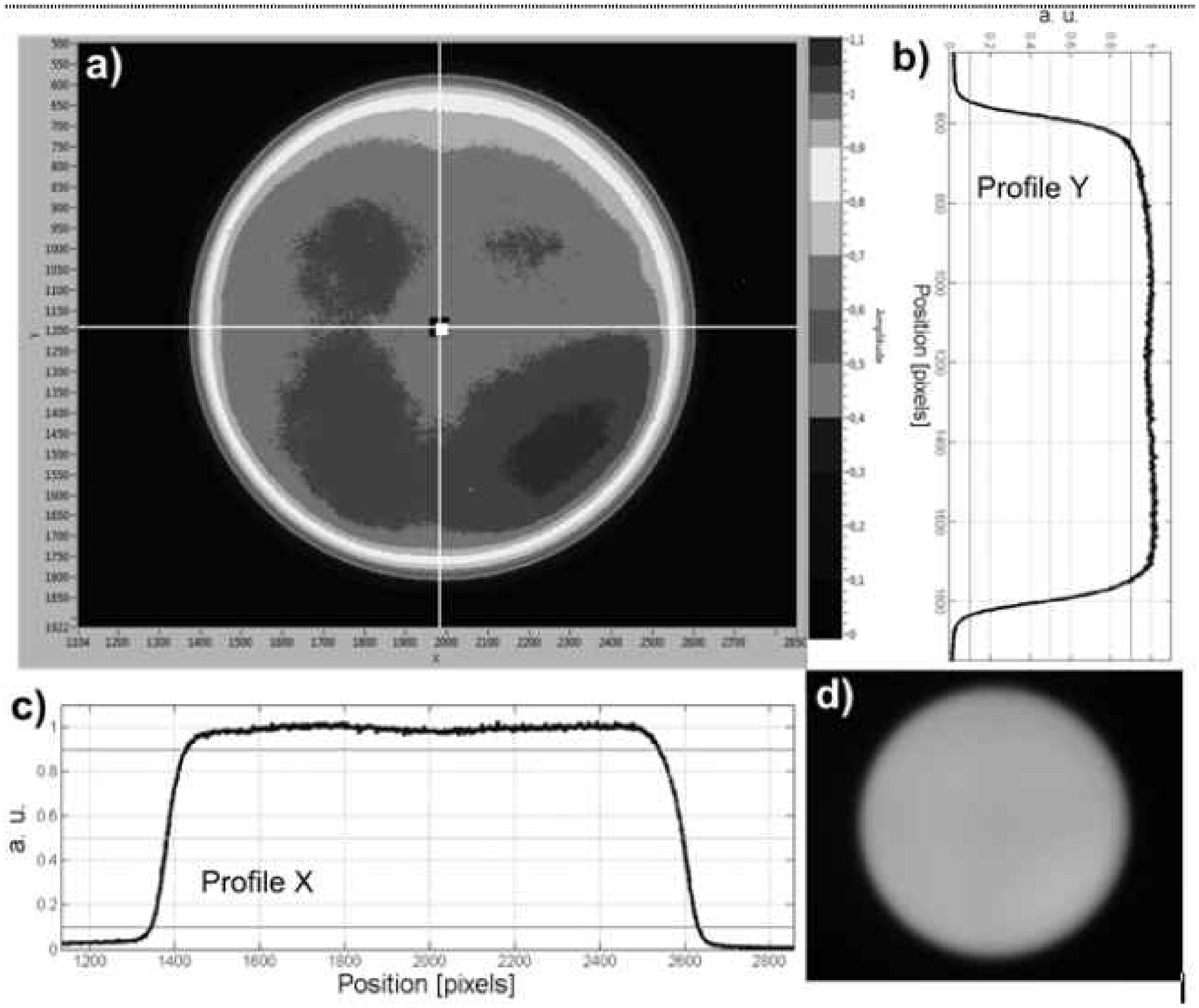


Boberek et al.
Rom. Rep. Phys.66, 2014.

Beam monitoring

Boberek et al.
Rom. Rep. Phys.66, 2014.

