International Symposium DETECTOR DEVELOPMENT

The HPPC: a new gaseous detector for Medical Imaging with high space and time resolution

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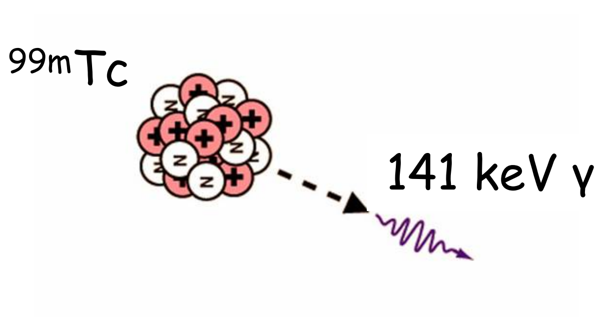
Outlook

- Nuclear Medicine applications: SPECT and PET
    - principles of operations
    - limitations and possible improvements
- Gaseous detectors for medical imaging
    - overview of present PET scanners
- The Micro-gap RPC basics
- The Hybrid Parallel Plate Chamber (HPPC)
    - Detector design
    - Material optimization
    - Simulated performances
- Conclusions and perspectives

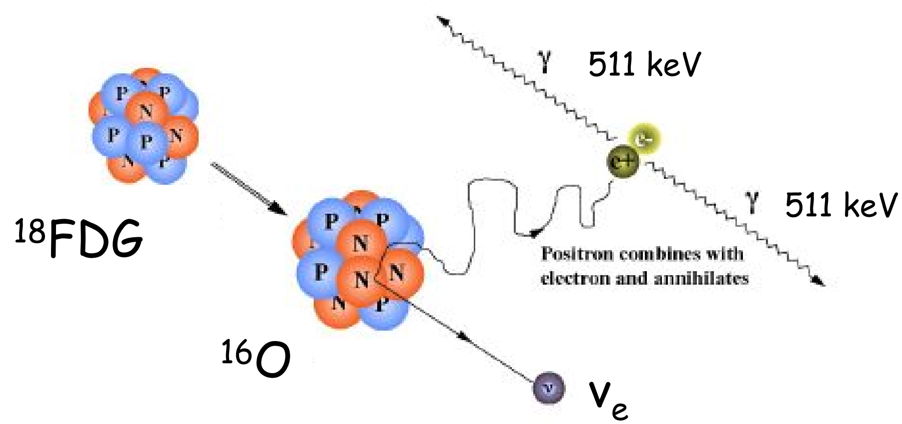
SPECT and PET

- SPECT (Single Photon Emission Computed Tomography) and PET (Positron Emission Tomography) are medical imaging techniques in which a radiotracer is injected into the subject to study.
- The concentration of tracer is measured by detecting the products of nuclear reactions.
- Differently from transmission imaging techniques (e.g. X-Rays) the information is both morphologic and physiologic

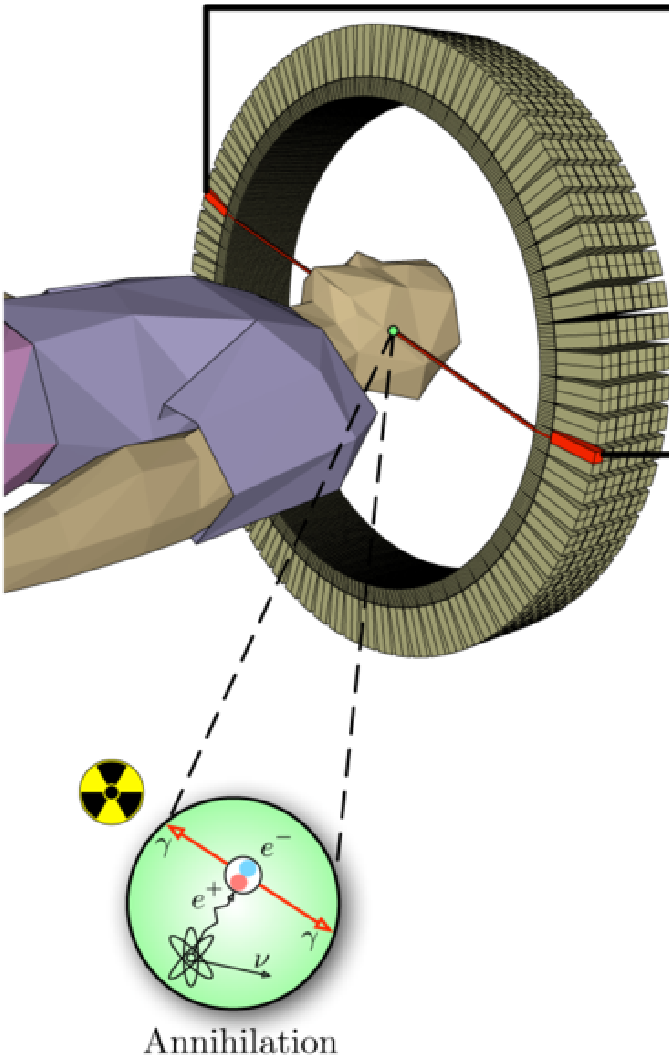
SPECT



PET

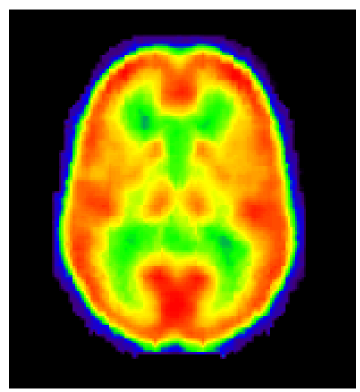


Positron Emission Tomography

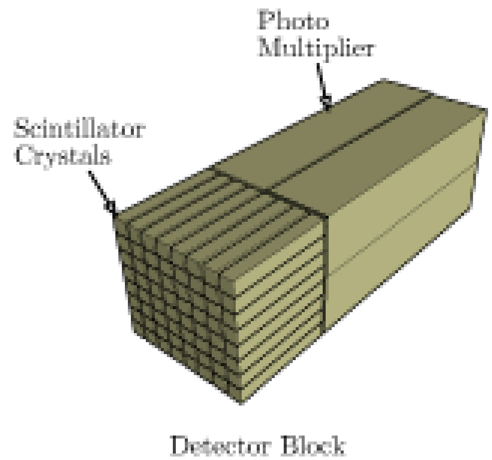


Coincidence unit of 2 anti-parallel photons

Tomographic reconstruction



Scintillator crystal
Multi-anode PMT



Typical image resolution
5 ÷ 10 mm

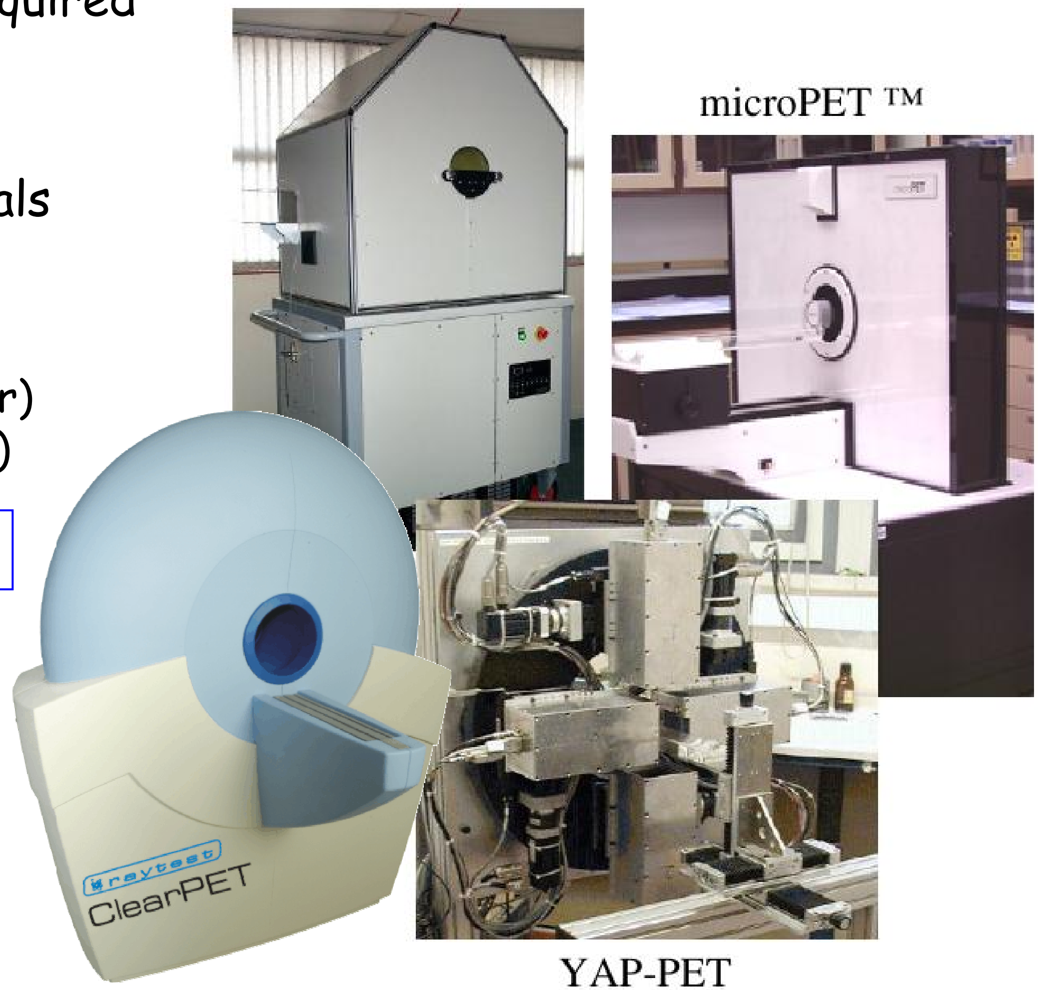
Small Animal PET

- Medicine experimentation on mice
- Very high image resolution required
- Low efficiency tolerated
(increase the dose)
- Mostly based on exotic crystals
YAP, LSO, LYSO, LuAP
- 2 gaseous detectors:
  - HIDAC (MWPC with Pb converter)
  - RPC-PET (RPC with Cu converter)

