A multigap RPC based detector for gamma rays

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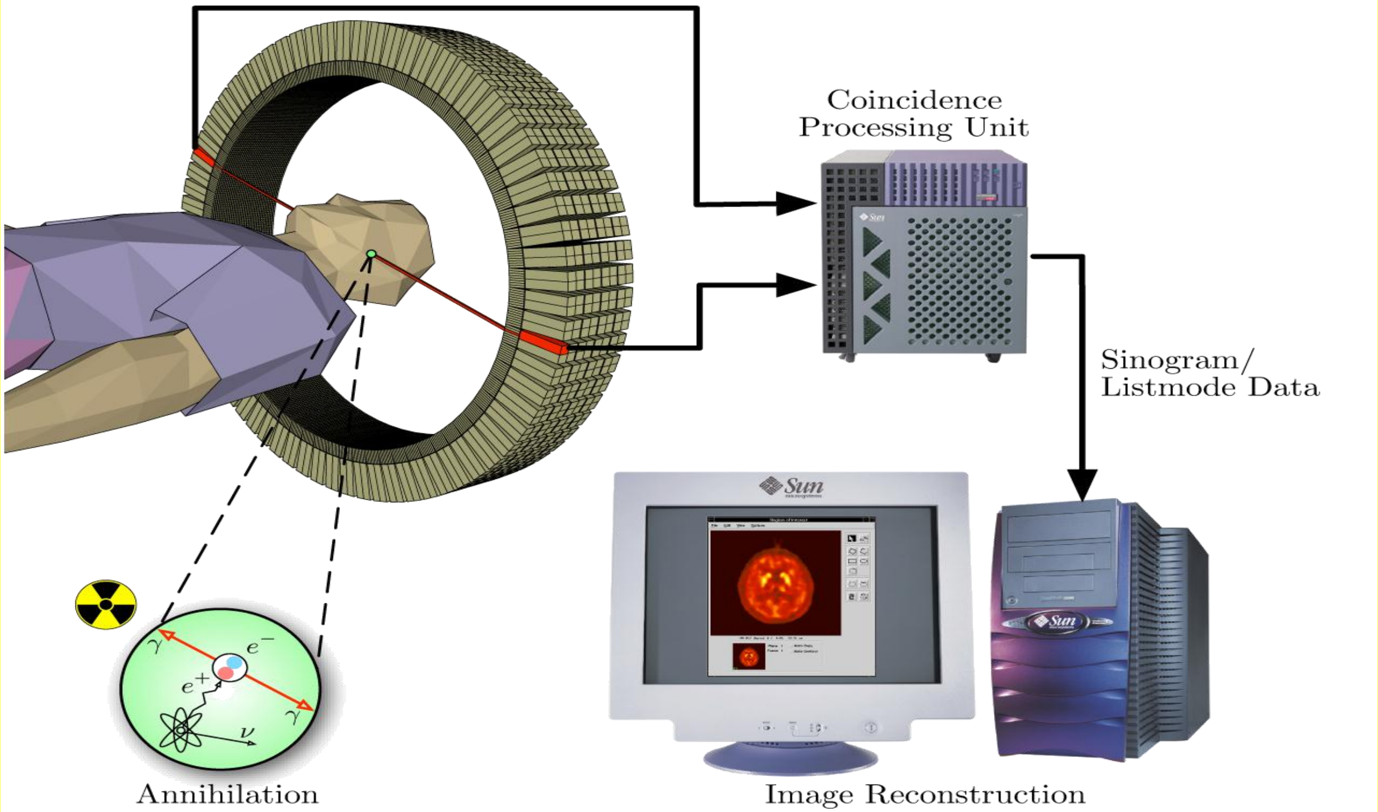
Content

- What is a Positron Emission Tomography (PET) ?
- What is an RPC ?
- Why to use RPCs in a PET system ?
- Different designs
- Simulation results
- First prototypes and tests
- Conclusions

Positron-Emission Tomography (PET)



PET is used on:

- **Humans by doctors for disease diagnosis (a typical dose is 8 mSv)**
- **On small animals by pharmaceutical companies for drug design (a typical dose is ~ Gy)**

The concept of emission and transmission tomography was introduced by David E. Kuhl, Luke Chapman and Roy Edwards in the late 1950s.

A good PET description:

- G. Muehllehner, J.S. Karp, *Phys. Med. Biol.* **51** (2006) R117-R137
- T.K Lewellen, *Phys. Med. Biol.* **53** (2008) R287-R317

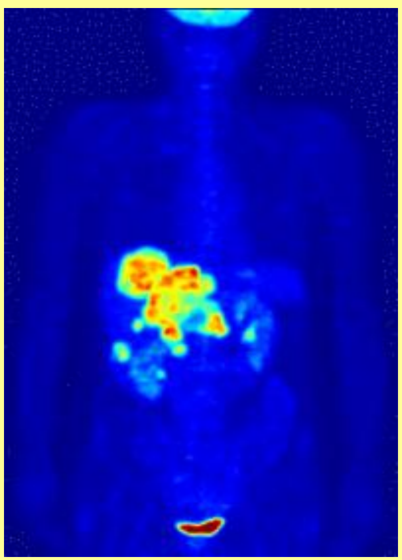
PET tracers

Usually cyclotrons are used to generate commonly used PET isotopes

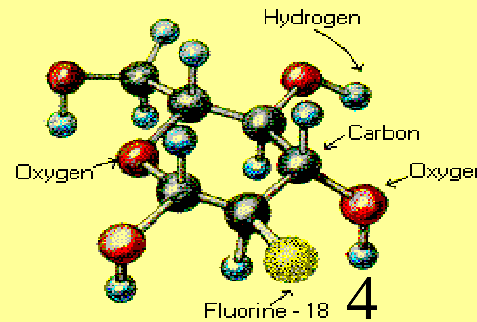
Isotope	Half life
	20.3 min
	2.03 min
	109.8 min
	98.0 min
	~10 min

Commonly used tracers:

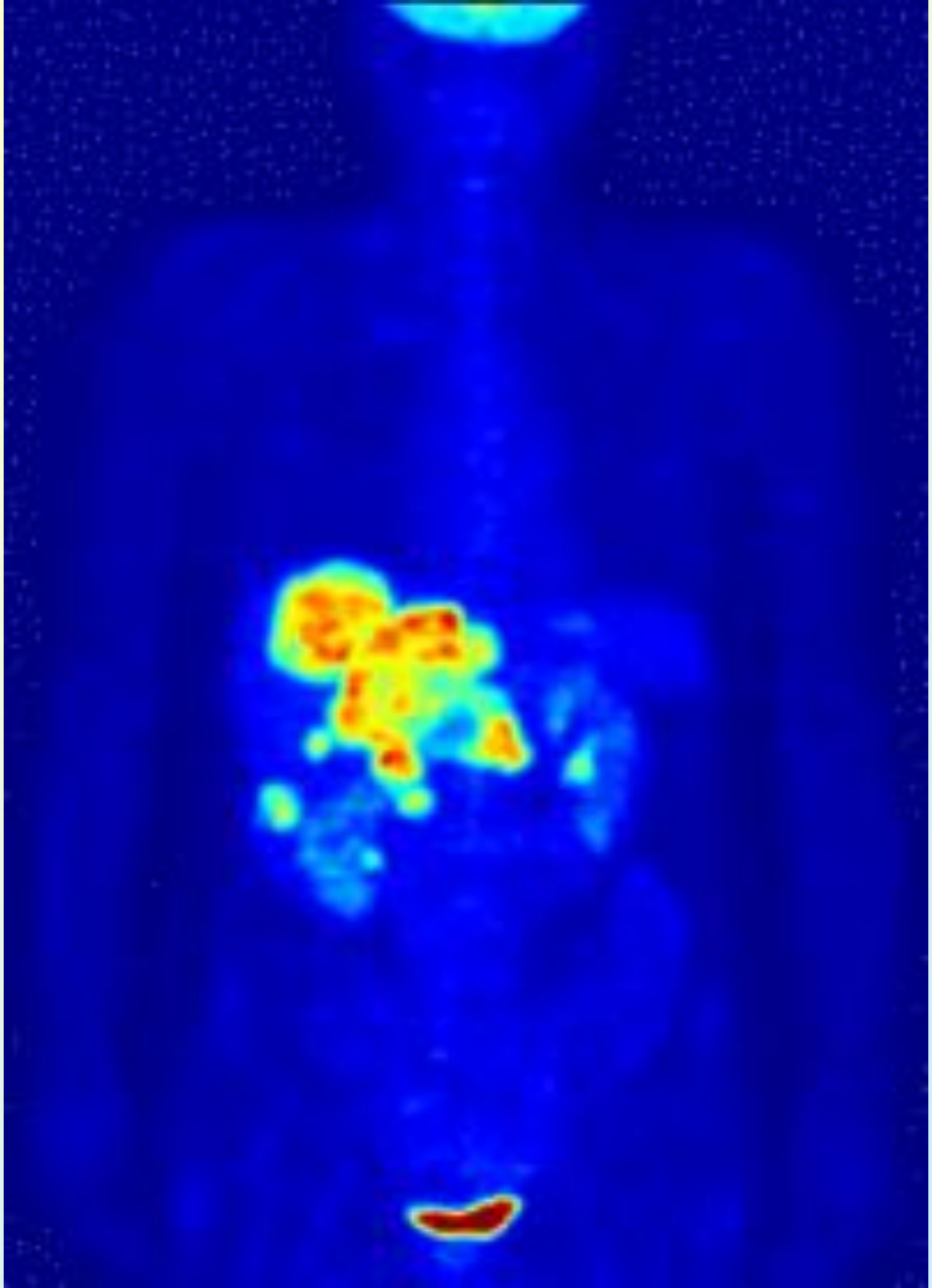
- water
- ammonia
- glucose and glucose analogues
- oxygen



FDG (fluorodeoxyglucose), as a glucose analogue, is taken up by high-glucose-using cells such as brain, kidney, and cancer cells.



Commercial PET



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PET modalities

- PET (dose ~ 8 mSv)
  - gives only functional/physiological information
  - poor/missing anatomical information
- PET-CT (dose ~ 16 mSv)
  - gives anatomical information
  - helps PET reconstruction
  - but higher dose, due to the X-rays (~ 16 mSv)
- PET-MRI (dose ~ 8 mSv)
  - gives anatomical information
  - soft tissue is visible on MRI
  - MRI gives additional morphological information
  - the dose is the same as in PET
  - but high magnetic field (affects PMTs)

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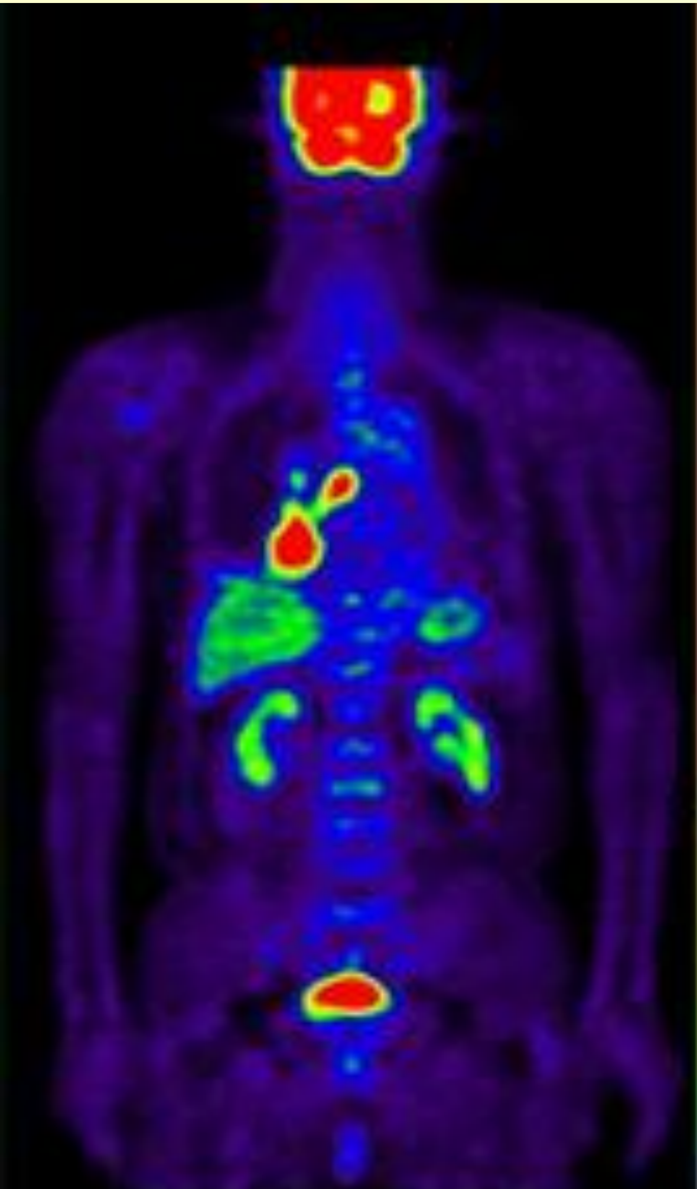
Natural background radiation (annul dose) 2.2 mSv