- Measurements in a 60 MeV proton beam.
- 2D beam profile characterization

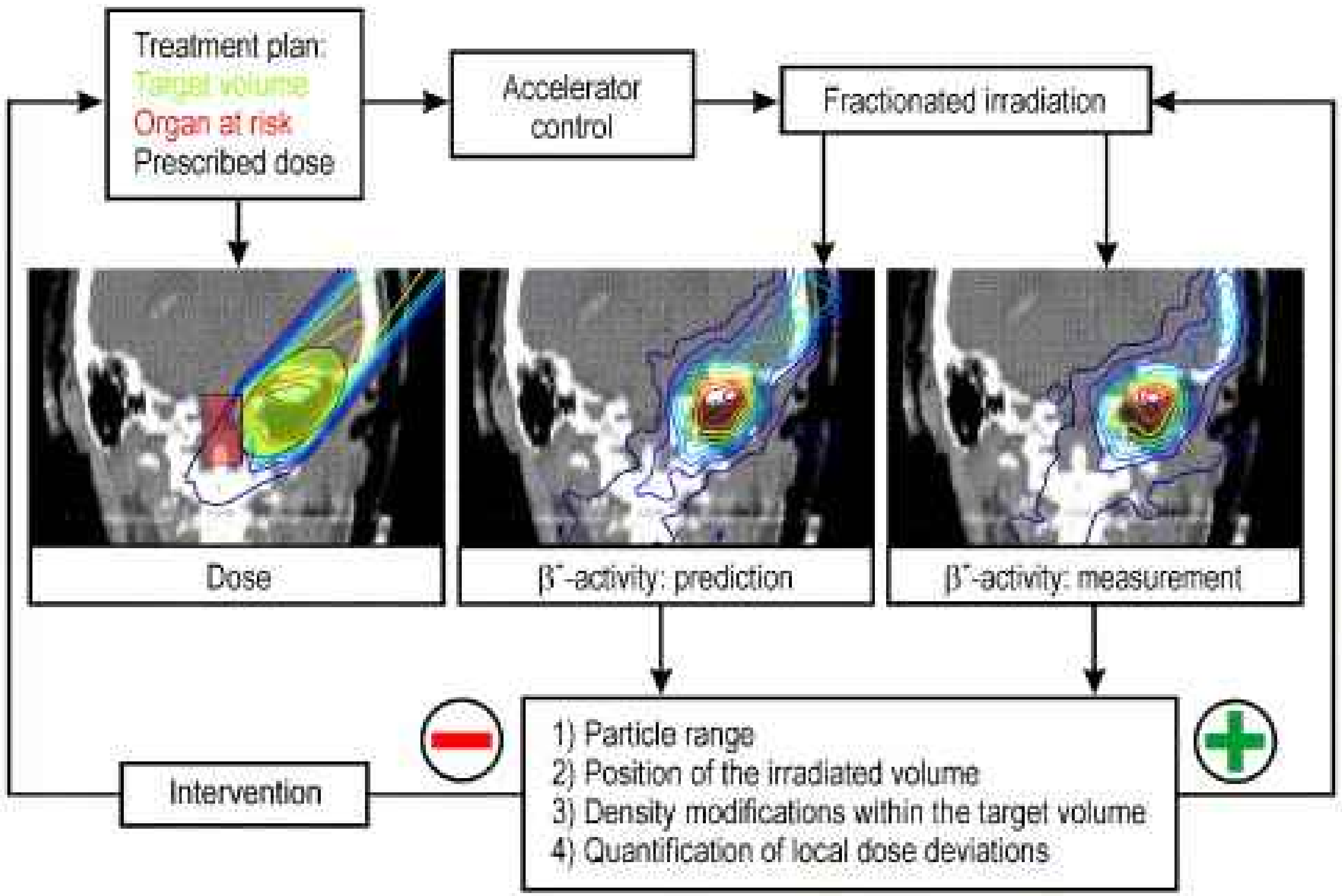


Dose monitoring in Hadron therapy

- PROBLEM: the dose administered can not be directly measured (as done in conventional radiotherapy).
- Secondary particles emitted during treatment can be used for monitoring the dose delivery.
- An accurate monitoring system is essential:
  - To verify dose delivery and correct for treatment deviations.
  - To reduce safety margins.