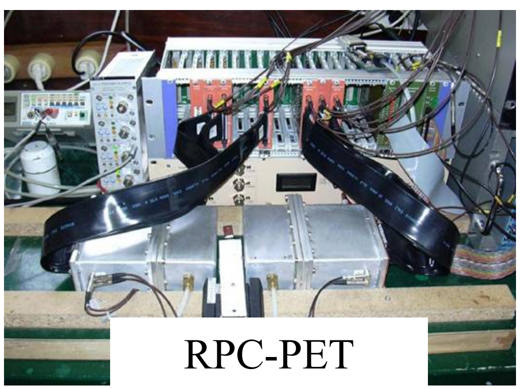
Spatial resolution: 2mm FWHM

HIDAC

microPET ™



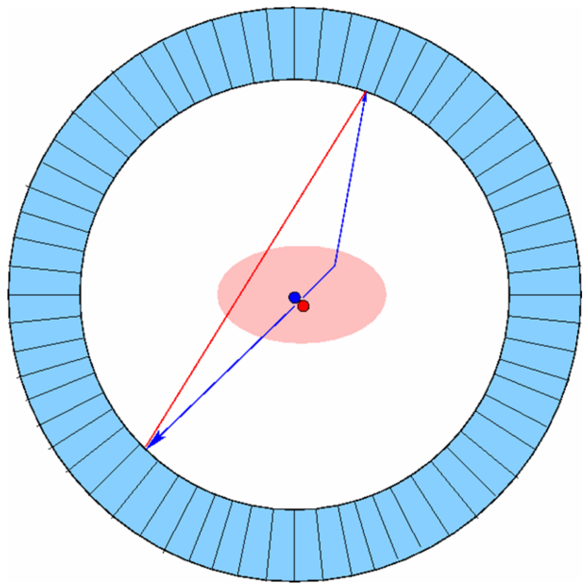
YAP-PET



RPC-PET

PET Image Degradation Sources

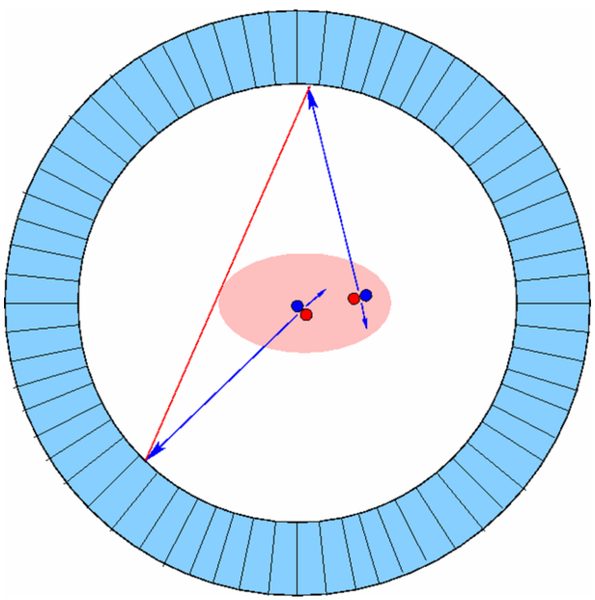
Scattered events



Anti-Compton with peak determination

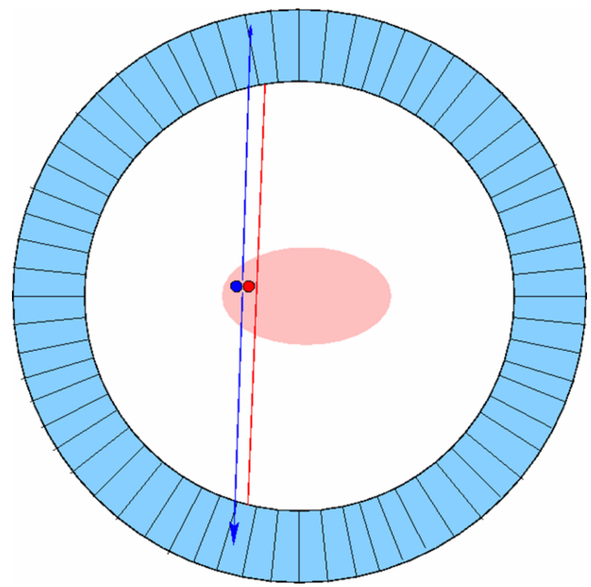
Energy resolution

Random coincidences



Off-center emission

Parallax error



Random events $\propto 2t_w$

Time resolution

TOF + DOI $\rightarrow$ constraint on Z reconstruction

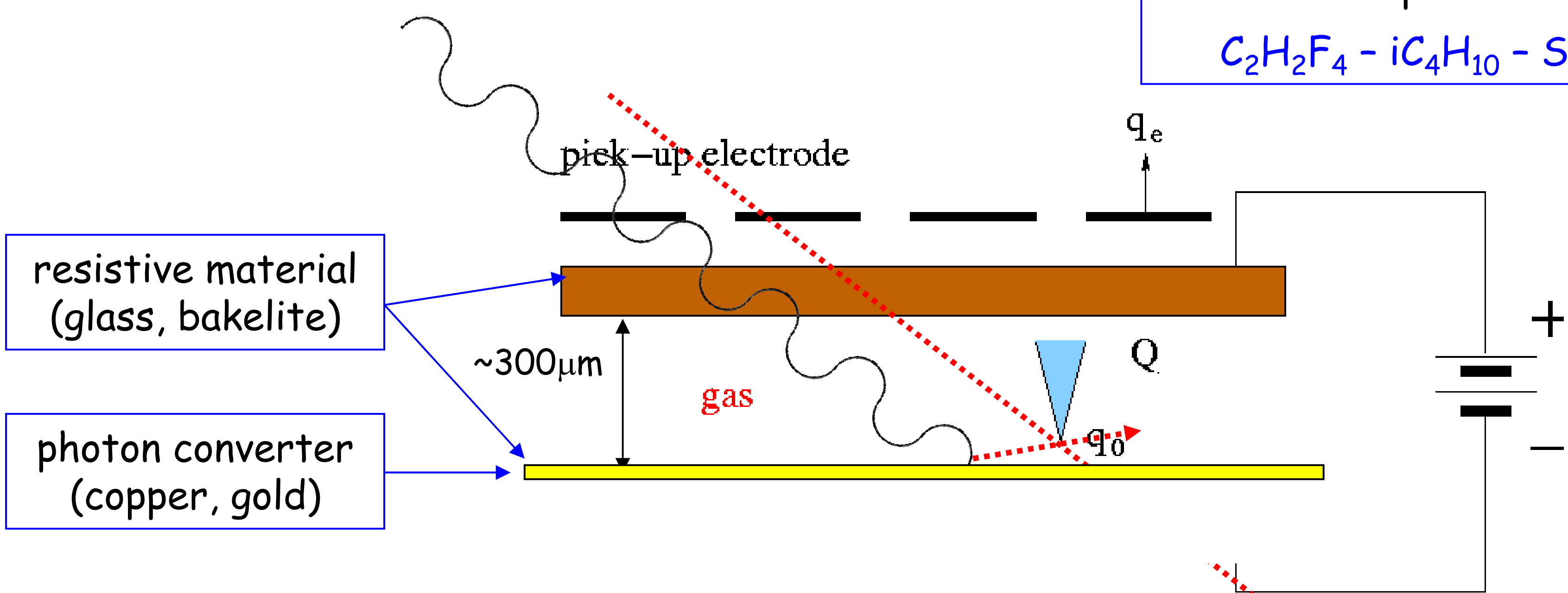
Depth Of Interaction determination

Microgap RPC Detectors

- Follow the concept of RPC developed by Santonico et al. (NIM A377 (1981) 187)
- Very thin gap (~300 μm) to enhance the time resolution (~100 ps →Δz~3cm)
- Robust, reliable and relatively inexpensive
- Can be used for photon detection with suitable converter
- Modularity naturally allows a multi-layer design to increase efficiency
- No energy measurement (could be done by dE/dx)

Avalanche operation with

$C_2H_2F_4$ - iC_4H_{10} - SF_6



Time Resolution of μRPC

- Time resolution of a RPC can be parameterized as:

  $$\Delta\tau = \lambda / v$$

  λ is the mean free path of electrons in avalanche

  v is drift velocity of electrons

- LOW λ and HIGH v can be obtained with dense/fast gas mixtures:

  $C_2H_2F_4$ - iC_4H_{10} - SF_6

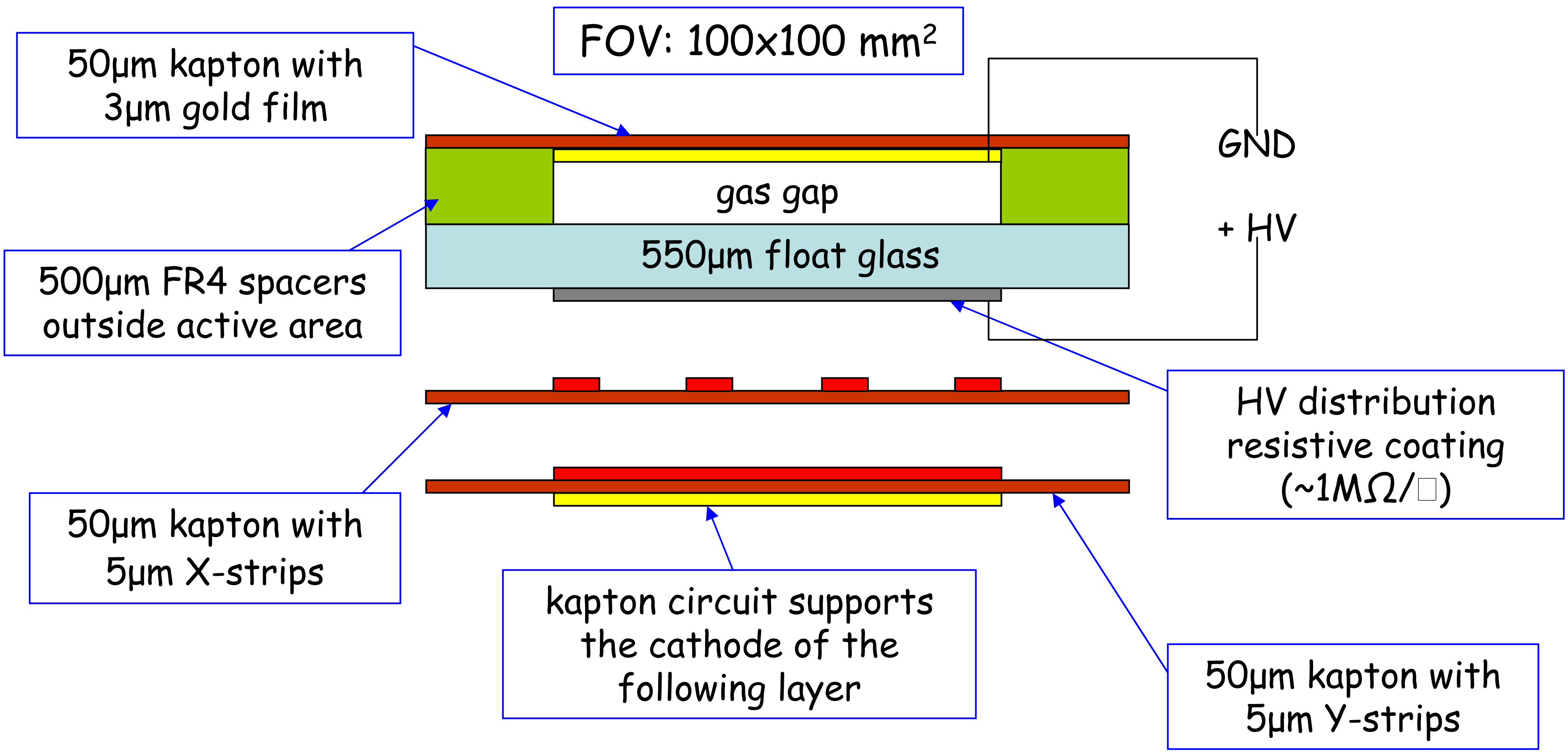
- Typical values: $\lambda \sim 10\mu m$, $v \sim 100\ \mu m/ns \rightarrow \Delta\tau \sim 100ps$
- To avoid discharges the gap must be reduced → MICROGAP
- Raether limit

  $G = e^{d/\lambda} < 10^8 \rightarrow$ for $\lambda \sim 10\mu m$ $\quad d_{gap} \sim 200\mu m$

- Single gap efficiency (MIPs): 80% (high ionization of freon gas: $Ni \sim 8mm^{-1}$)

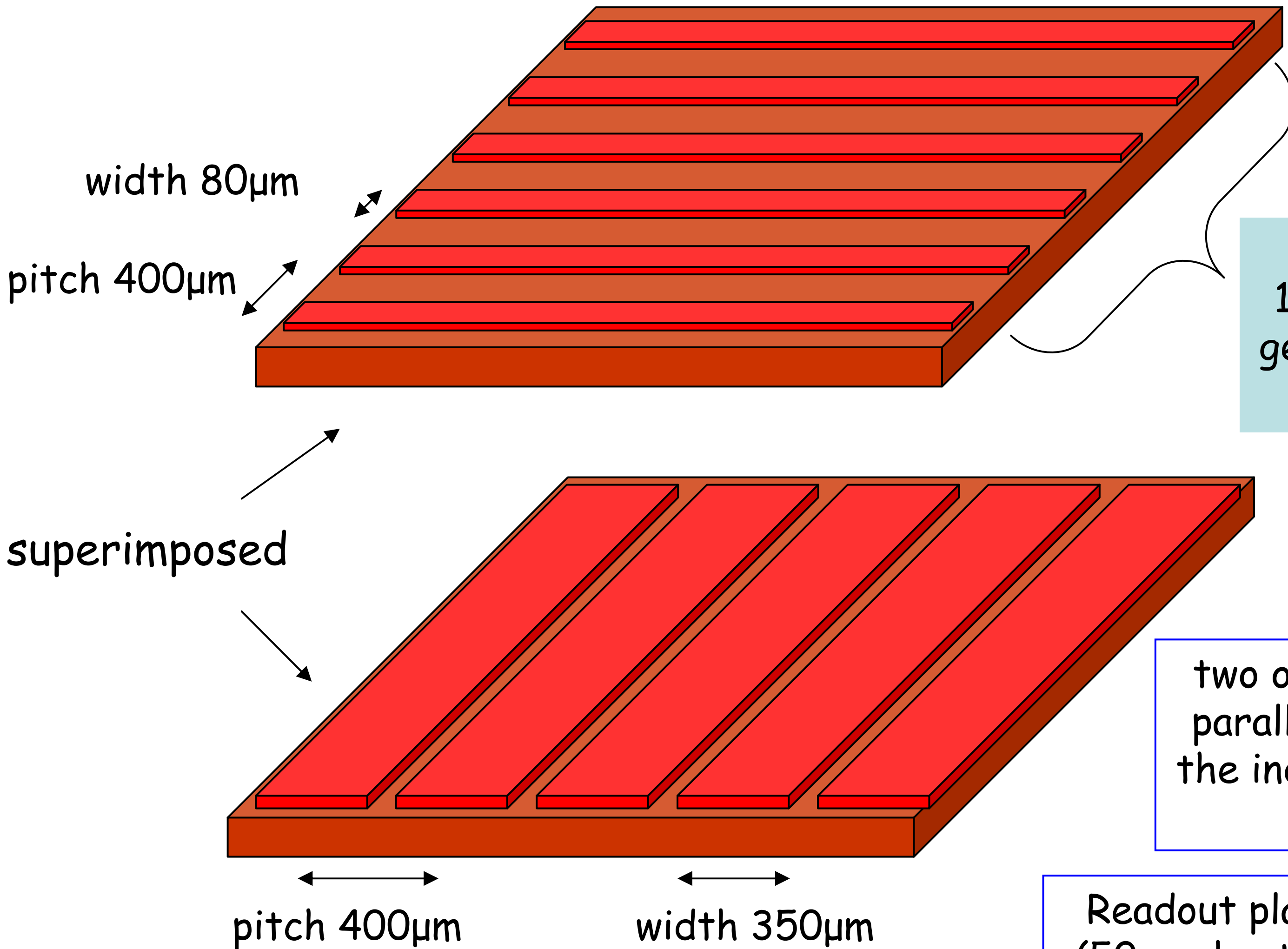
Hybrid Parallel Plate Counter

Hybrid: the anode is resistive (glass), the cathode is conductive (gold)



Many single layers are stacked to realize one detector

Readout Details



the strips are 10-fold ORed to get 4 mm readout pitch

two orthogonal sets of parallel strips perform the inductive readout of the signal

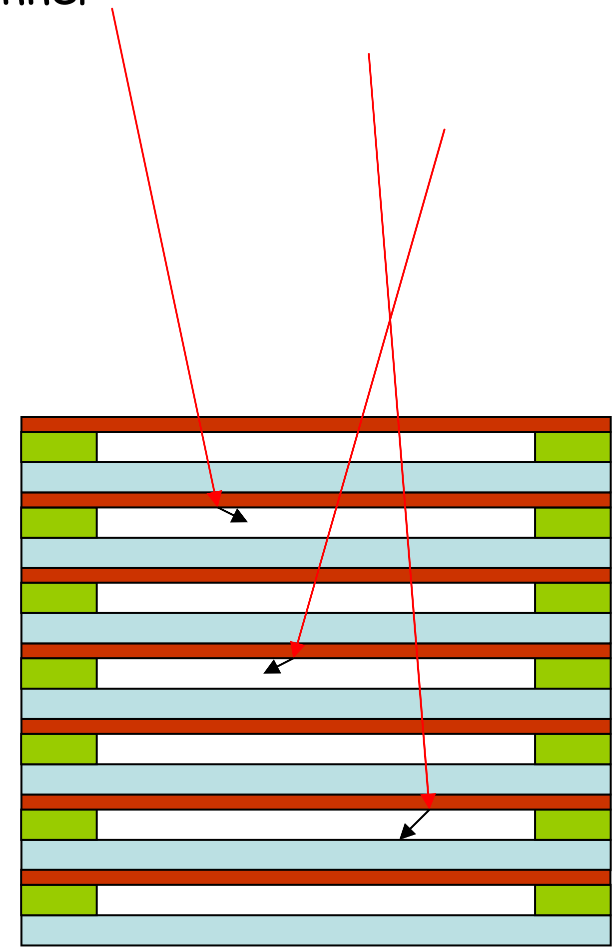
Readout planes made of PCB (50 µm kapton + 5 µm copper)