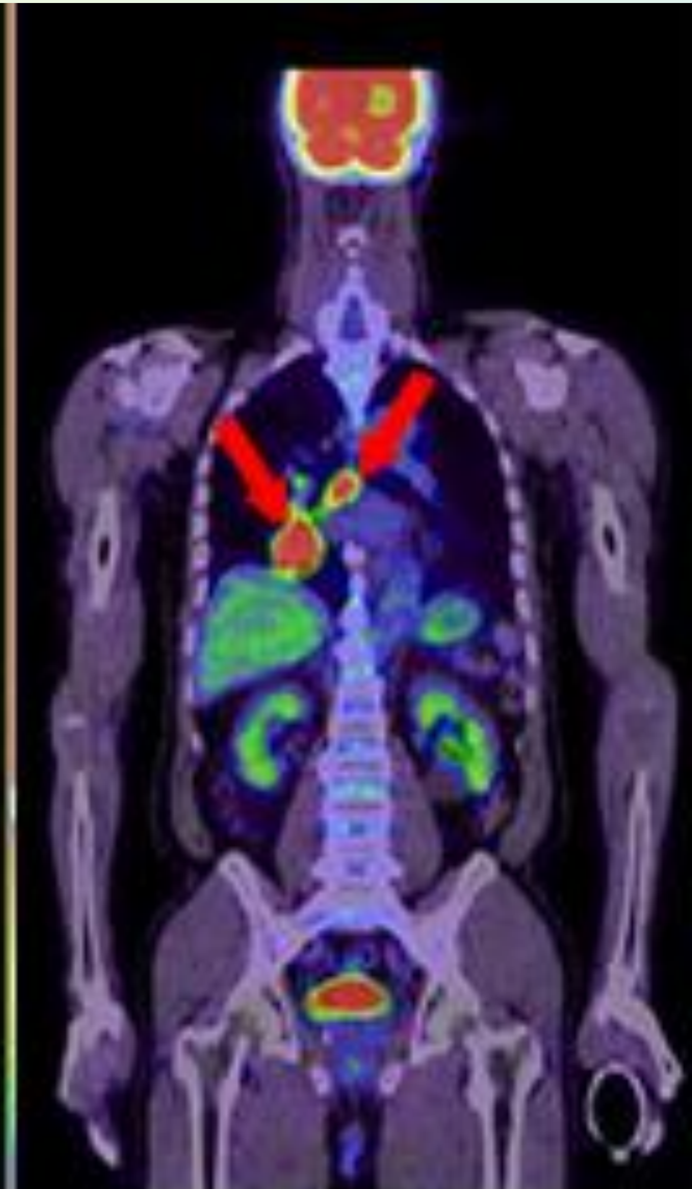
Single X-ray dose (for chest) 0.02 mSv

PET

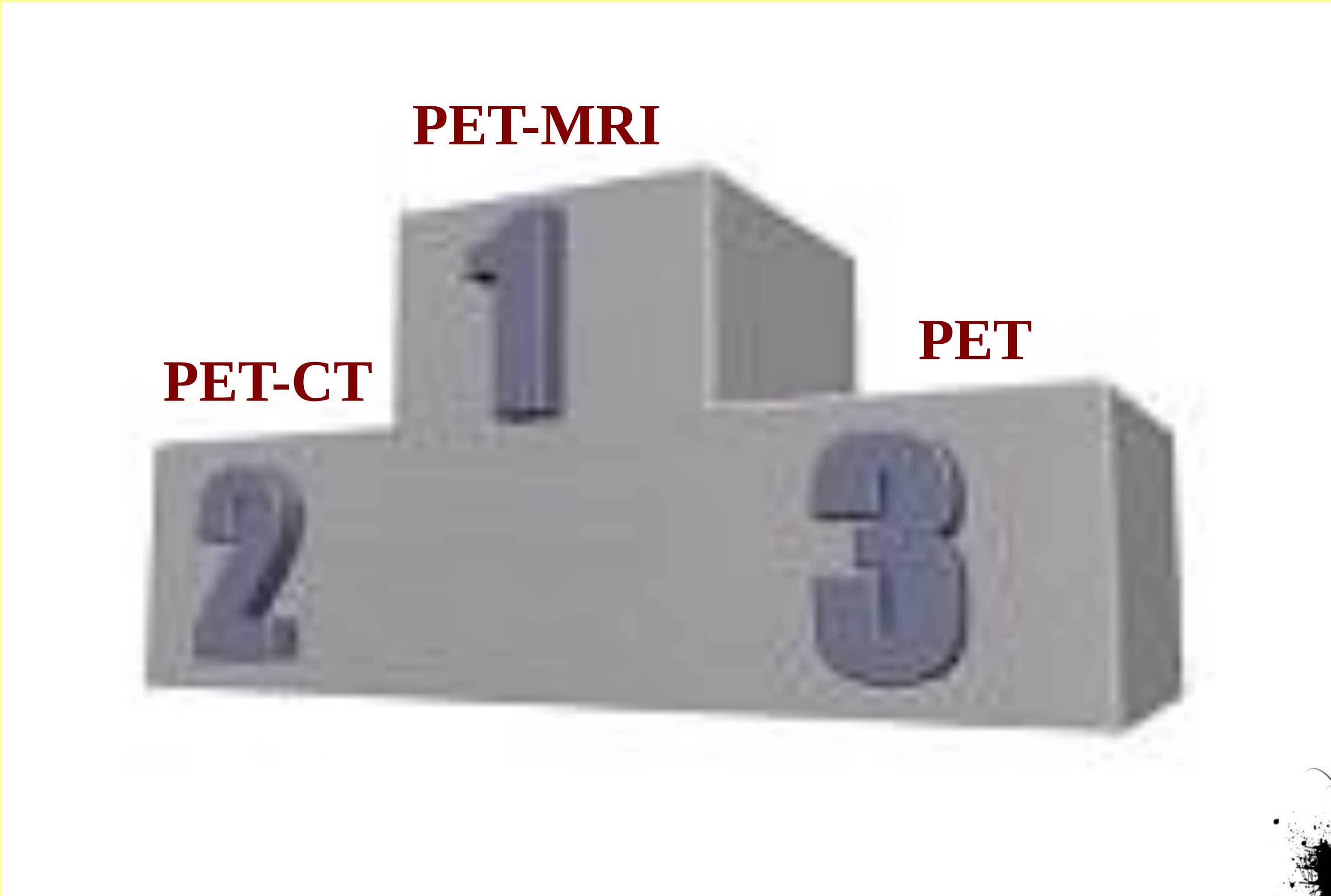


CT

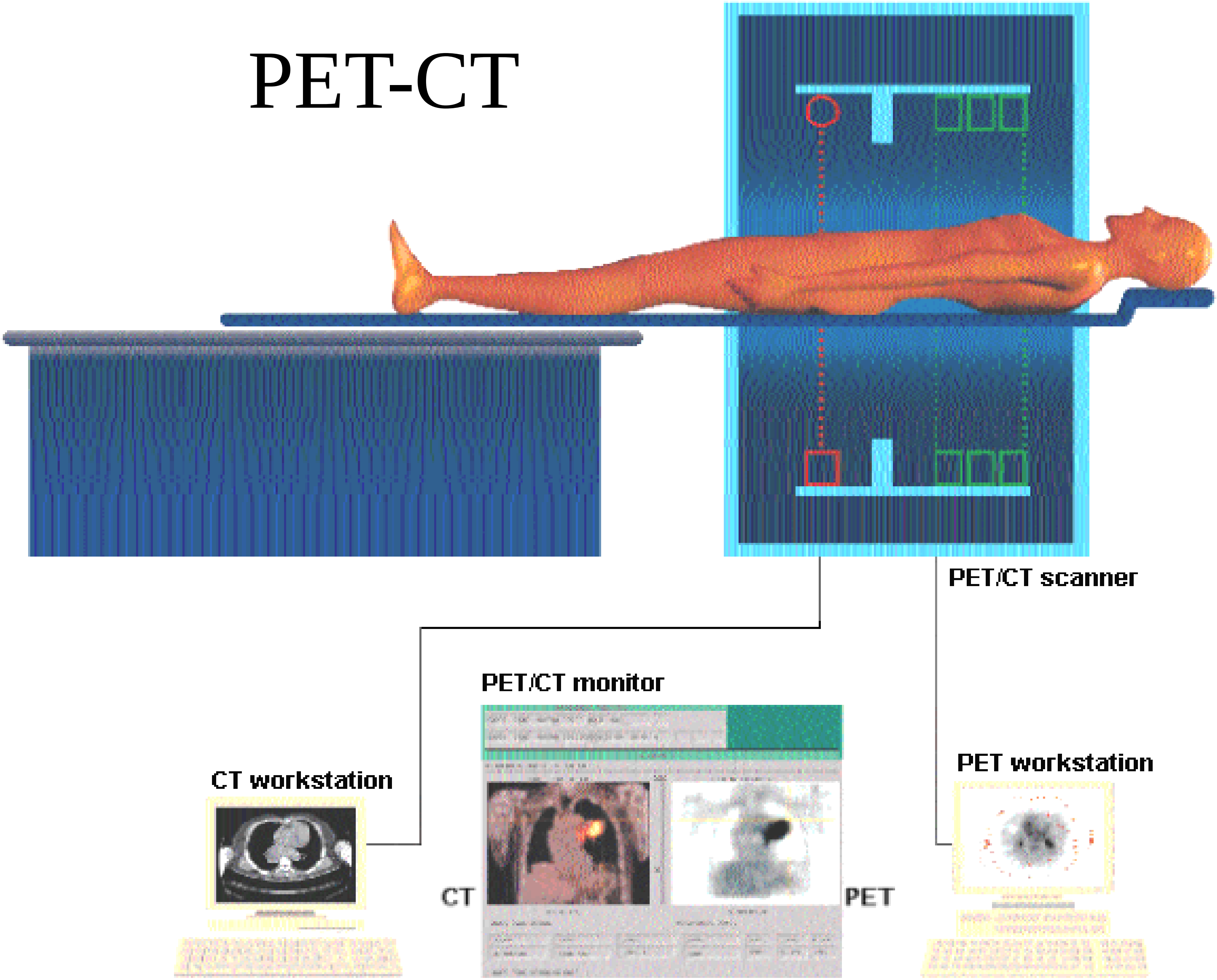
PET-CT



According to the medical doctors:

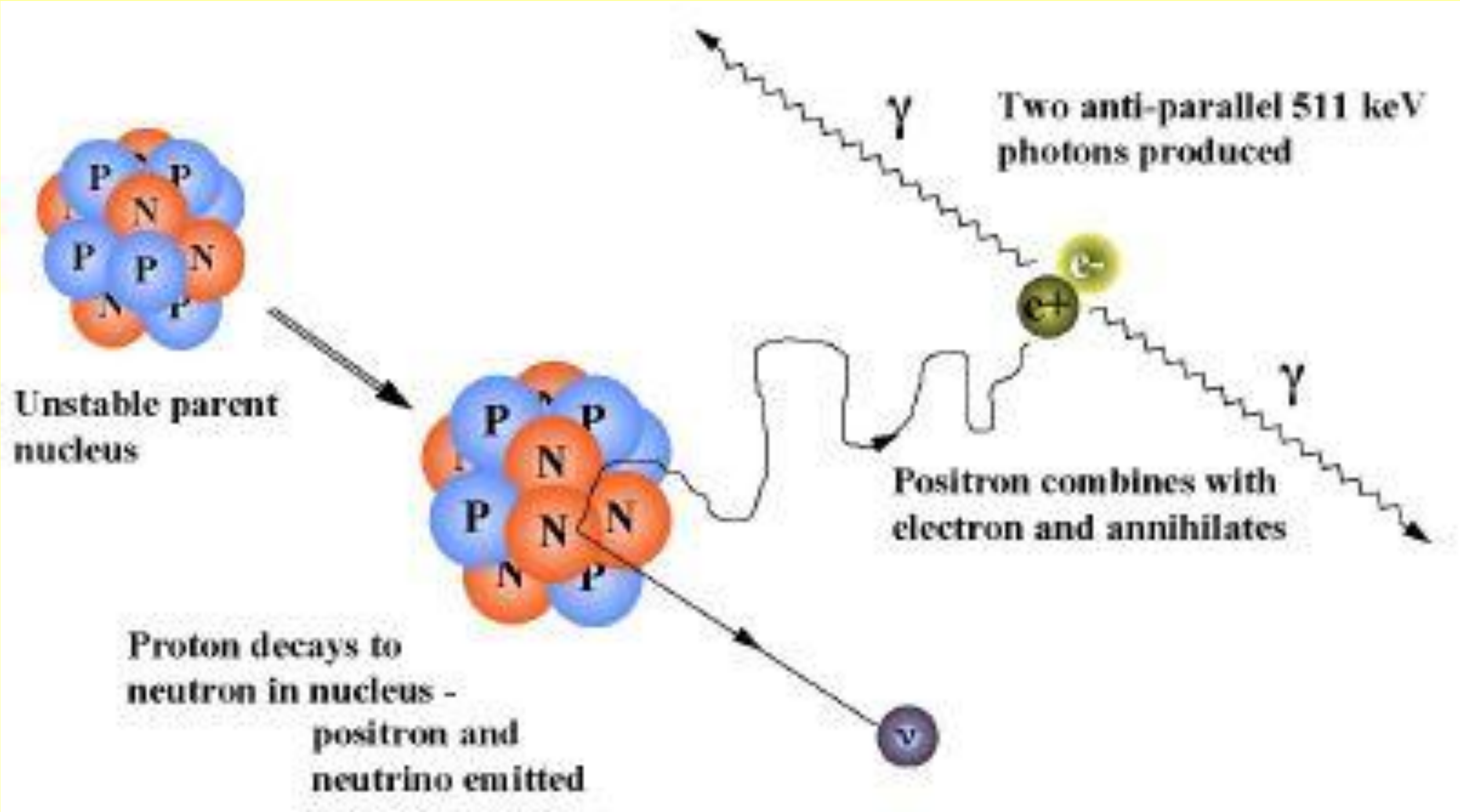


PET-CT


PET/CT scanner
PET/CT monitor
CT workstation
PET workstation
CT
PET

Prim

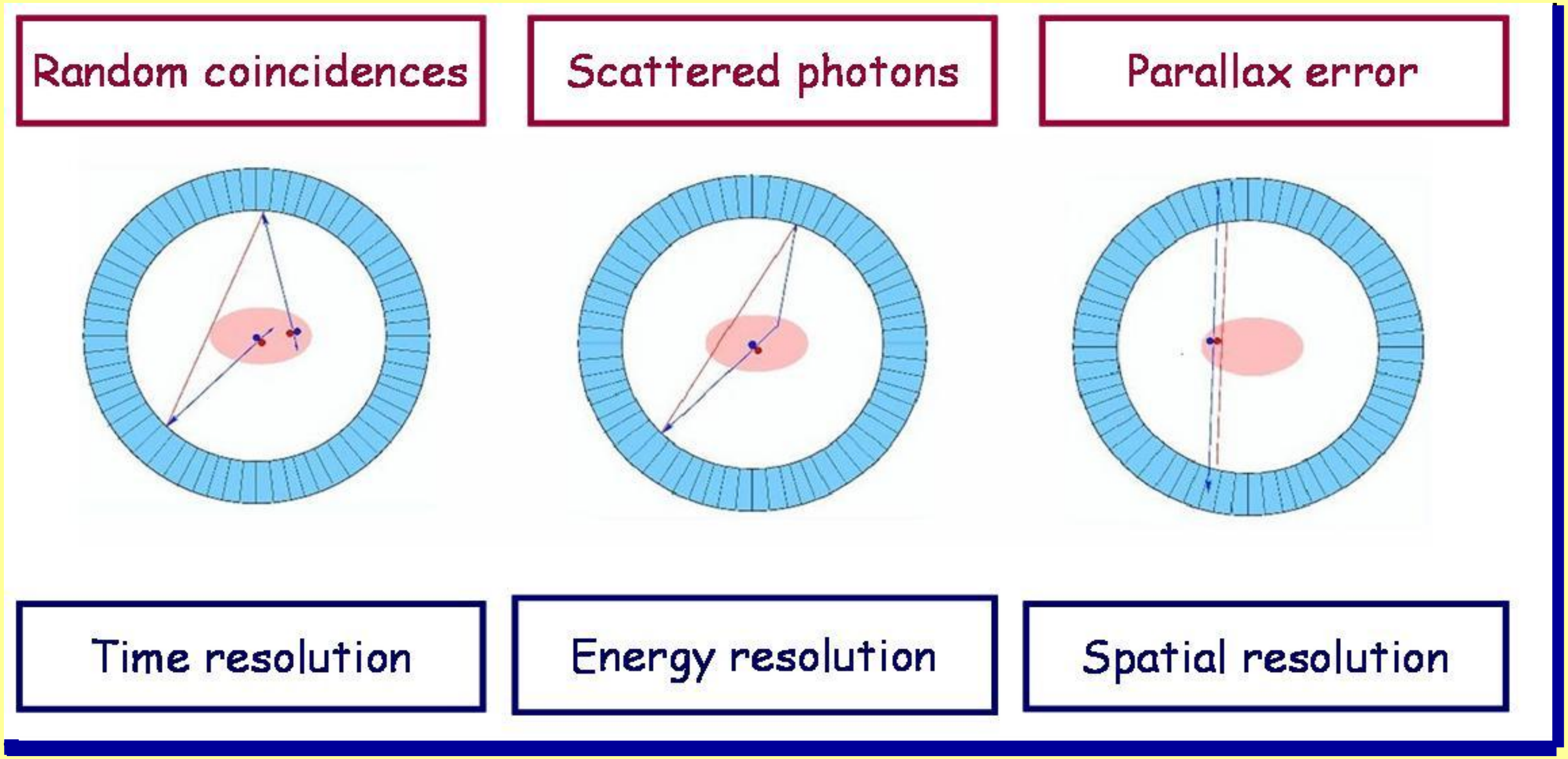
PET – physical limitations & problems



"Intrinsic" limitations are:

- **positron range in the medium**
- **photons non-collinearity**

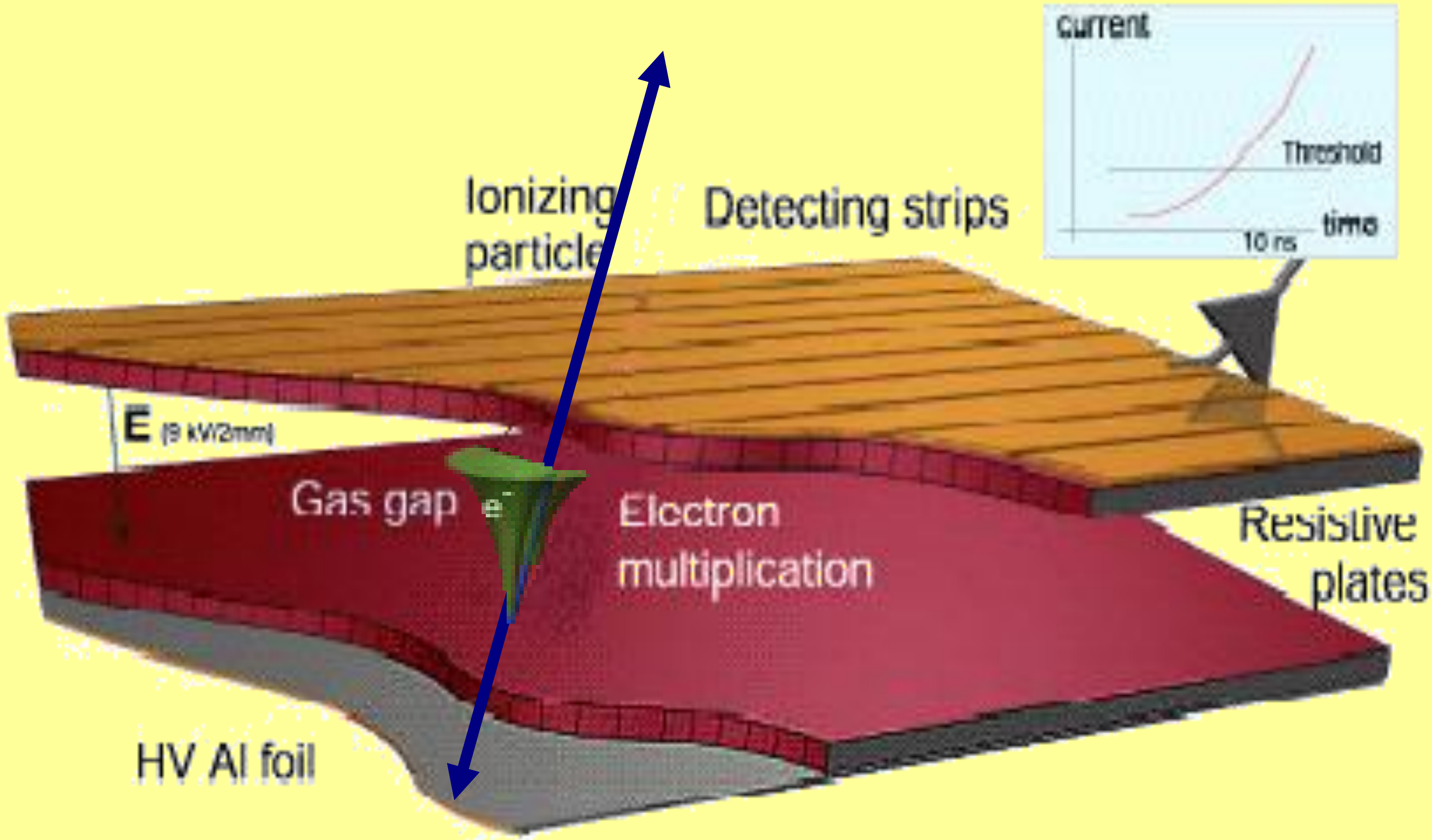
PET – physical limitations & problems



- B.J. Pichler, H.F. Wehrl, M.S. Judenhofer, *J. Nucl. Med.* **49/2** (2008) 5–23
- N.E. Bolus et al., *J. Nucl. Med. Technol.* **37/2** (2009) 63-71

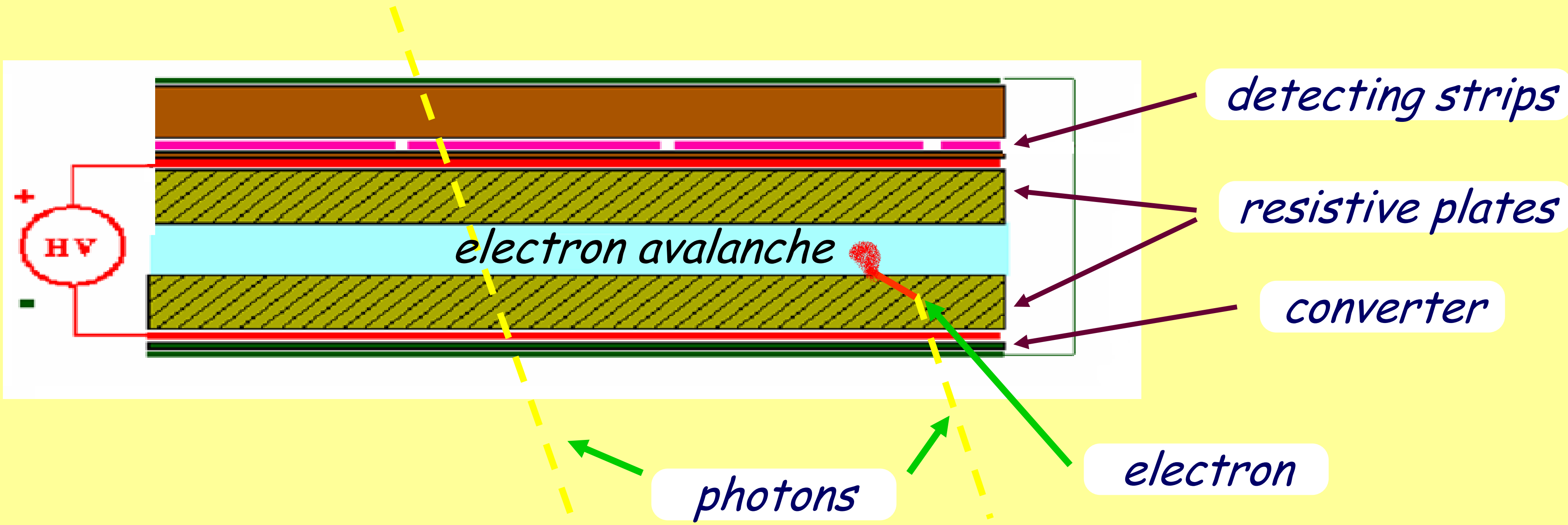
For small animal PET the random coincidence and spatial resolution are the main limitations