Dose monitoring in Hadron therapy

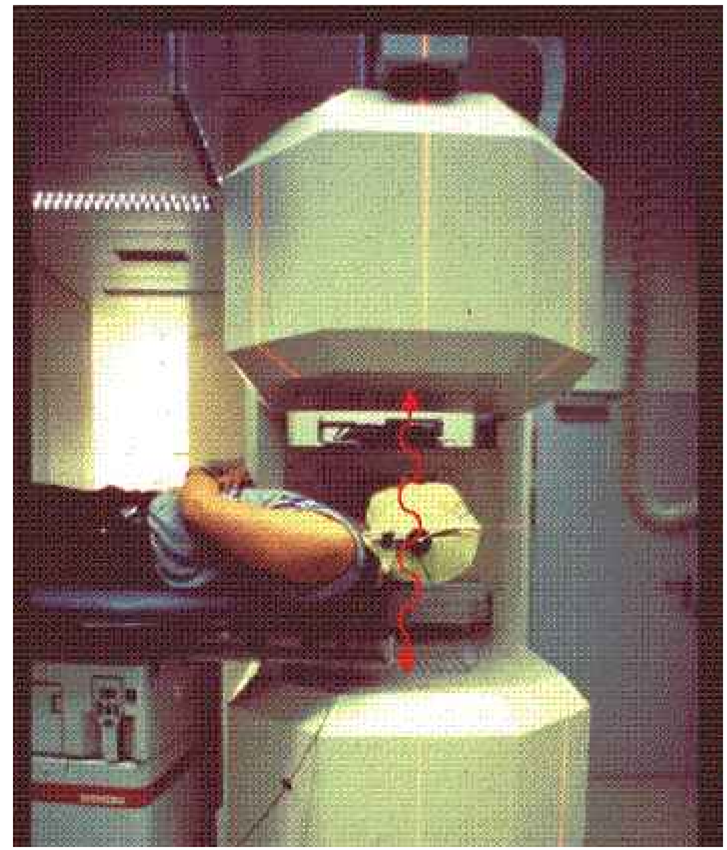
- Positron Emission Tomography (PET) + MC currently employed.



•Dose verification: comparison of dose planned and estimated from detected β+ activity.

PET for dose monitoring

- Irradiated tissue nuclei become positron emitters (O, C).
- In-beam, in-room, offline



- In-beam -> gaps. Improved results with TOF-PET
- Many groups working on such systems.

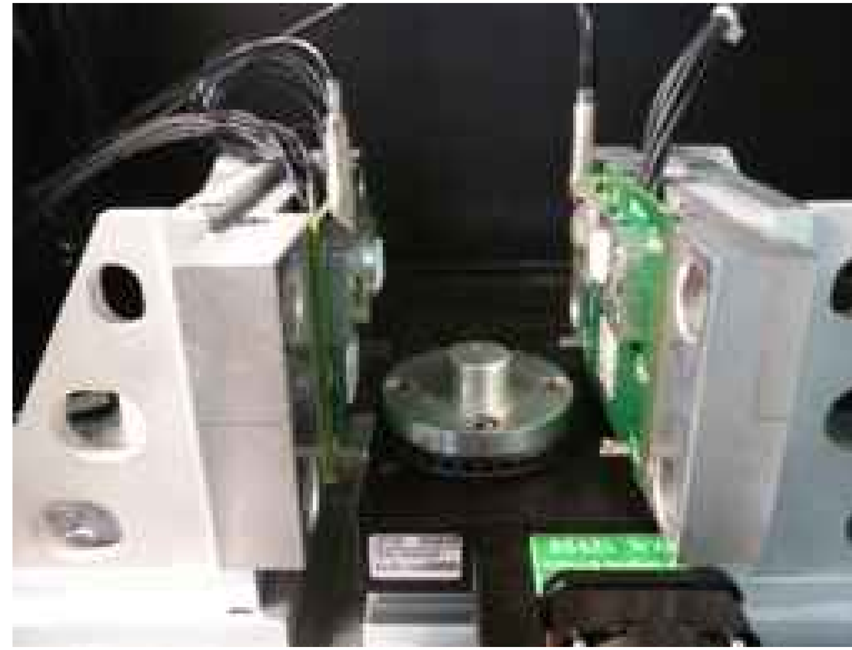
Dose monitoring in hadron therapy

- Limitations:
  - Positron production does not follow irradiation immediately
  - Biological washout- activity carried away by metabolic processes
  - Low amount of β+ activity induced- low efficiency
  - Difficult online studies – in-beam -> partial ring
  - Photons produce significant background
- Attempted solutions:
  - Fast transfer to PET and accurate biological models.
  - TOF-PET as an option for in-beam.
    - Crystal based
    - Resistive Plate Chamber (RPC)-based