Hybrid Parallel Plate Counter

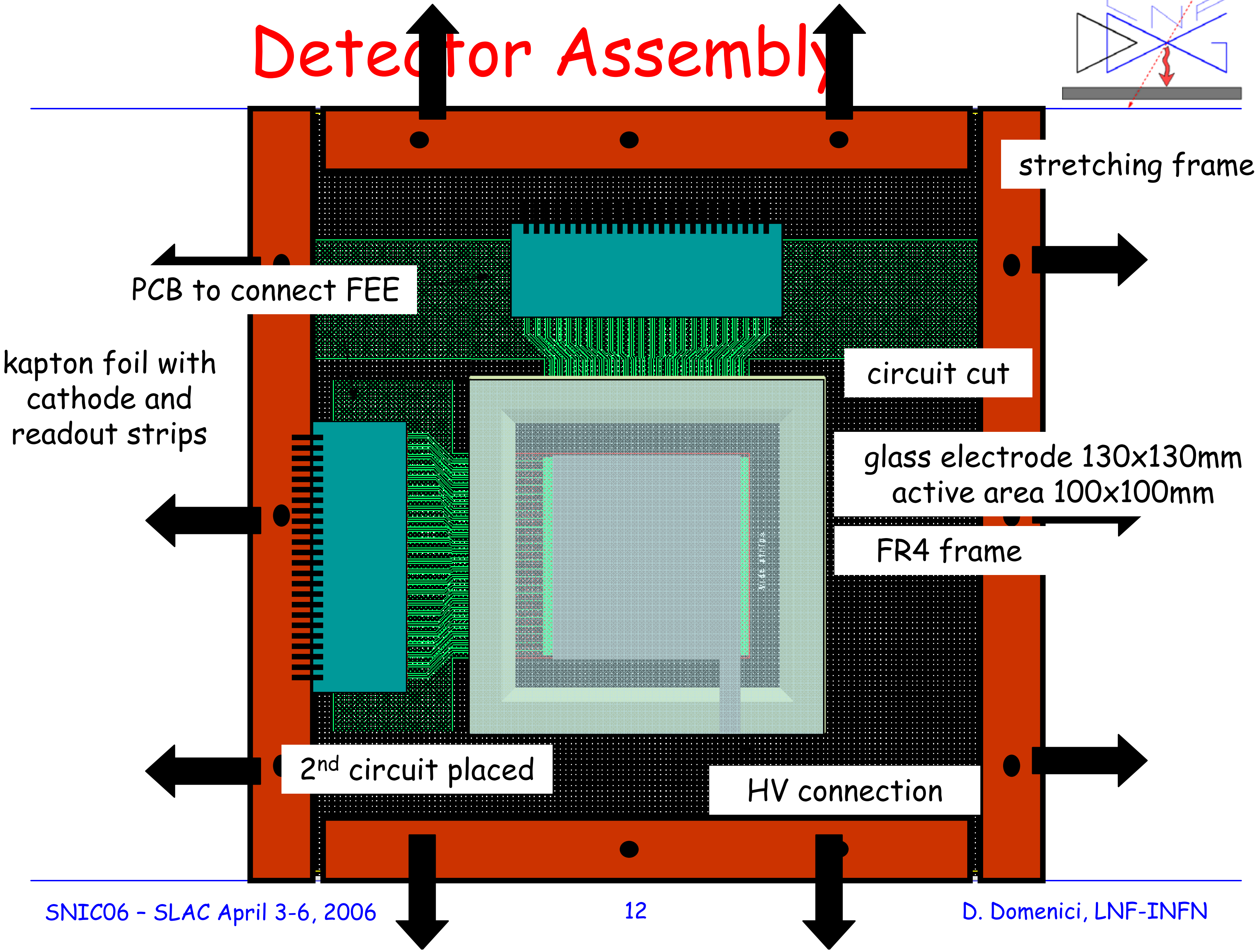
Basic design of HPPC for high-resolution PET scanner

First HPPC prototype

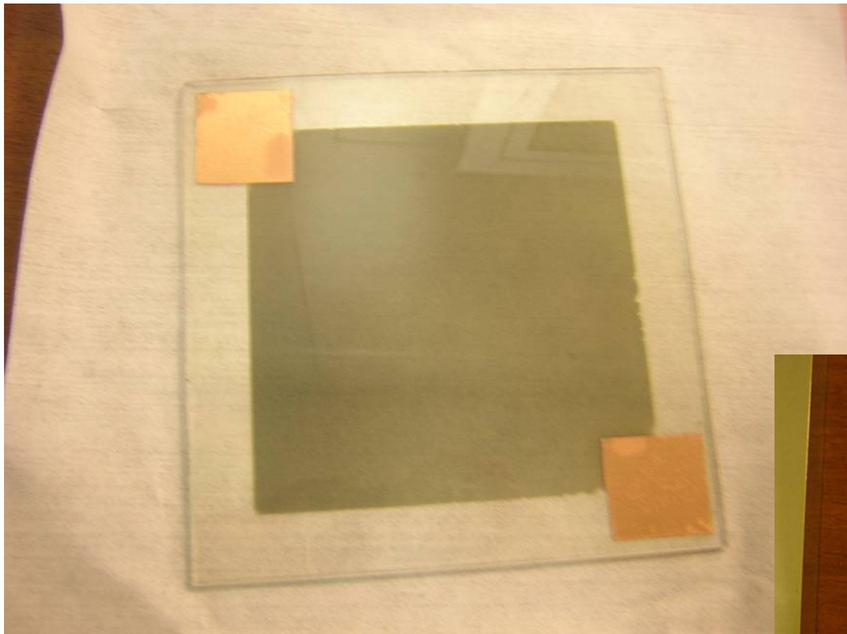
- 48 stacked single RPC
- Readout planes are 4-fold ORed
- X-Y: 4 mm digital readout pitch
(OR of 10 strips: 1.2 mm spatial resolution)
- Z: ~2 mm measurement of Depth Of Interaction
(OR of 4 layers: 12 planes for parallax correction)
- ~200 ps time resolution
- ~10% photon efficiency
- ~100x100 mm^2 Field Of View
- 2 heads for coincidences detection