Resistive-Plate Chambers (RPC)



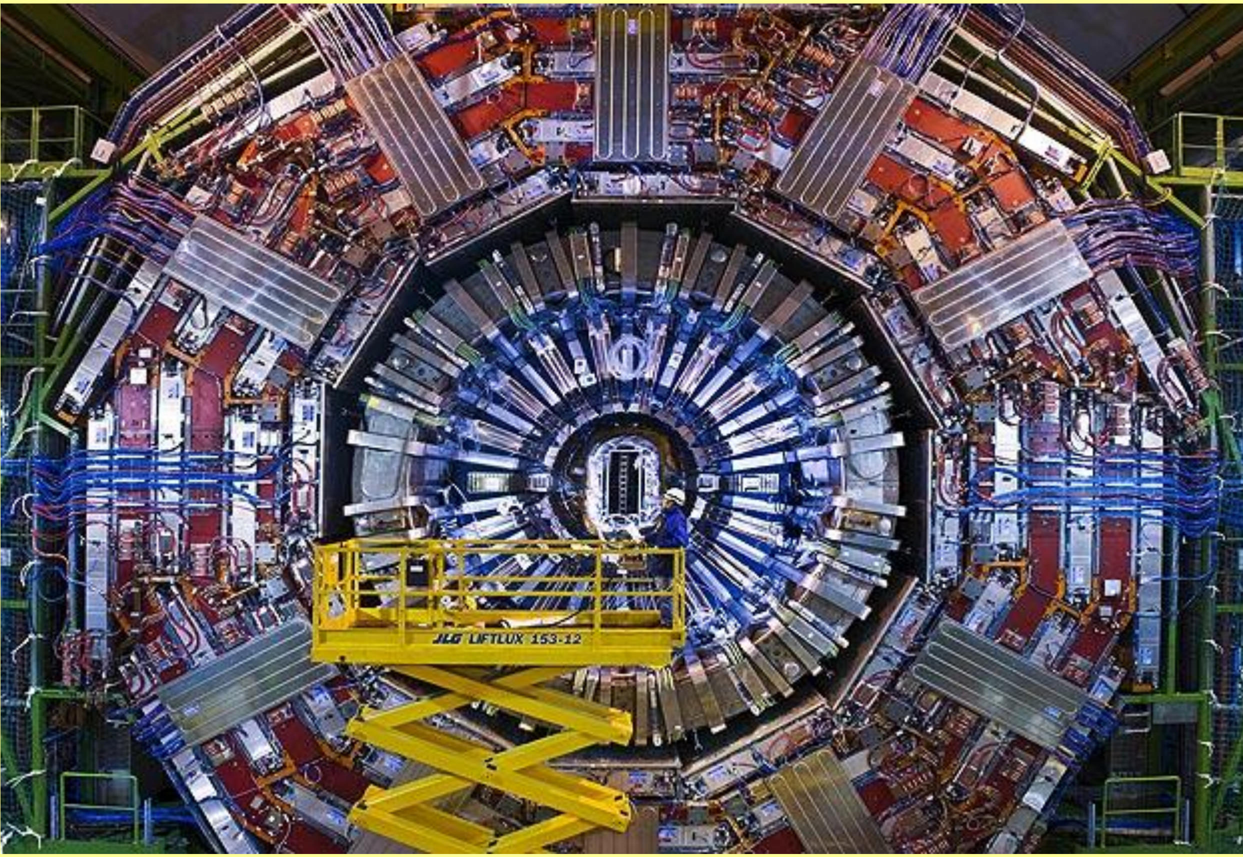
- R. Santonico and R. Cardarelli , *Nucl. Instr. Meth.* **A187**, 377-380 (1981)

RPC-PET



- ❖ P. Fonte, A. Smirnitski, M.C.S. Williams, *NIM A* **443**, 201-204 (2000)
- ❖ A. Blanco et al., *Nucl. Instr. Meth.* **A508**, 88-93 (2003)

RPCs – a journey from fundamental research to applications



Scintillator-based vs RPC-based PET

- High price
- Higher sensitivity for scattered photons
- Energy measurement
- Parallax error
- Time resolution > 200 ps
- Spatial resolution ~ 2-3 mm
- PMT, APD, ...
- FOV 16-25 cm

- Much cheaper
- Sensitivity decreases with E
- Practically no parallax error
- Time resolution ~ 30 ps* , even 20 ps, Williams et al. Nucl. Instr. Meth. A 594 (2008) 39-43
- Spatial resolution ~ 300 μm
- No need of PMTs
- Not affected by magnetic fields
- Large area → large FOV ~ 1 m
- Main problem: to increase the efficiency for 511 KeV photons

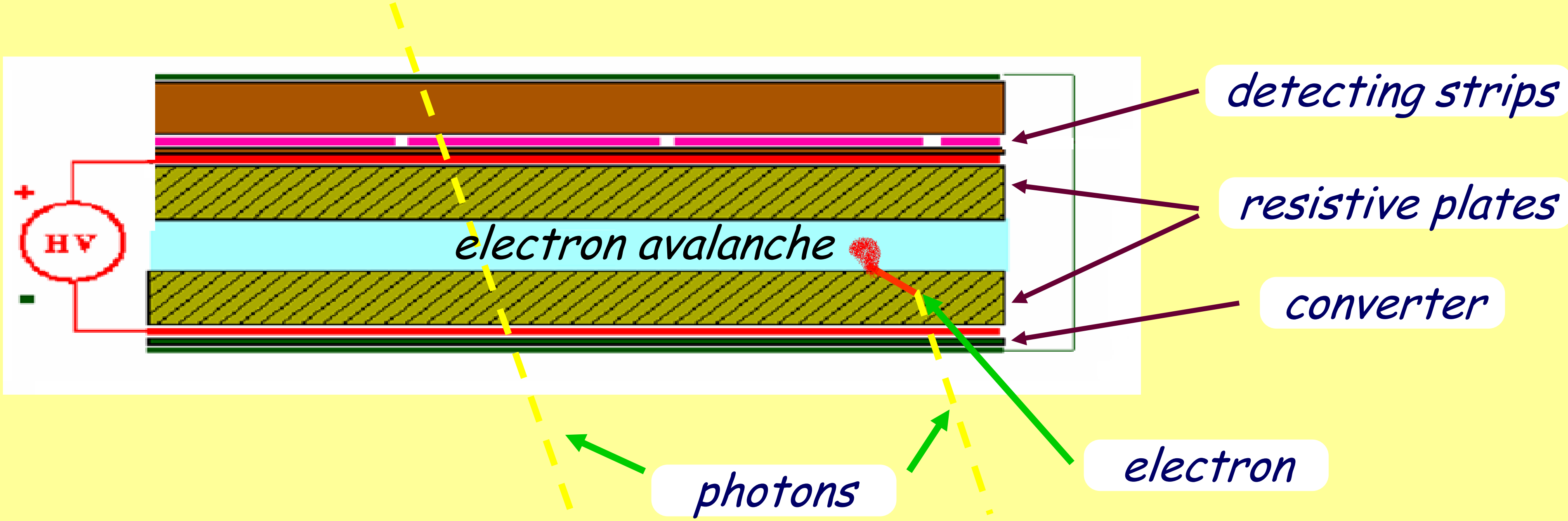
*The quoted resolution is for charged particles and is not so good for gammas, but WHY ?

❖ C. Lippmann et al., Nucl.Instr. Meth. A 602 (2009) 735-739

❖ L. Lopez et al., Nucl.Instr. Meth. A 573 (2007) 4-7.

❖ A. Blanco et al., Nucl. Instr. Meth. A 508 (2003) 70-74.

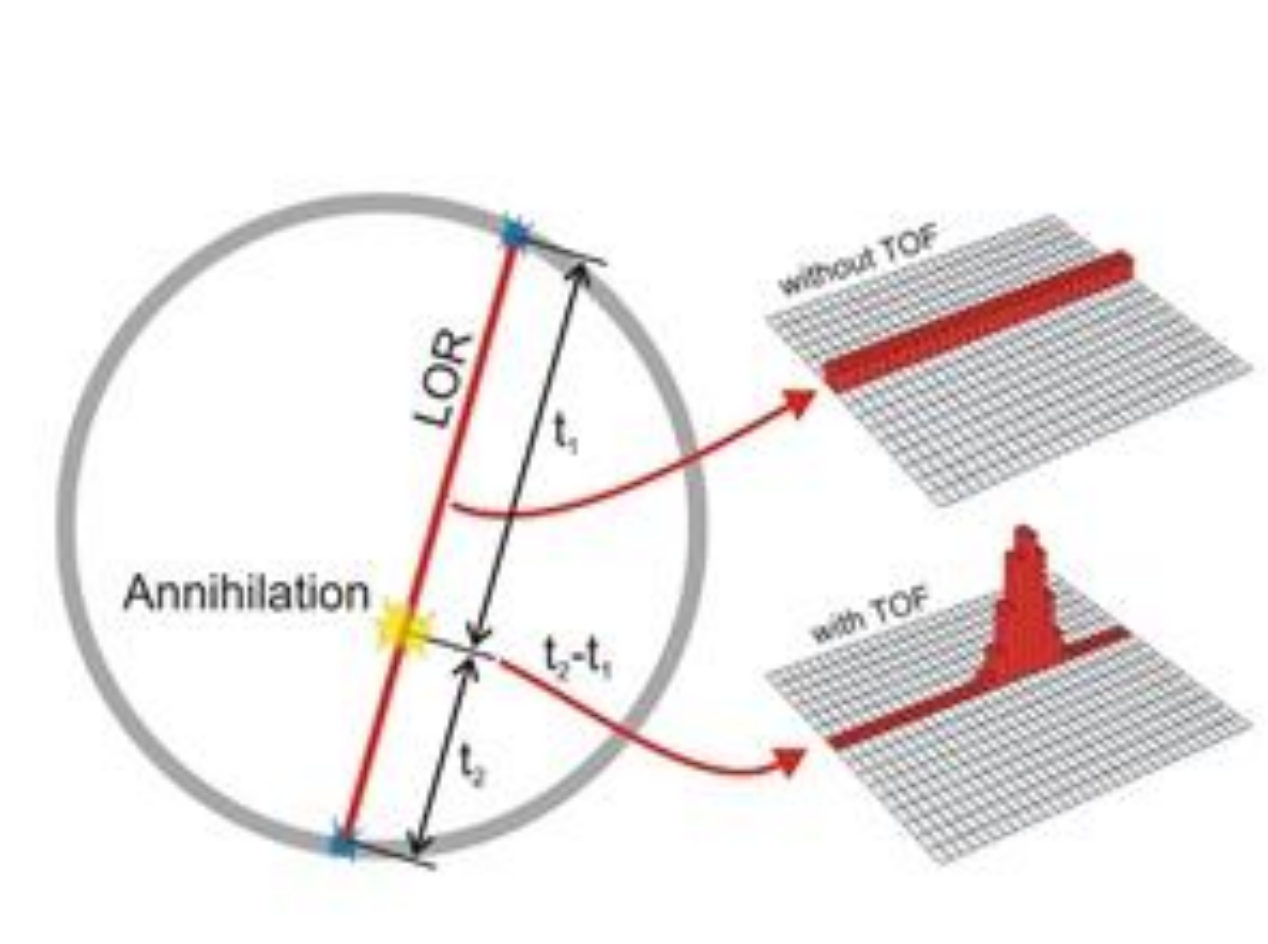
RPC-PET



RPCs for PET are proposed by:

- ❖ P. Fonte, A. Smirnitski, M.C.S. Williams, *NIM* **A 443**, 201-204 (2000)
- ❖ A. Blanco et al., *Nucl. Instr. Meth.* **A508**, 88-93 (2003)

PET ToF



Without ToF:
ΔZ = LOR (~70 cm)

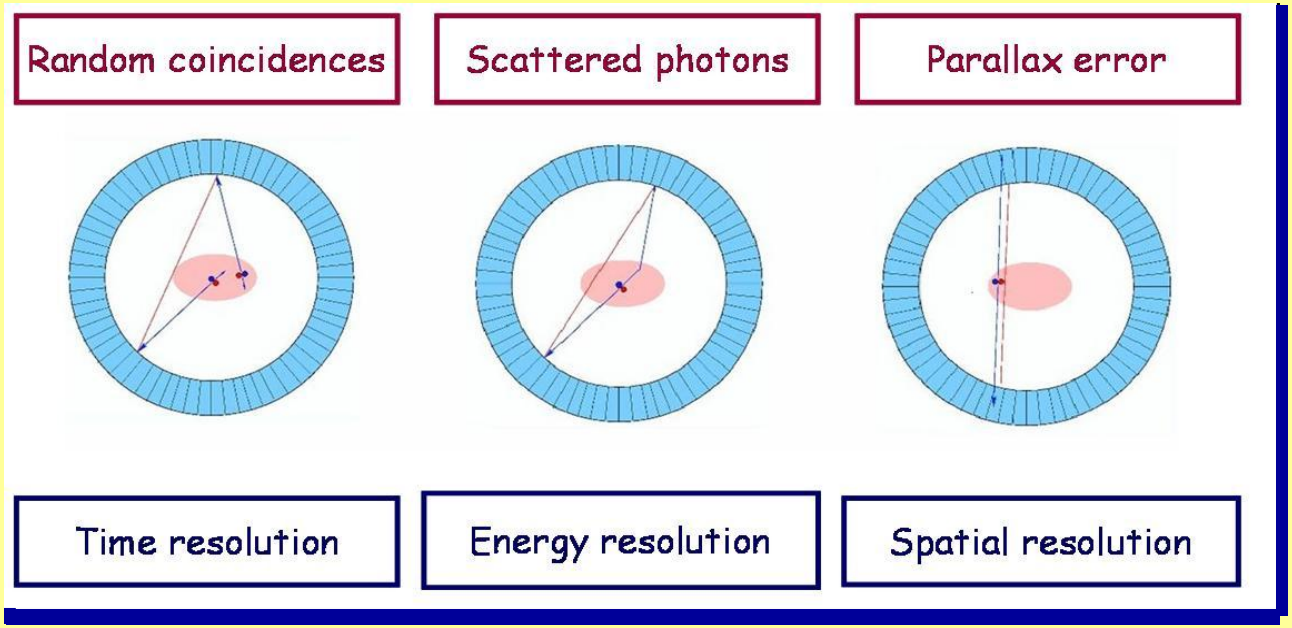
With ToF:
$\Delta Z = C.(t_2 - t_1)/2$

if $\Delta t \sim 100$ ps =>
$\Delta Z \sim 2$ cm

RPC

PET – ToF

- ~20 times lower dose
- faster acquisition (to study the dynamics of the physiological processes)
- no complicated reconstruction
- (almost) no random coincidence
- (partial) Compton suppression by ToF



RPC PET R&D @ Sofia University

- **Two main goals:**

To increase the efficiency for 511 keV photons

To suppress Compton scattered photons

- Photon spectrum simulation (done)
- GEANT simulation of different RPC designs (done)
- GEANT simulation of multigap RPC (done)
- Prototype building and tests (in progress ...)

- N. Ilieva et al., *API Conf. Proc.* ***1203,*** 820-825, (2010)
- G.Georgiev et al., RPC2012 proceedings (2012)

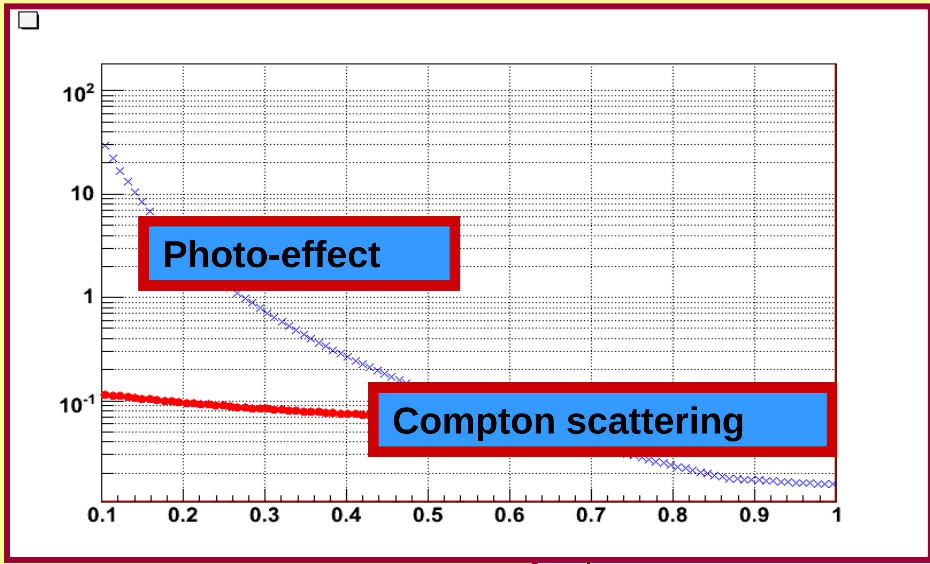
RPC-PET: design & optimization

- *The simulations are performed, using* **Geant4** www.geant4.org/geant4
    - ***Compton scattering, photo-effect***
    - ***multiple scattering, ionization, Bremsstrahlung***
- Detector „basic unit":

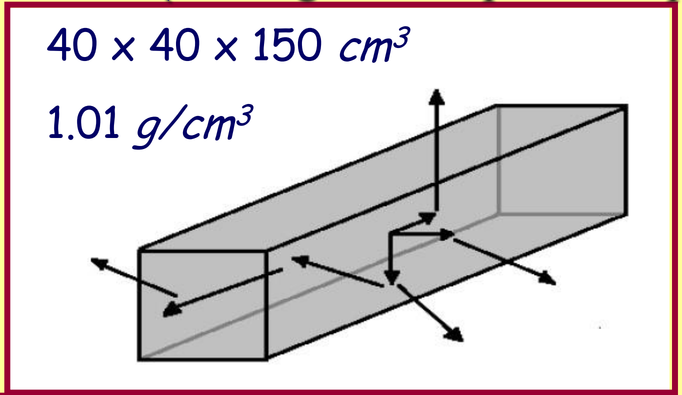
  two glass plates, 2 *mm*

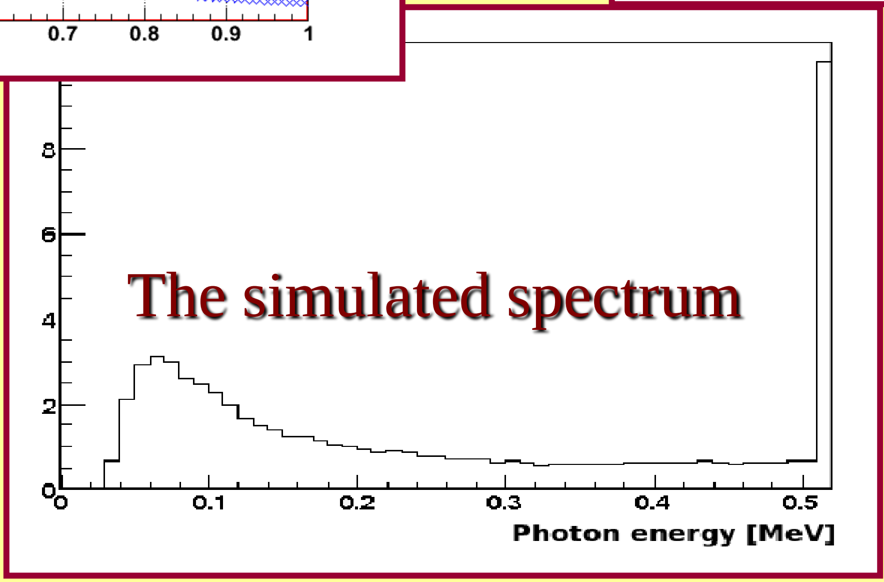
  gas gap 300 *μm*
- Gas composition (for material budget): 85% $C_2H_2F_4$ + 5% i-C_4H_{10} + 10% SF_6
- *Two designs are considered:*
    - *Gas-Converter (GC)*
    - *Gas-Converter-Insulator (GCI)*

Photon propagation in the human body



The body model
(homogeneous parallelepiped)





38% are absorbed

82% of the remaining are with E < 511 *KeV* (*or* 51% of the initial gammas)

18% of the remaining *(or 11% of the initial gammas) are suitable for PET*

Contents:

O	*61.4 %*
C	*22.9 %*
H	*10.0 %*
N	*2.6 %*
Ca	*1.4 %*
P	*1.1 %*
K	*0.2 %*
S	*0.2 %*
Na	*0.1 %*
Cl	*0.1 %*

Electron yield in the gas

Successful photons conversion : at least one interaction within the converter has lead to the ejection of an electron into the gas gap:

- photon interaction in the converter
- electron propagation to the gas

$$\frac{dN}{dx} = kN_\gamma - sN$$

$$N = a(1 - e^{-x/b})$$

$$N = a(e^{-x/c} - e^{-x/b})$$

k photon interaction coefficient

N_γ number of photons at *x*

s electron interaction coefficient

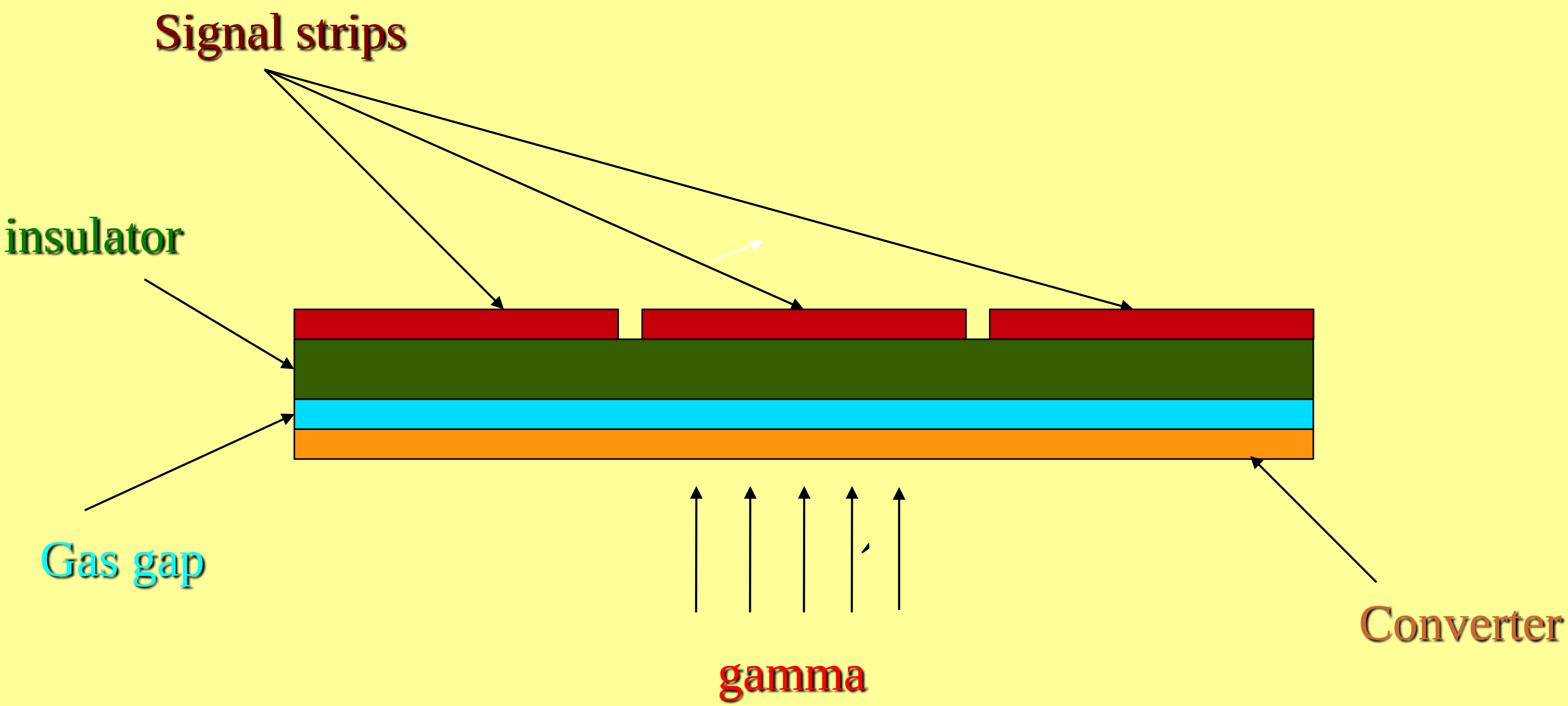
N number of electrons, entering the gas

C photon attenuation coefficient

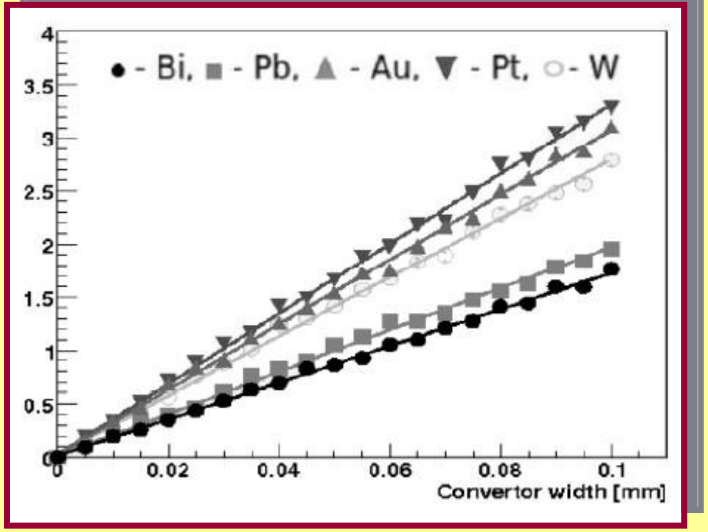
Thin converter; **a** is max e yield;
saturation → 95% yield thickness

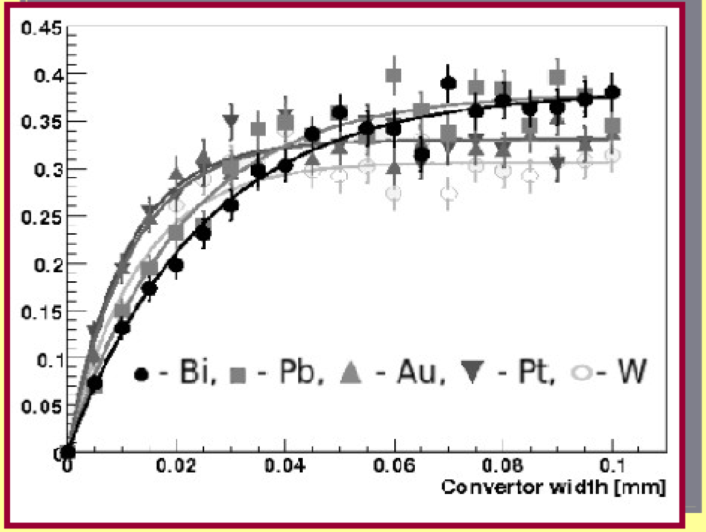
Gas – converter design

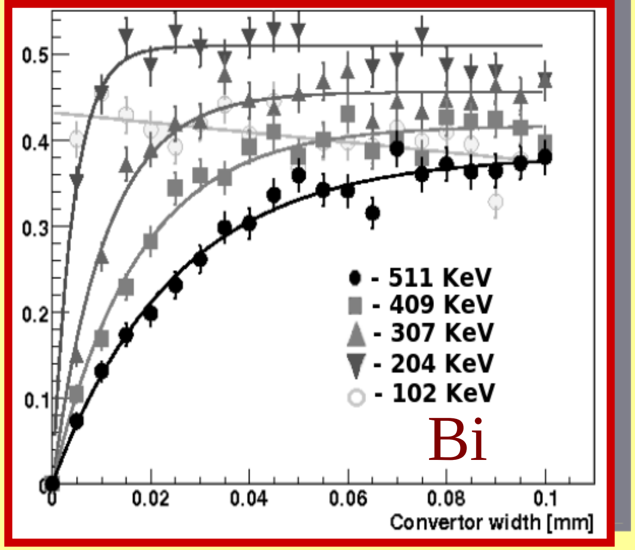
Maximal electron yield (0.3 ÷ 0.38) %



Gas – converter design







e^- yield for 5 different converter materials
(% from the initial photon number)

e^- yield and ejected electrons for 5 different converter materials.
(% from the initial photon number)

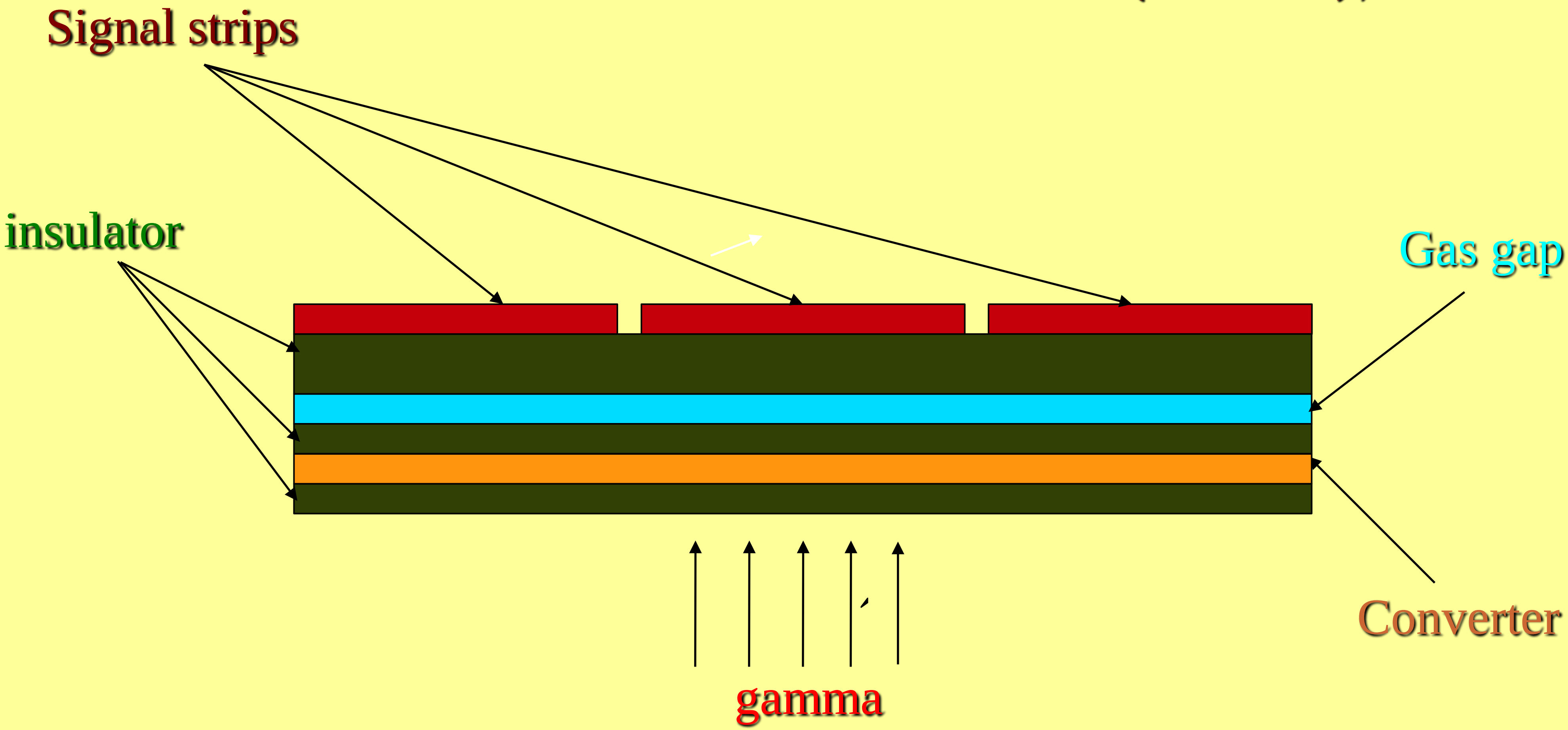
***BUT** higher sensitivity for **scattered** in the body photons !*

Gas – insulator – converter design

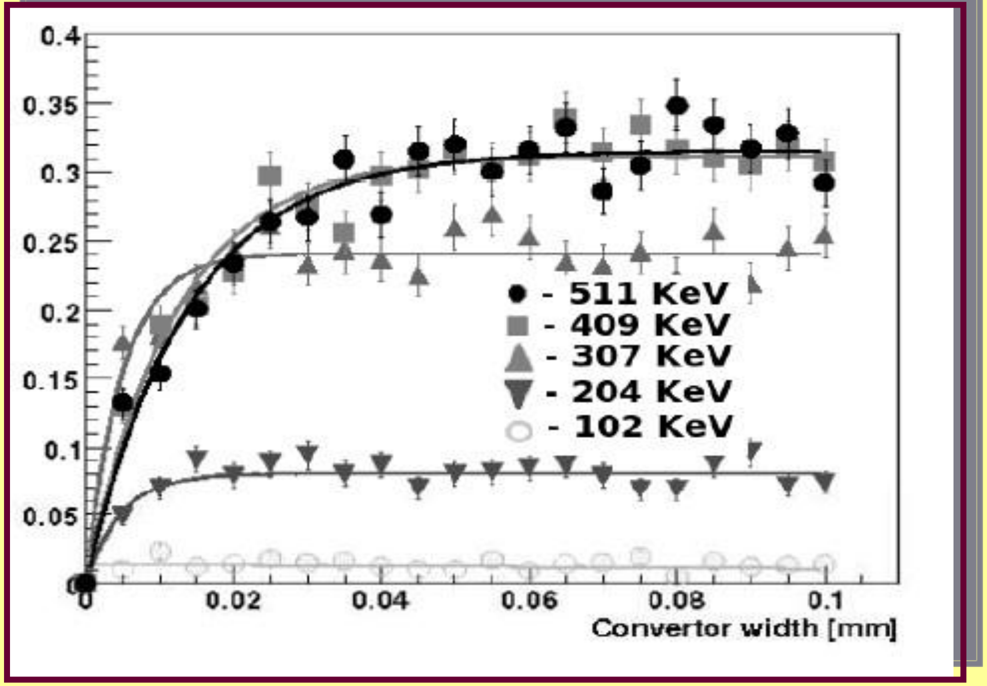
Maximal electron yield for 511 *KeV* photons (0.315 ± 0.005) %