Dose monitoring in hadron therapy

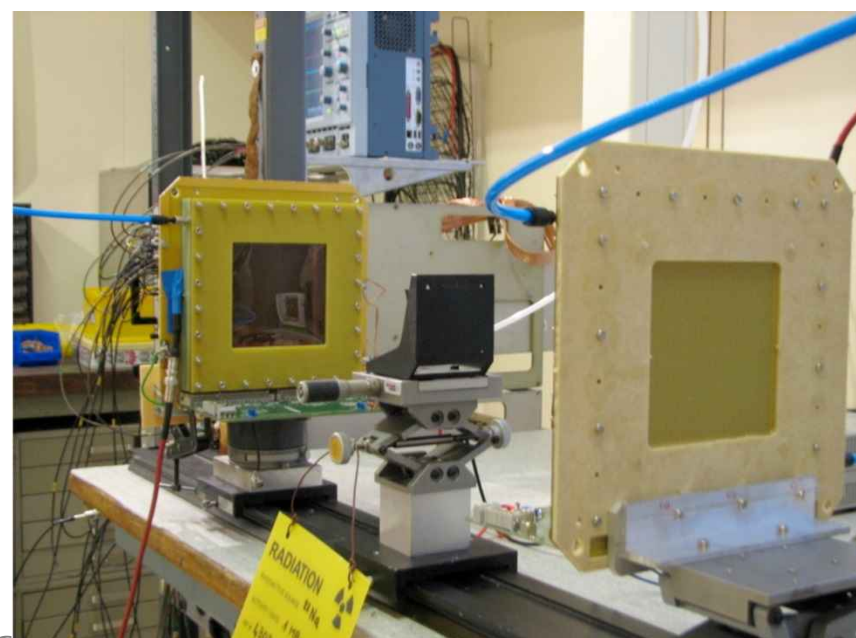
- Crystal-based PET:

64 LYSO Crystals
1.5 × 1.5 × 10 mm²
+ SiPMs



Del Guerra et al., Nucl. Instr. Meth A (2011)

- RPC-based PET:



Amaldi et al., *Nucl. Instr. Meth. Phys. Res. A* 629 (2011) 337.

ENVISION

Simulated crystal vs. RPC PET

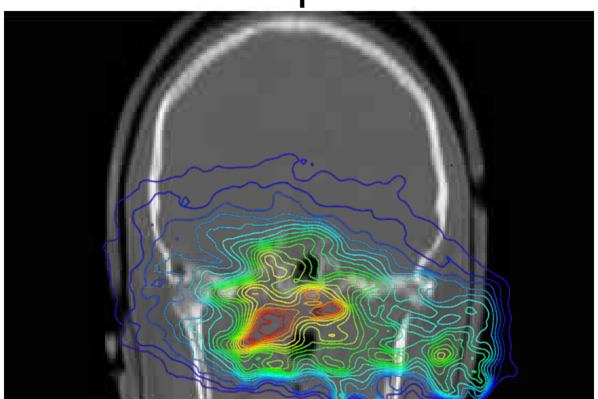
CRYSTAL-BASED PET

LYSO Crystals 4×4 × 22 mm^3
Diameter: 90 cm
Axial field of view: 18 cm
Energy resolution @ 511 keV: 11%
Time resolution FWHM: 600 ps (200 ps, 400 ps)

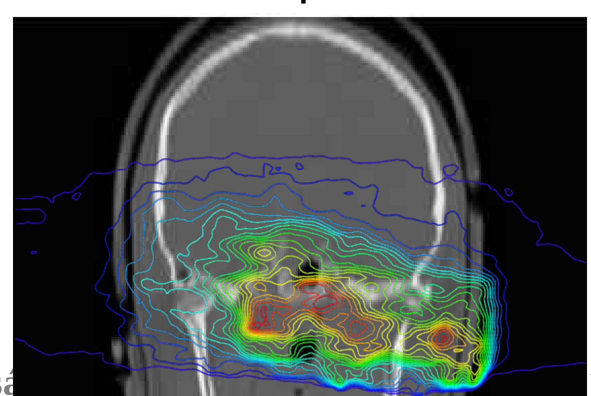
RPC-BASED PET

3.2 × 120 × 300 mm^3 Modules
Diameter: 80 cm
Axial field of view: 30 cm
Modules per head: 20, 40, 60
Time resolution: FWHM 50, 100, 200 ps