Detector Assembly

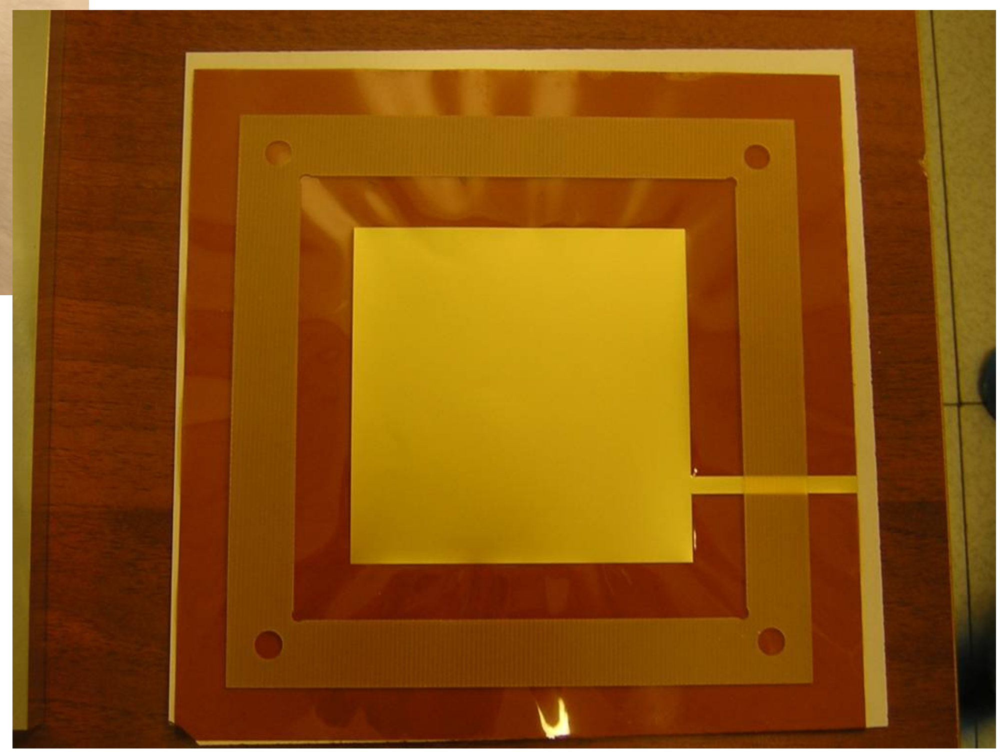


Prototype Parts

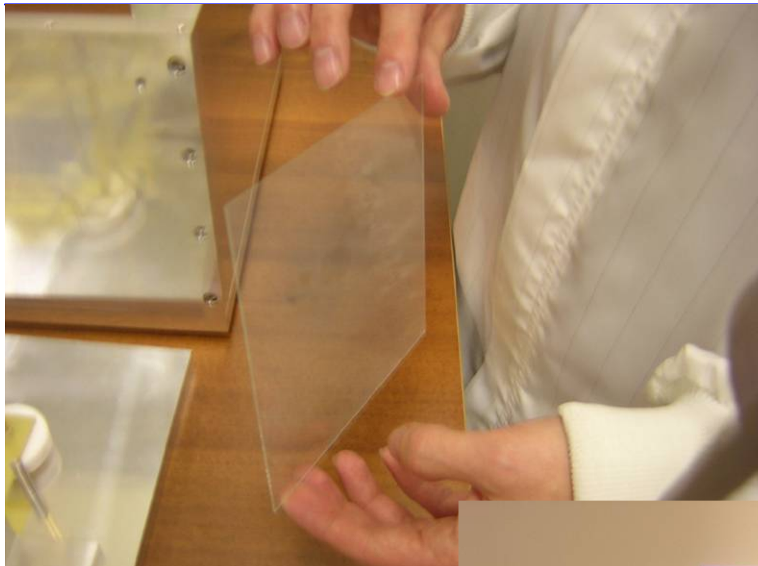


Glass electrode with resistive coating to distribute HV

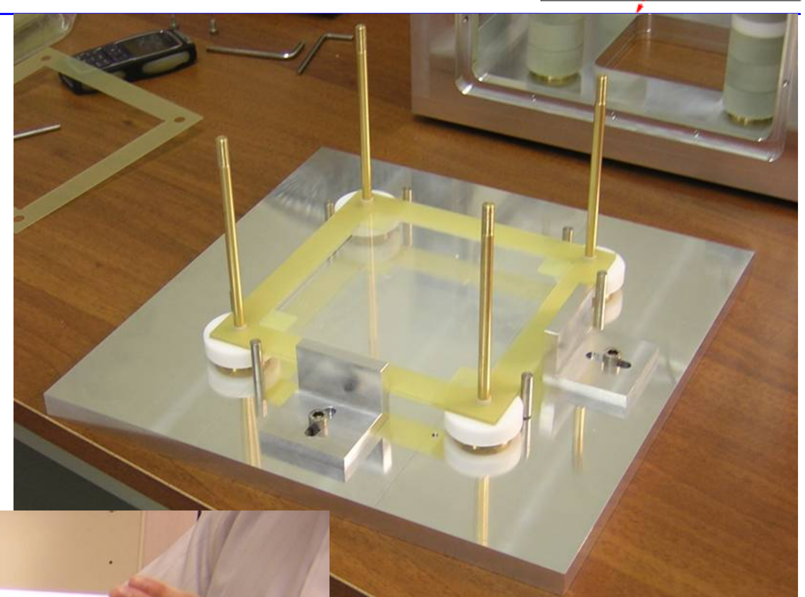
Gold electrode deposited on kapton foil with FR4 frame



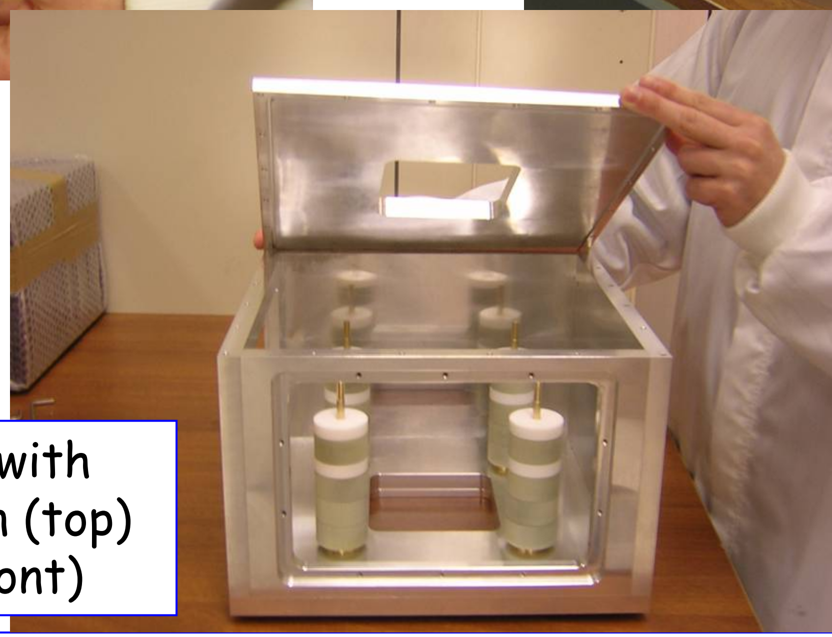
Prototype Parts



130x130 thin glass (0.5 mm)

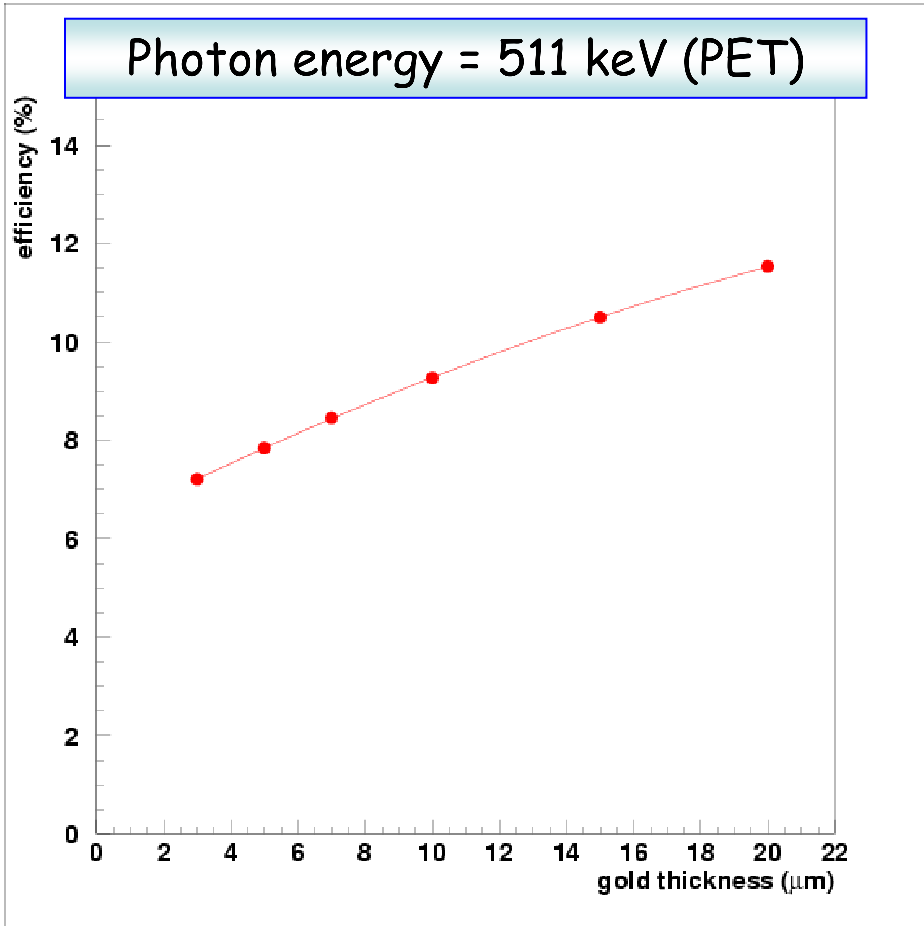


Assembly tool with references to stack layers



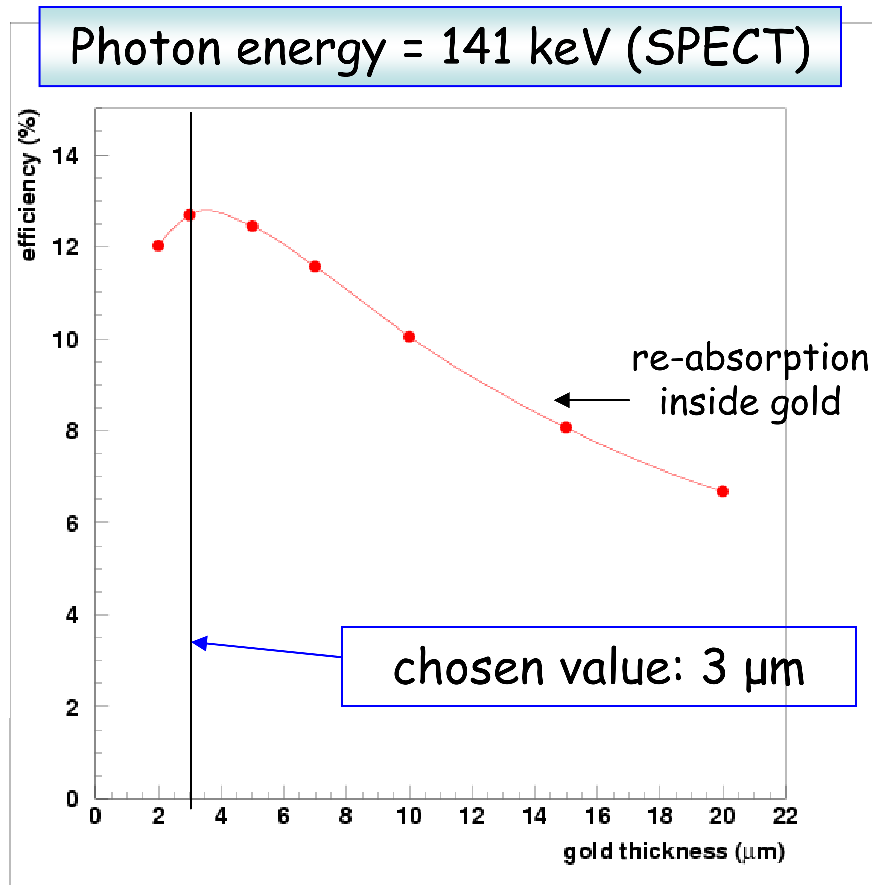
Final detector box with windows for radiation (top) and electronics (front)