~ 0.17% lower than in GC design

95% level (40.7 ± 3.0) *µm*



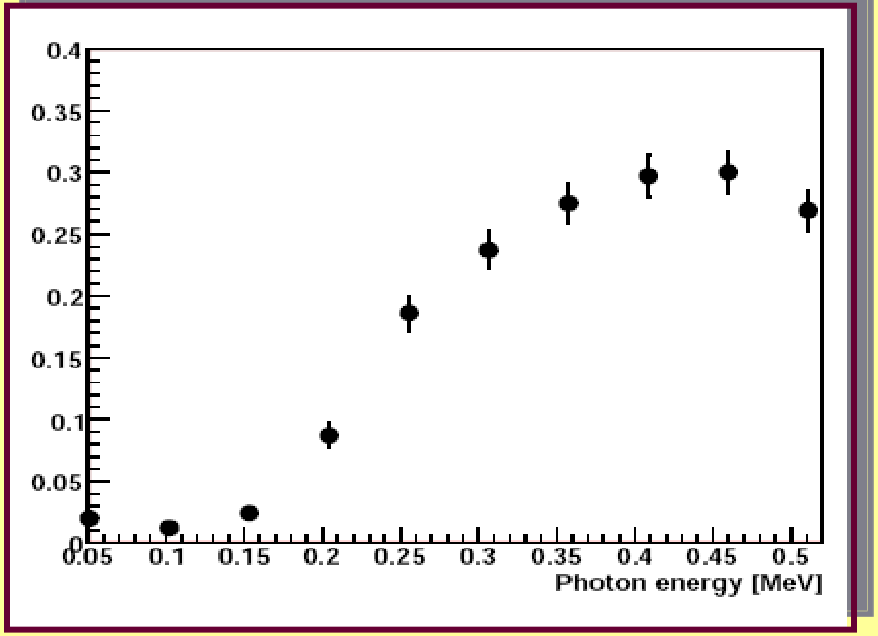
Gas – insulator - converter design



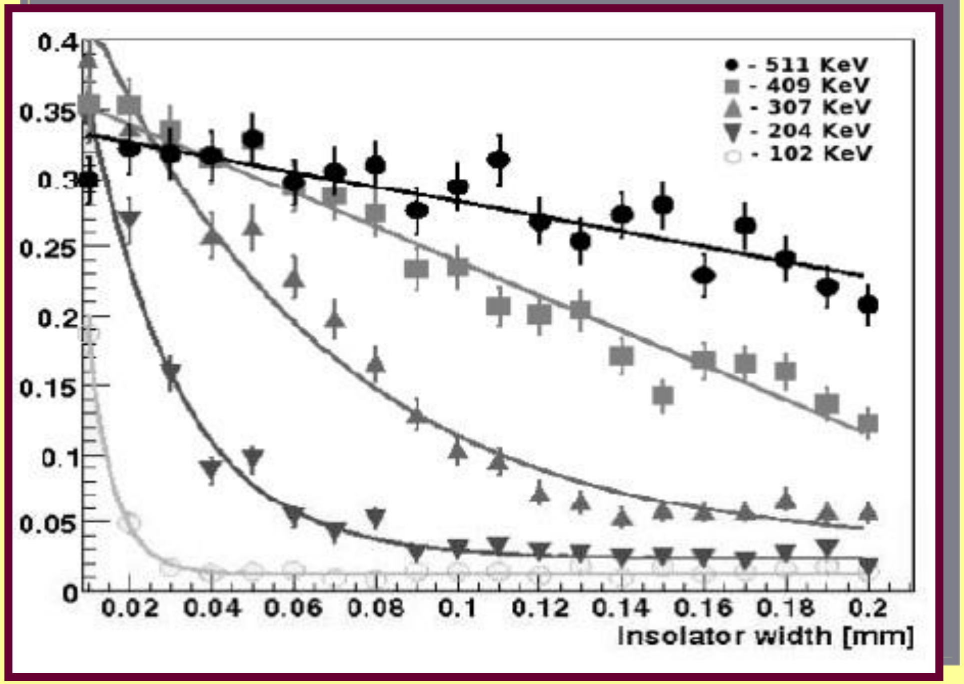
e$^-$ yield / converter width

40 *μm*

e$^-$ yield / photon energy / 40 *μm*



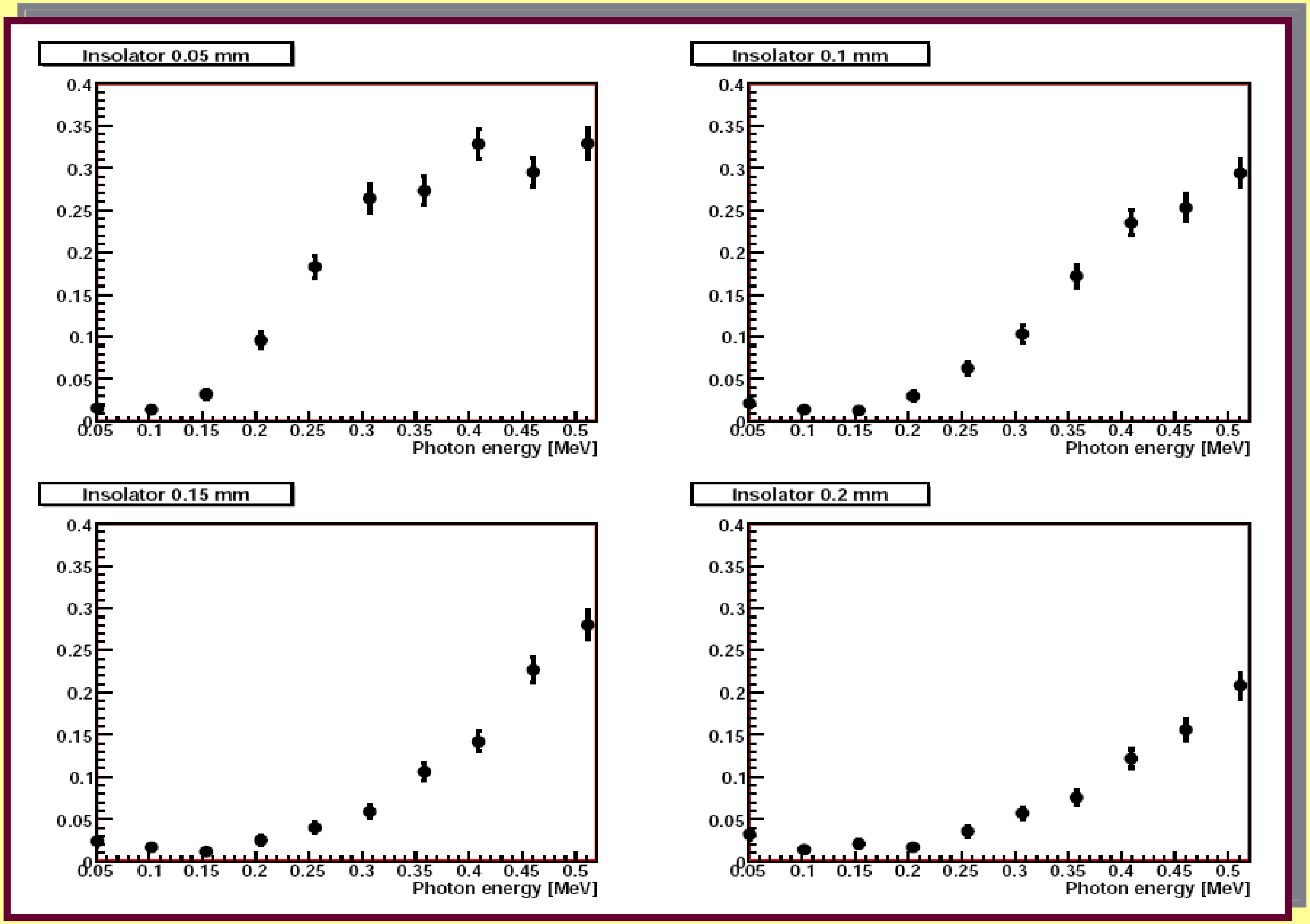
Gas – insulator - converter design



e^- yield / insulator width

100 ÷ 200 μm

Gas – insulator - converter design



0.1 *mm* insulator:

511 *KeV* -26% reduction

307 *KeV* -68% reduction

yield ~ 3:1

0.2 *mm* insulator:

511 *KeV* -40% reduction

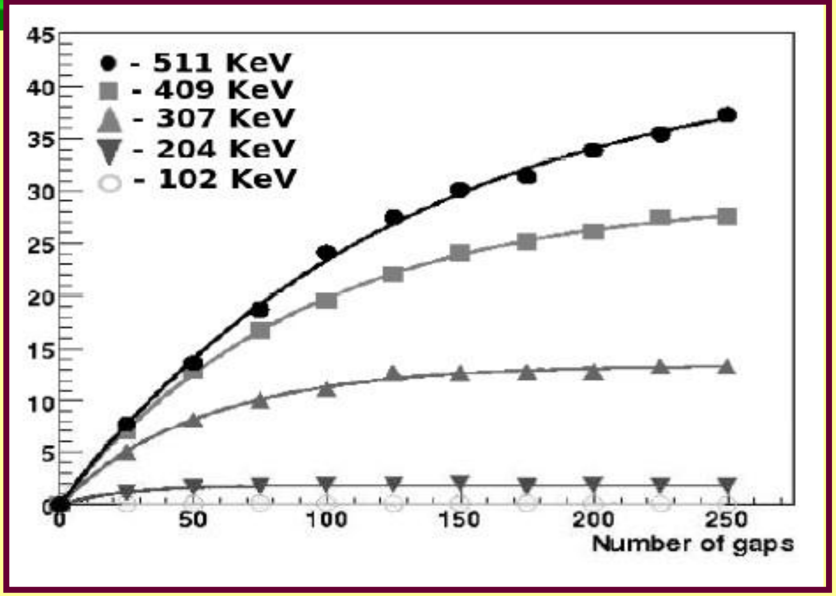
307 *KeV* -90% reduction

yield ~ 5:1

The reduction is in Comparison to GC design.