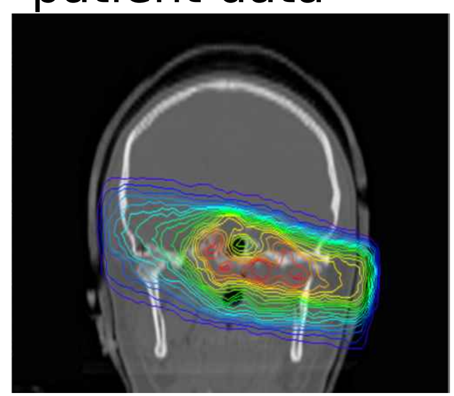
GEMINI 200 ps



GEMINI 600 ps

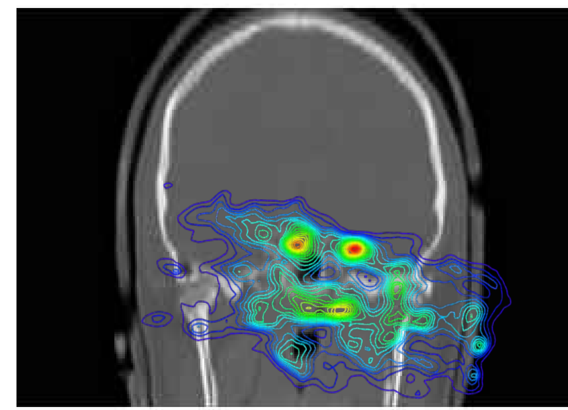


Simulated Annihilation points from patient data

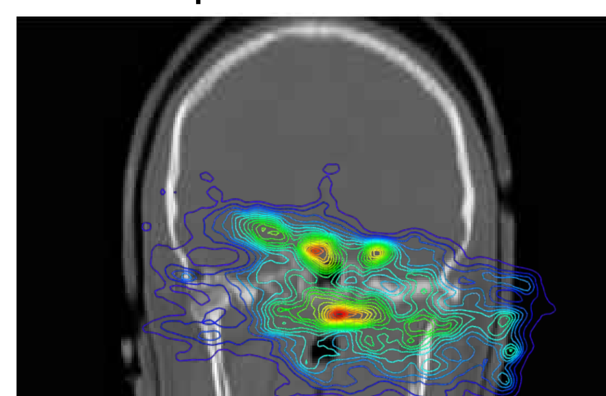


I. Torres-Espallardo et. al. Phys. Med. Biol. 60 N187, 2015.

RPC 100 ps

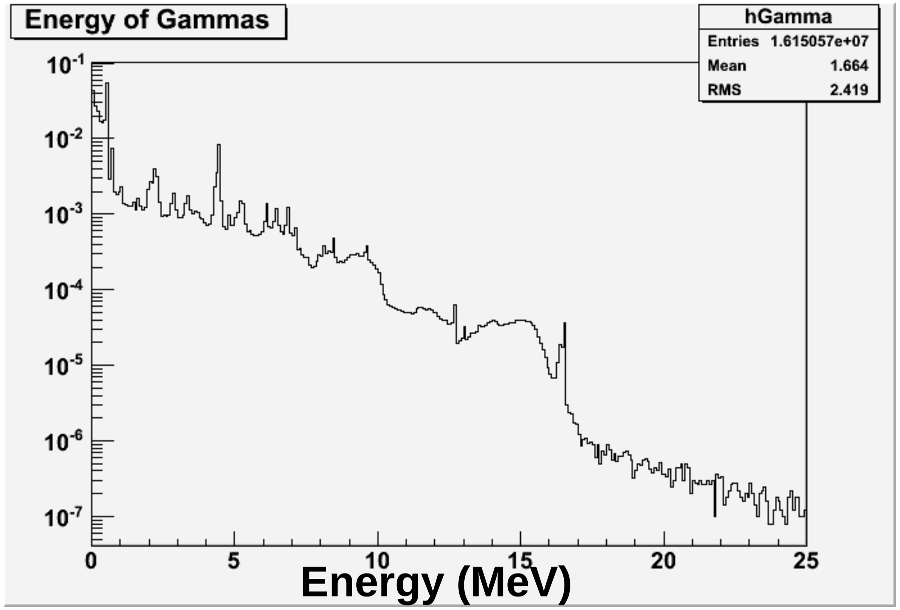


RPC 200ps



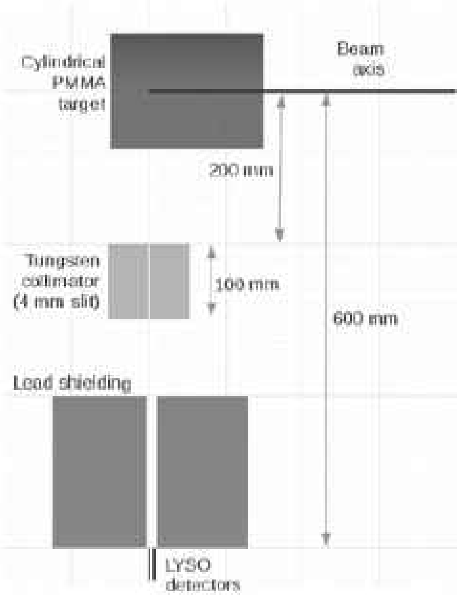
Dose monitoring in hadron therapy