Efficiency vs gold thickness



48 gaps

All simulations performed with FLUKA



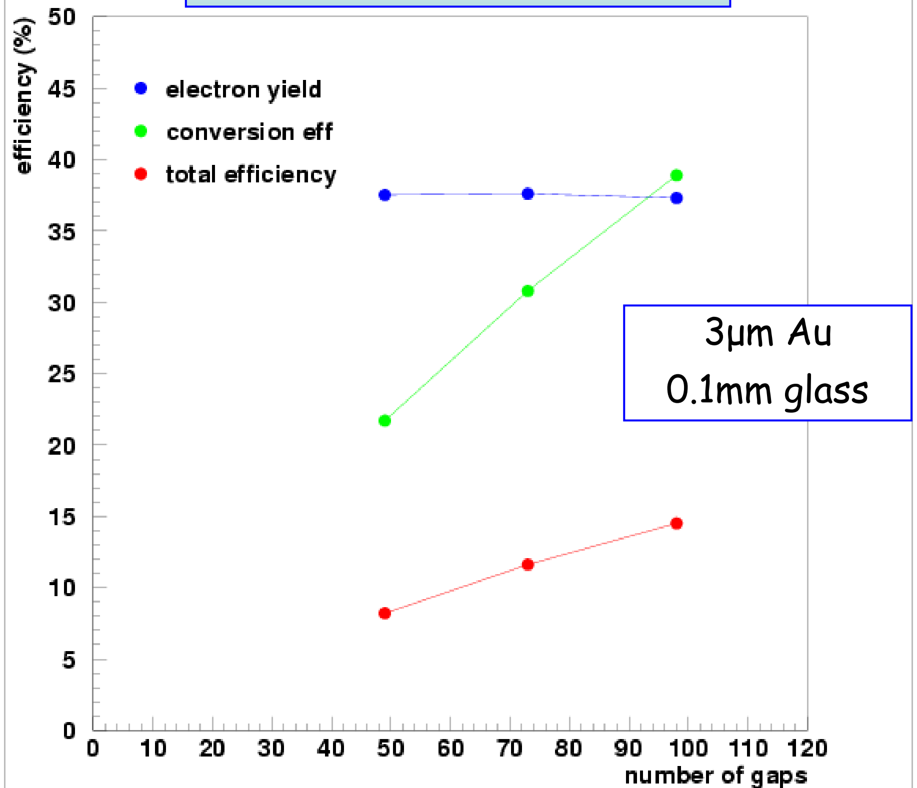
Efficiency - PET (511 keV)

$$\text{el. yield} = \frac{\text{ionizing } e^-}{\text{converted } \gamma}$$

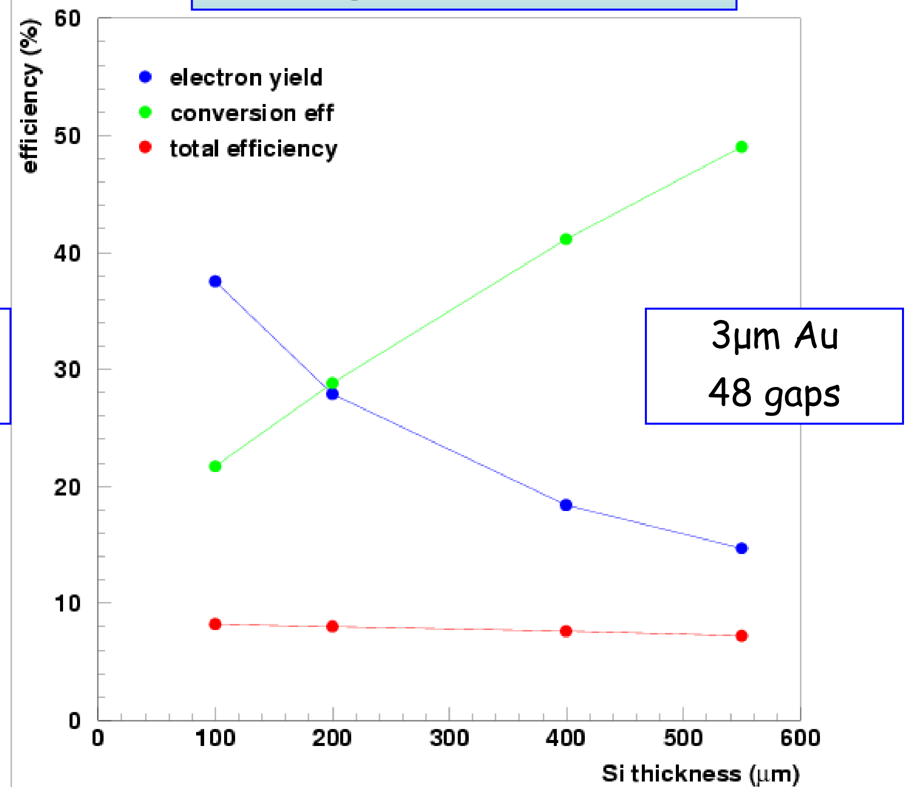
$$\text{conversion eff.} = \frac{\text{converted } \gamma}{\text{incoming } \gamma}$$

$$\text{total eff.} = \frac{\text{ionizing } e^-}{\text{incoming } \gamma}$$

ε vs number of gaps

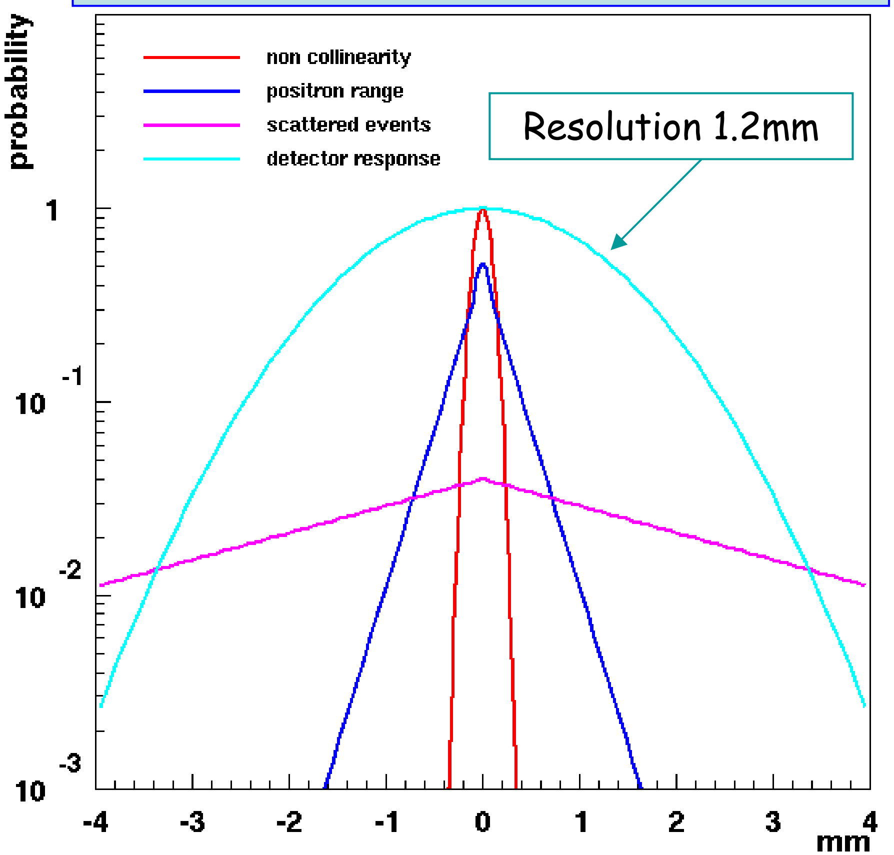


ε vs glass thickness



Intrinsic resolution limits

Prototype expected resolution



Annihilation photons non-collinearity

$$D(x) = \exp(-x^2/2\sigma^2) \quad \sigma = 9.36 \times 10^{-4} d_s$$

d_s is the system diameter (100 mm)

Positron range

$$D(x) = C_1 \exp(-k_1 x) + (1 - C_1)\exp(-k_2 x)$$

$C_1 = 0.529$; $k_1 = 46.2\text{mm}^{-1}$; $k_2 = 3.75\text{mm}^{-1}$

Scattered events

$$D(x) = C_2 \exp(-k_3 x)$$

$C_2 = 0.04$; $k_3 = 0.32\text{mm}^{-1}$

All parameters from

Phys. Med. Biol. 44 (1999) 781

J. Nucl. Med. 34 (1993) 101

IEEE TNS 33 (1986) 565

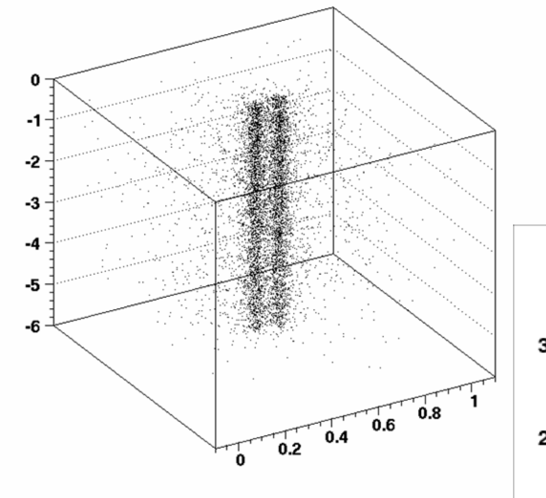
Proc. IEEE MIC (2004) M2-177

Photon Position Sensitivity

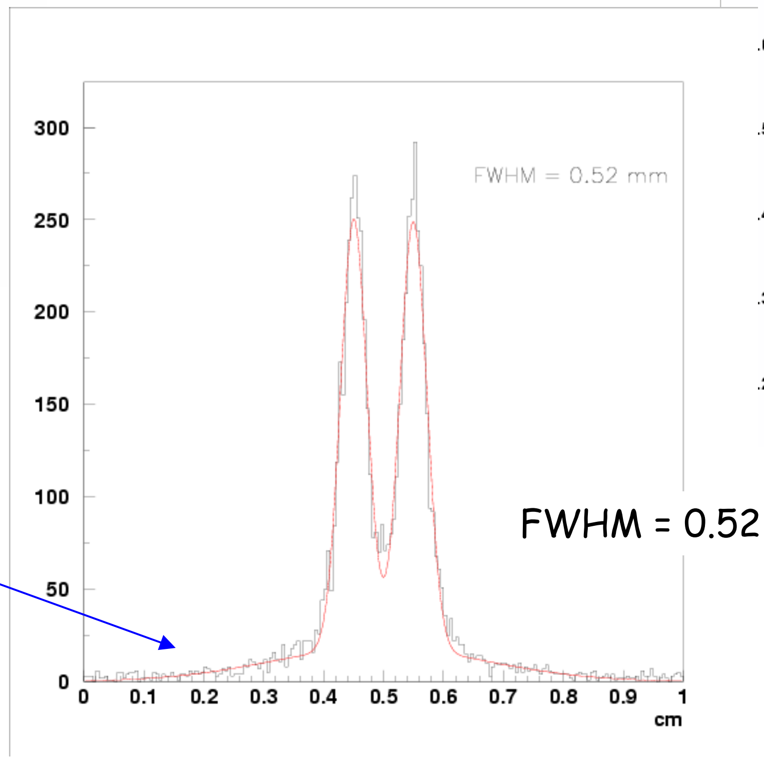
hit spatial position

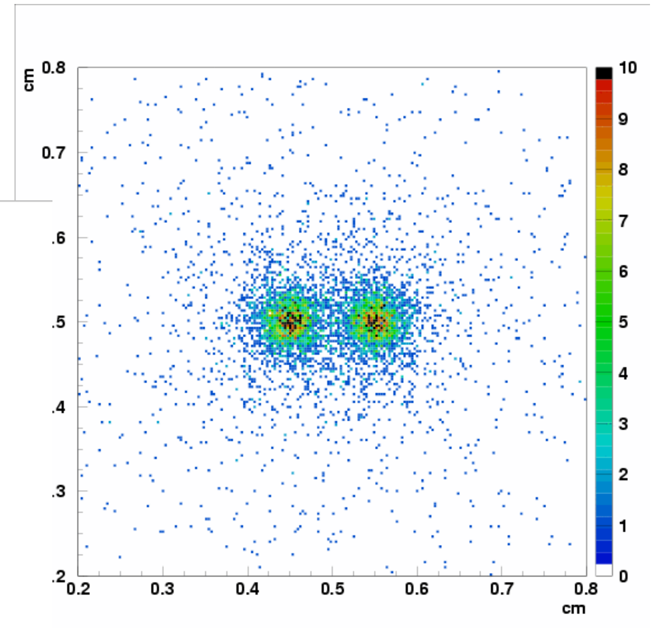
2 gaussian (σ = 0.2 mm)
sources separated by 1mm

X-Y view



peak separation





~5% fraction of scattered events

FWHM = 0.52 mm

10% degradation on resolution due to electron range

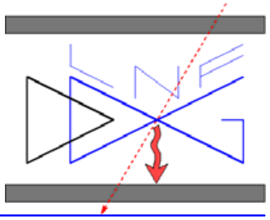
Conclusions and Perspectives

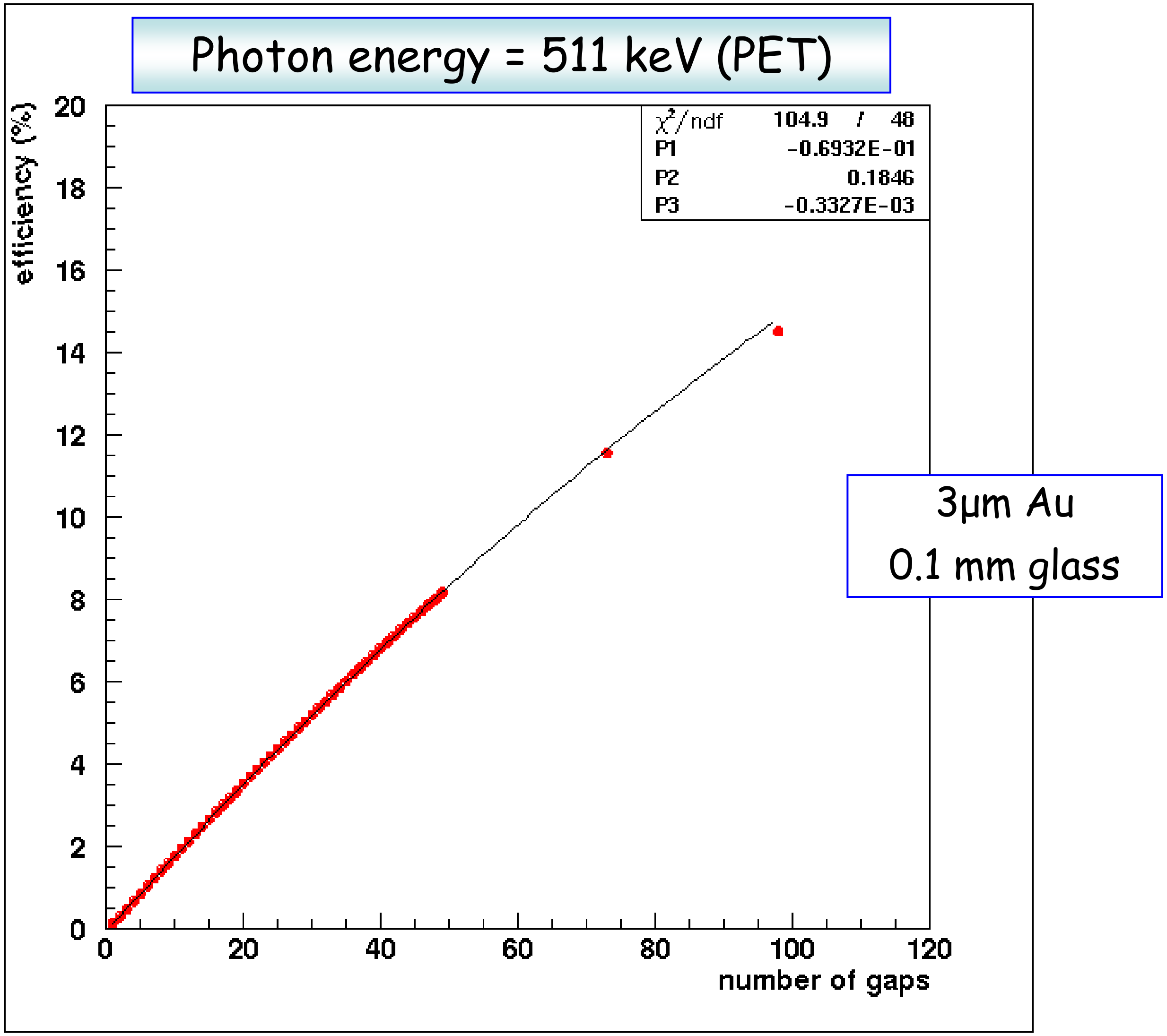
- HPPC: the LNF-INFN detector for Medical Imaging
- Gaseous detectors are valid alternatives to scintillator-based gamma cameras
- Micro-gap RPC technology exploited to achieve:
  - good space resolution and DOI measurement ⇒ better image quality
  - excellent time resolution ⇒ random counting suppression, reconstruction improvement
  - multi-layer ⇒ relative good efficiency
- Parameters optimized by detailed simulation
- Detector design finalized and all parts ordered