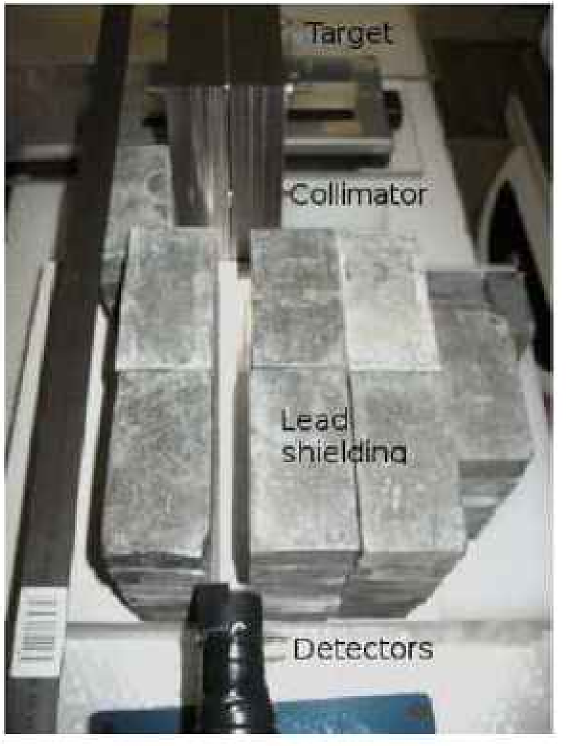
- Alternative: Prompt gammas also emitted from nuclei excited during therapy and can be used for this purpose.
  - Emission ~ns after irradiation.
  - ~ 7 times more particles/cGy
- Emitted in a continuous energy spectrum with energies of MeVs.



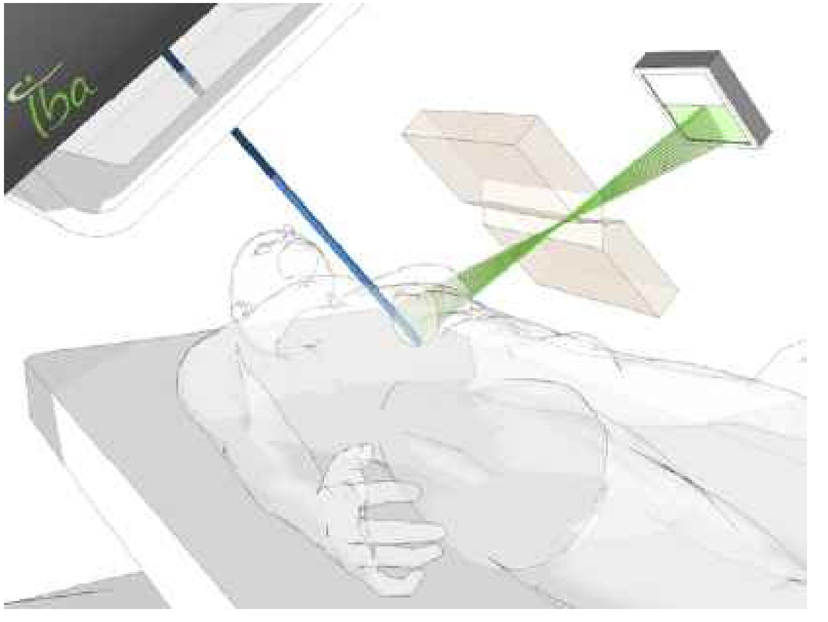
Collimated systems

- Conventional gamma cameras not suited for such high energies.
- Collimated cameras -projection.





F. Roellinghoff et al.
Phys. Med. Biol. 59 (2014)

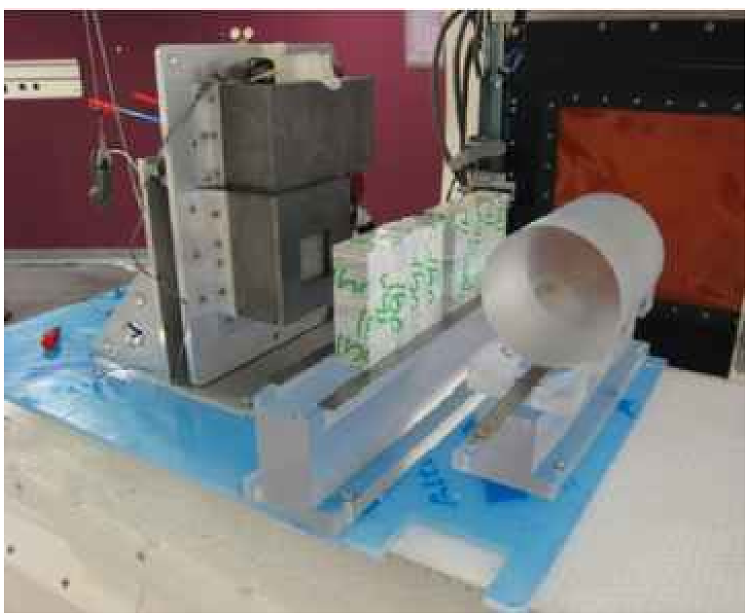


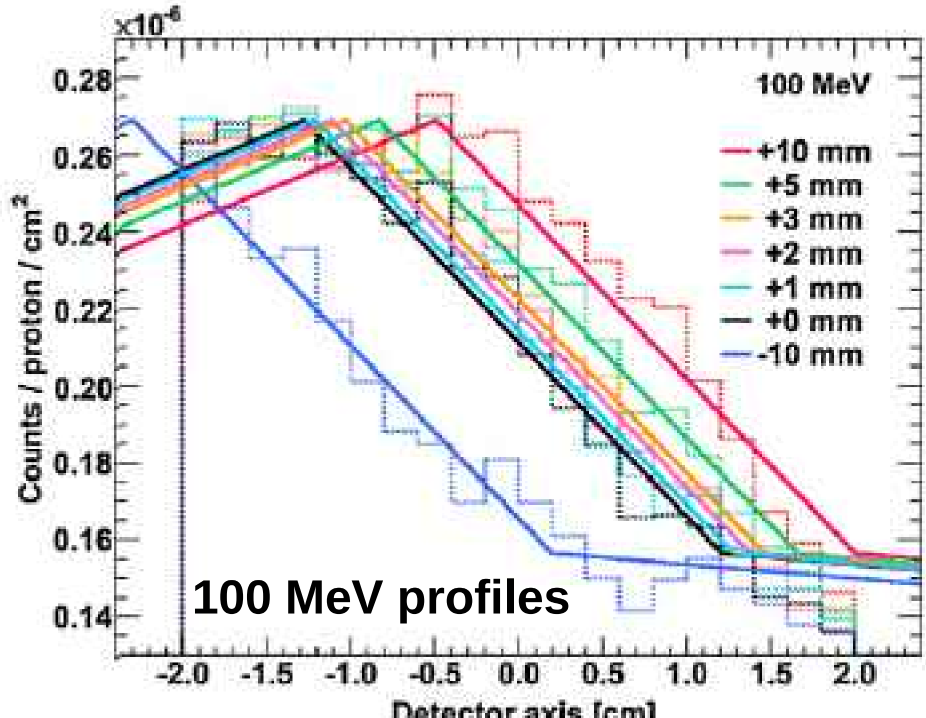
J. Smeets.
Phys. Med. Biol. 57 (2012)

Collimated systems

J. Smeets.
Phys. Med. Biol. 57 (2012)

- Slit system:
  - Tungsten collimator, PMMA target
  - Modified HiCam system; 1 cm thick continuous LYSO scintillator crystal + SDD.
- Data at 100 and 160 MeV. Profiles moving the target.