- Next steps
  - construction of the first double-head (48+48 layers) detector
  - test with a mouse size phantom filled with radiotracer
  - development of a dedicated FE electronics

We would like to acknowledge our technicians: E.Iacuessa, S.Lauciani and G.Papalino

Efficiency vs number of gaps





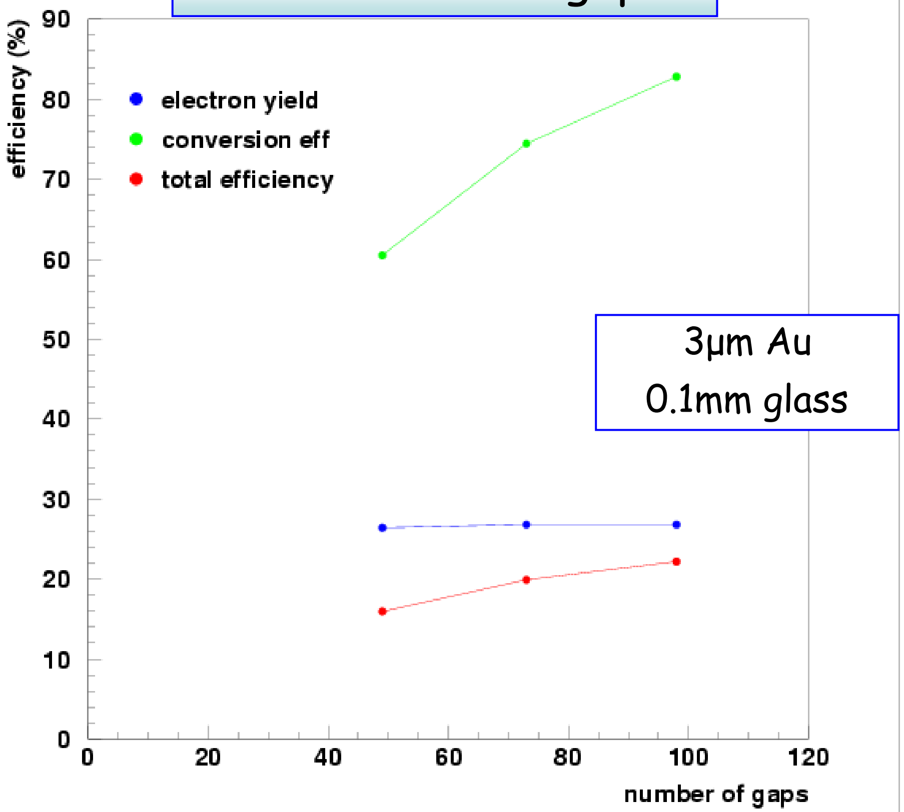
Efficiency - SPECT (141 keV)

$$\text{el. yield} = \frac{\text{ionizing } e^-}{\text{converted } \gamma}$$

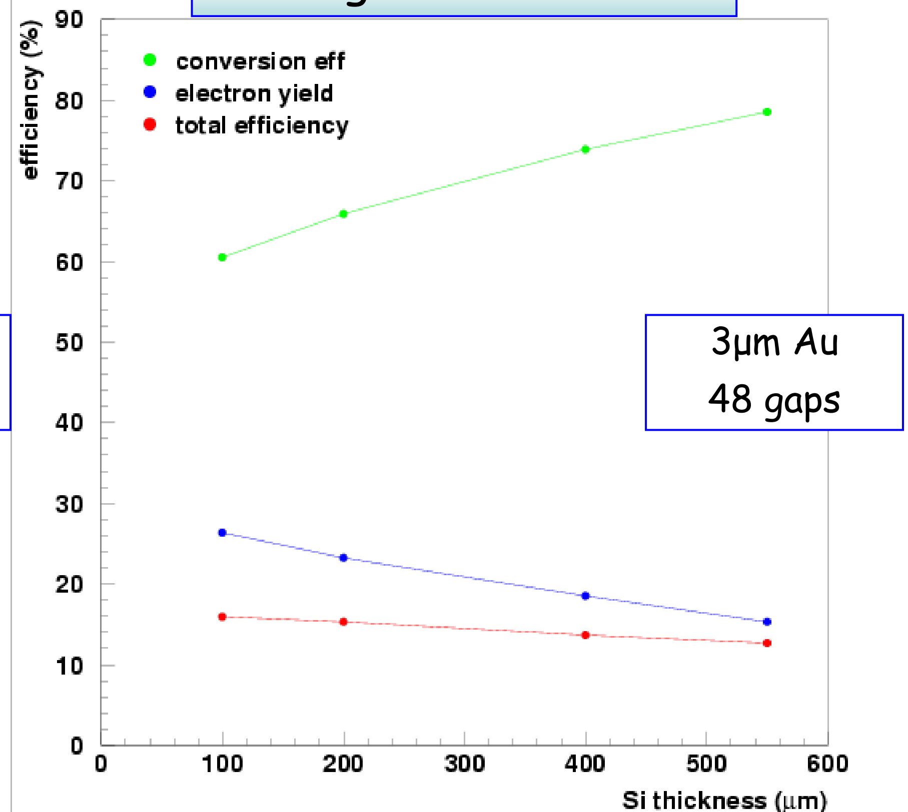
$$\text{conversion eff.} = \frac{\text{converted } \gamma}{\text{incoming } \gamma}$$

$$\text{total eff.} = \frac{\text{ionizing } e^-}{\text{incoming } \gamma}$$

ε vs number of gaps

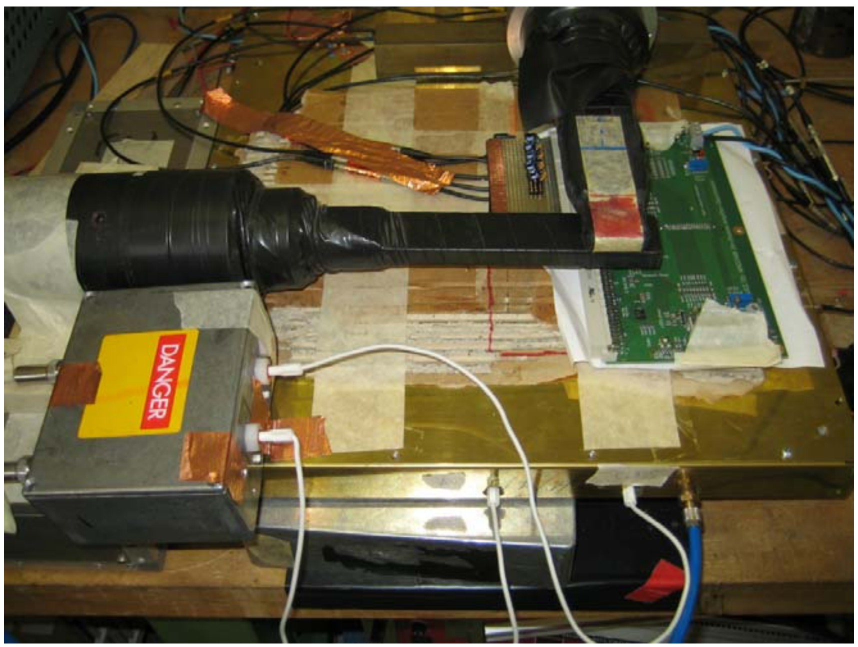


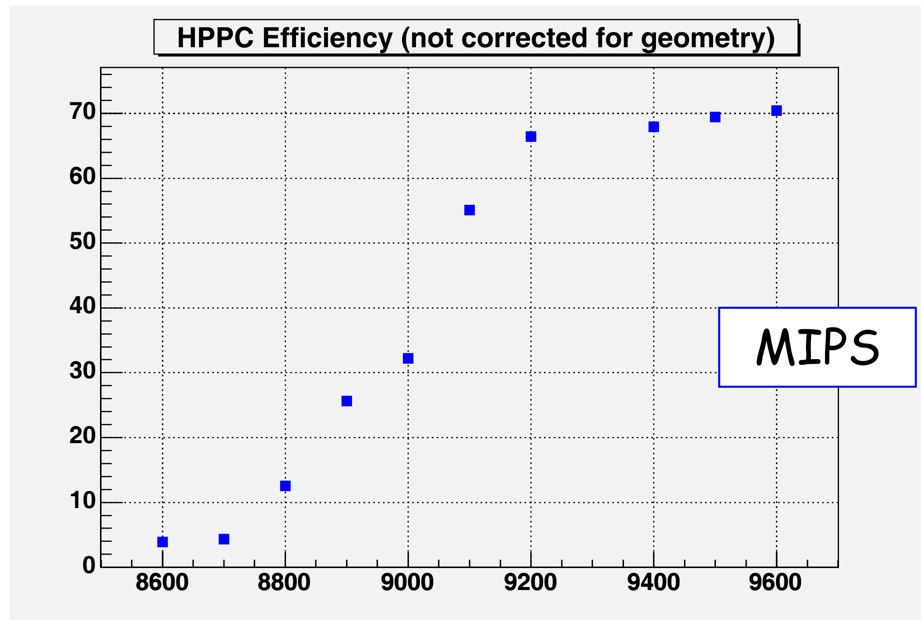
ε vs glass thickness



Cosmic Ray Measurements

- We started a cosmic rays test on a very preliminary prototype (2mm gas gap)
- Next step is to build the first prototype and test it with gamma sources





MIPS

gas mixture

$C_2H_2F_4$:iC_4H_{10} = 96:4