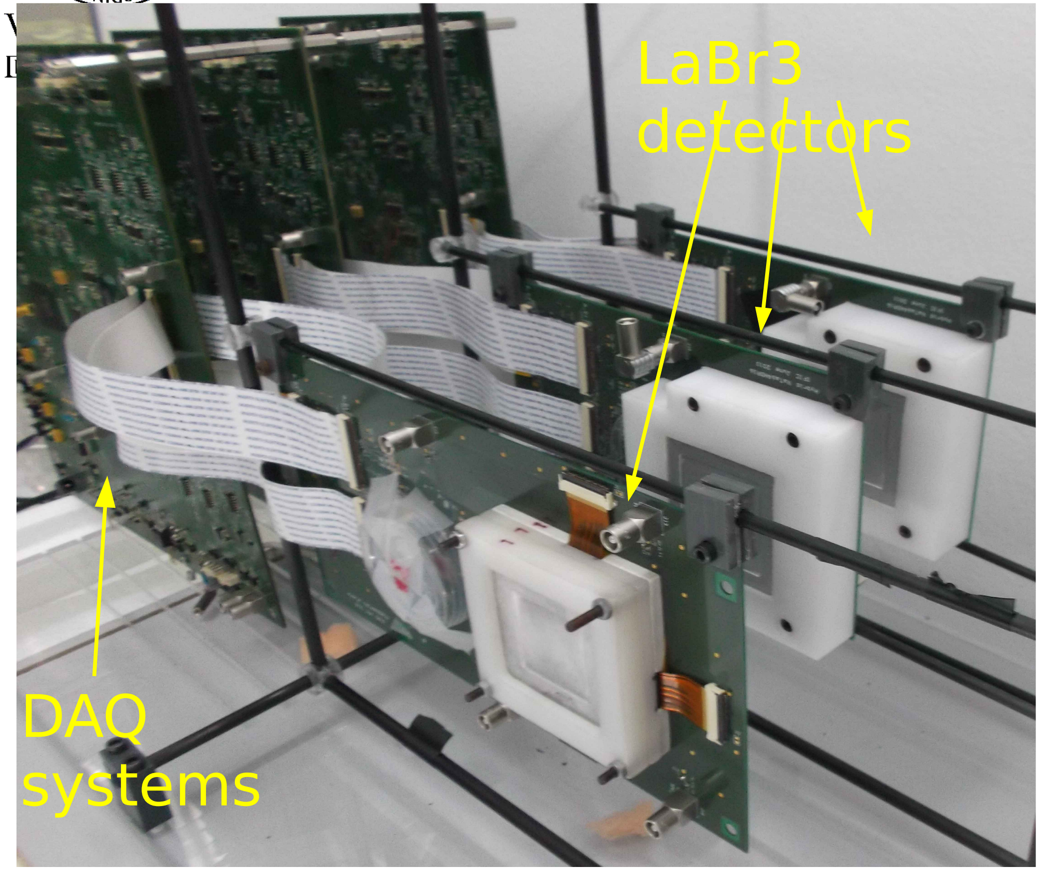


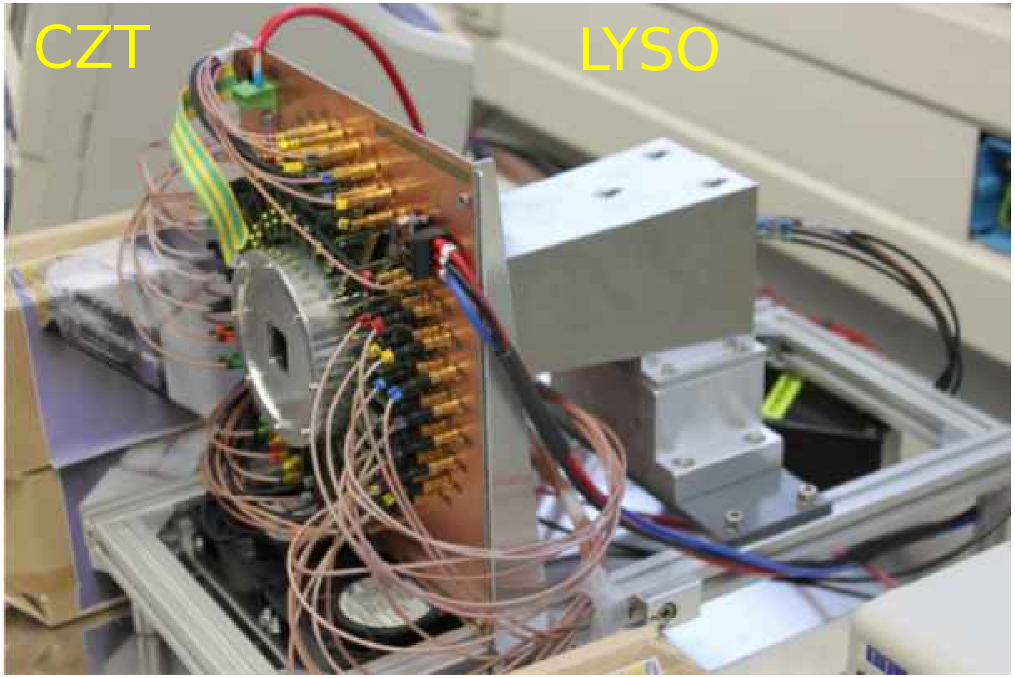
Also Scintillators + PMTs, SiPMs, DSiPMs

Compton cameras in HT

- ENVISION:
  - CZT – 2/3 planes.
  - Si + scintillator.
  - $LaBr_3$+ SiPMs.

- Prototypes tested in lab (images reconstructed) and in beam.
- Technologically challenging.





Conclusions

- Room for improvement in many areas.
- Significant advances in small systems.

  How to translate them to clinical systems at a reasonable cost?
- No longer one detector for all apps.
  - Apply the strengths of each detector to each application.
  - Keep doing basic research.
  - Transfer and apply.

Acknowledgements

- ENVISION project, co-funded by the European Commission under FP7 Grant Agreement num 241851 and ENTERVISION project.
- Ministerio de Economía y competitividad/Plan Nacional de I+D+i (FPA2010-14891, FIS2011-14585-E), Universitat de València (UV-INV-PRECOMP12-80755) and Generalitat Valenciana (GV/2013/133).
- Ministerio de Economía y Competitividad. Ramón y Cajal Programme.

Thank you! Questions?