Multi-gap GIC design

$$N = \Sigma_i a_0 e^{-(i-1)x/c}(e^{-x/c} - e^{-x/b})$$

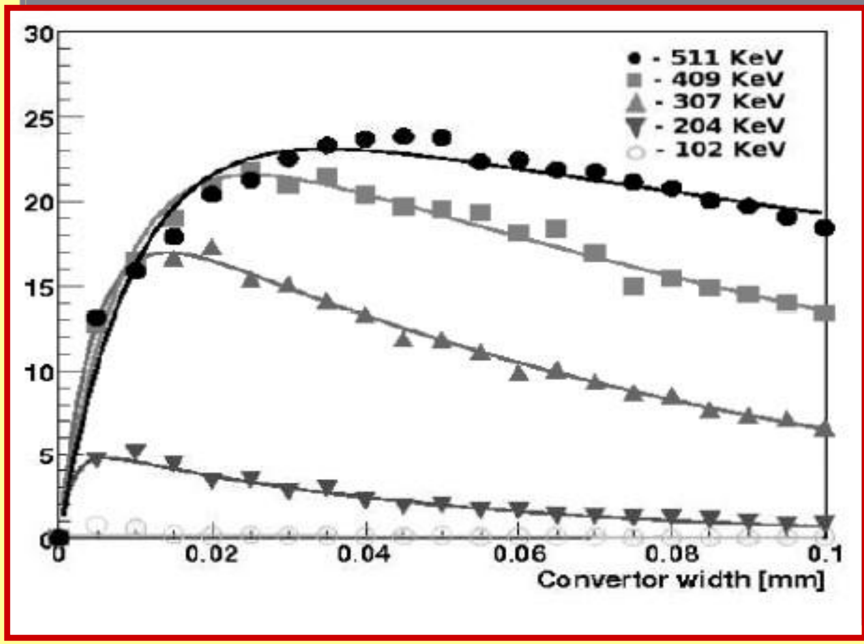


max yield *511 KeV* ~ 43%,
95% level - at 381 ± 13 gaps

100 gaps provide sufficient
- amplification
- lower-energy photons suppression

A typical PET scintillator has efficiency ~ 20-25%

Multi-gap GIC design



Max yield for 511 *KeV:*

(23.8 ± 0.4)%

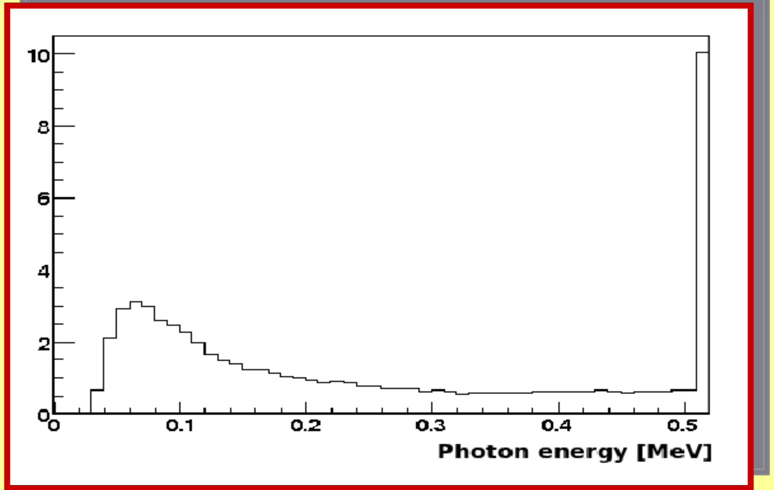
converter Bi, 50 *μm*

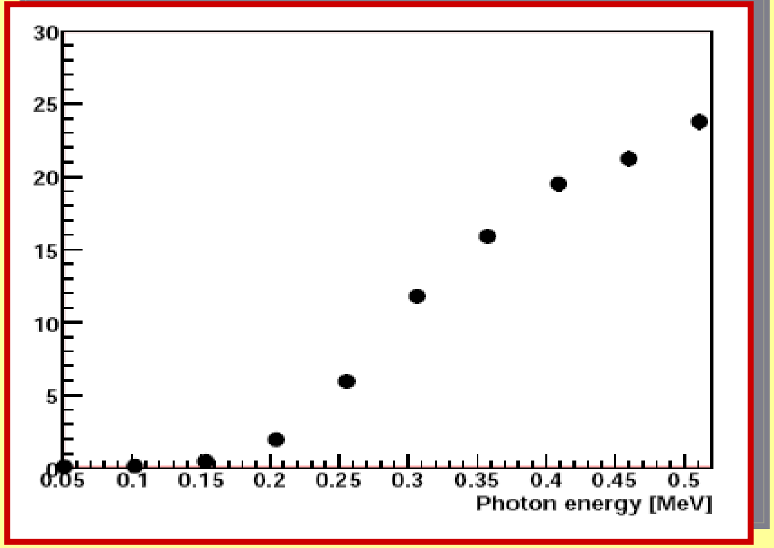
glass 50 *μm*

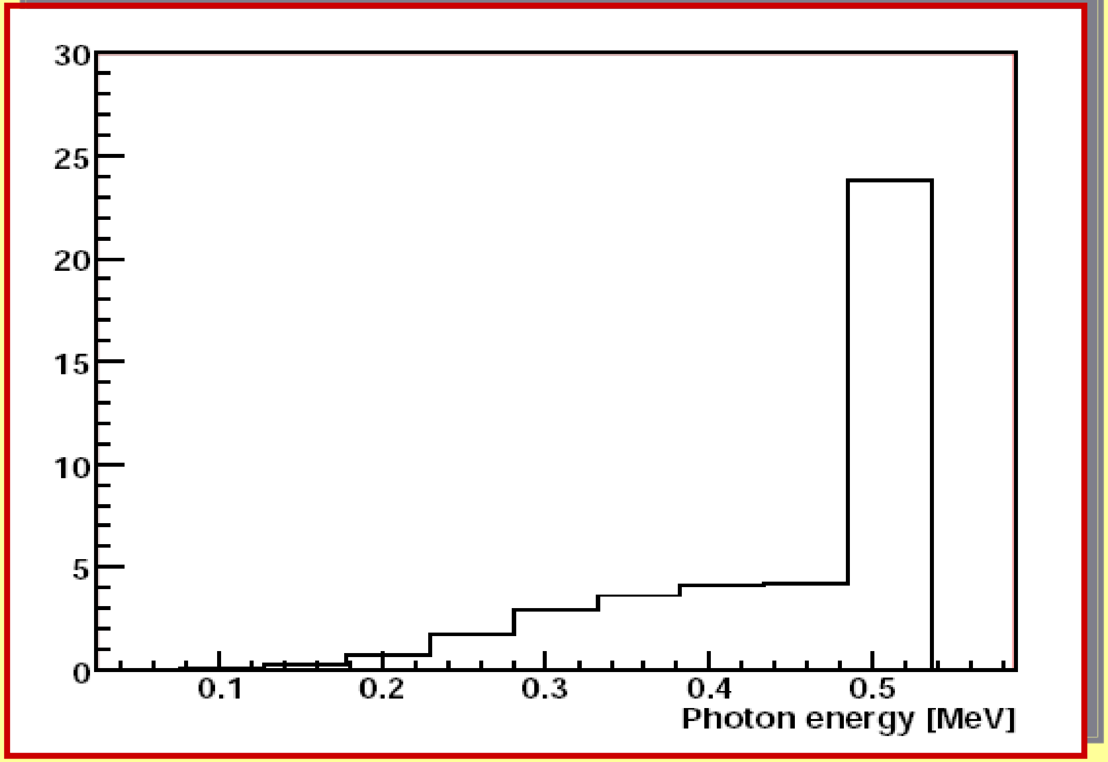
Highest sensitivity for 511 *KeV*

511 / 307 ~ 2:1

Multi-gap GIC design







86% from the registered photons have energies > 383 *KeV*

Our prototypes ...

RPCs in an avalanche mode.

	small prototype	full scale prototype
number of gaps	6	6
gas gap	200 μm	200 μm
glass thickness	150 μm	100 μm
dimensions	$120mm \times 70mm$	$350mm \times 70mm$

Electrodes should have “exact” resistivity, very smooth surface, etc.

So one needs to be very careful with the materials for the electrodes.

Our prototypes ...

Our prototypes are made out of FLOATING GLASS

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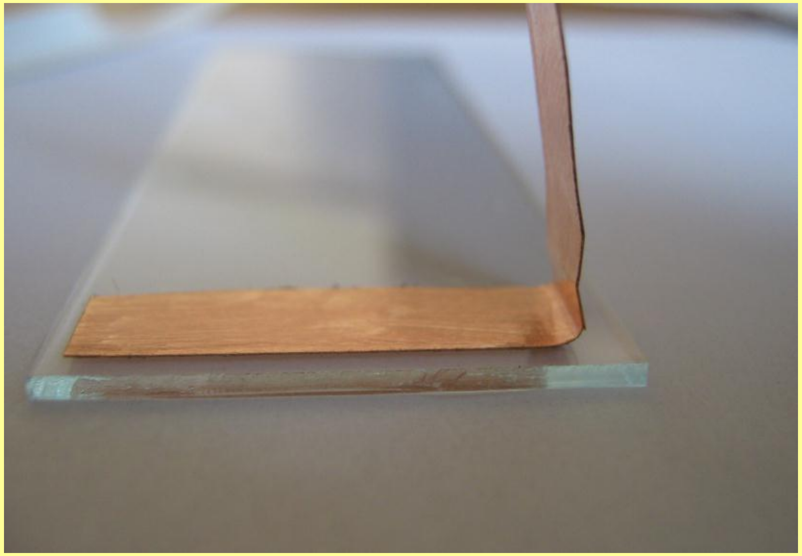
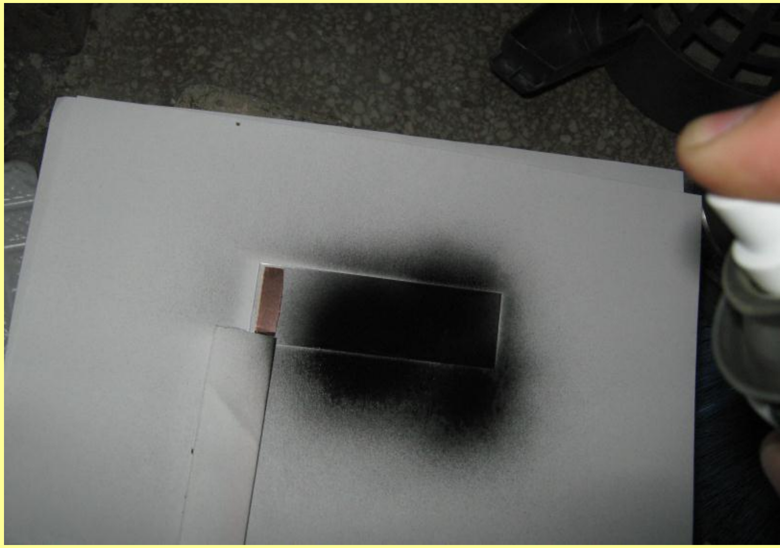
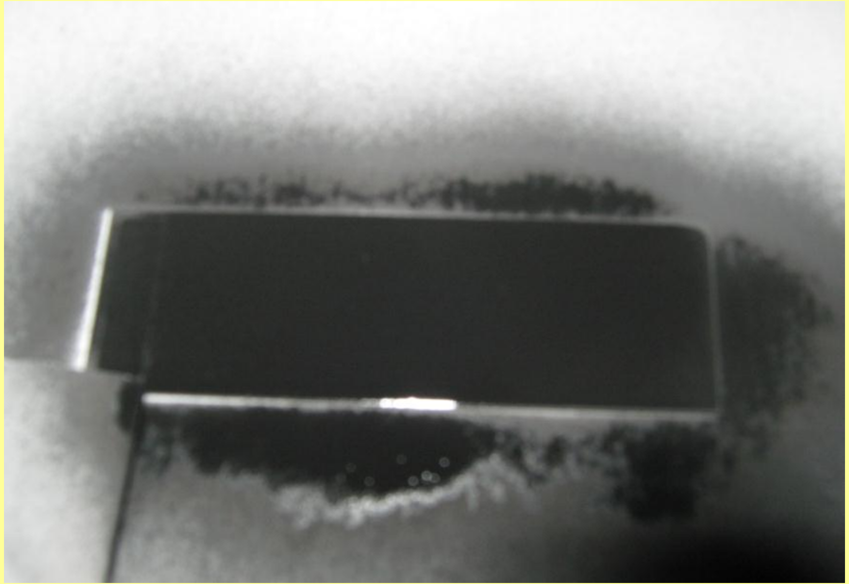


HV electrodes formation (small prototypes 120x70 mm)





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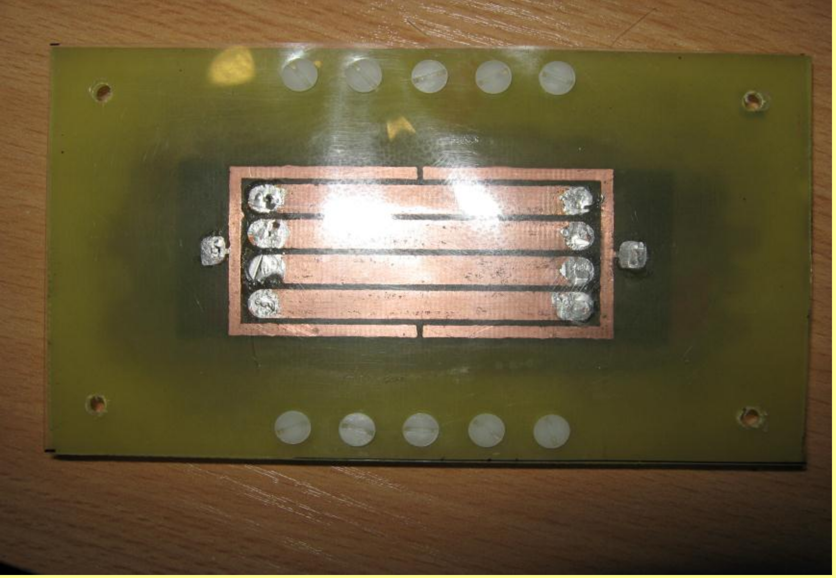
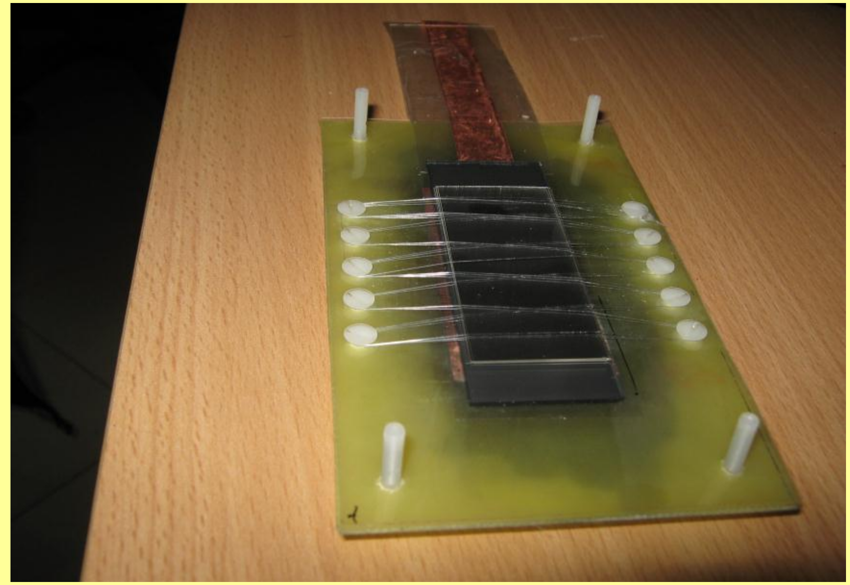
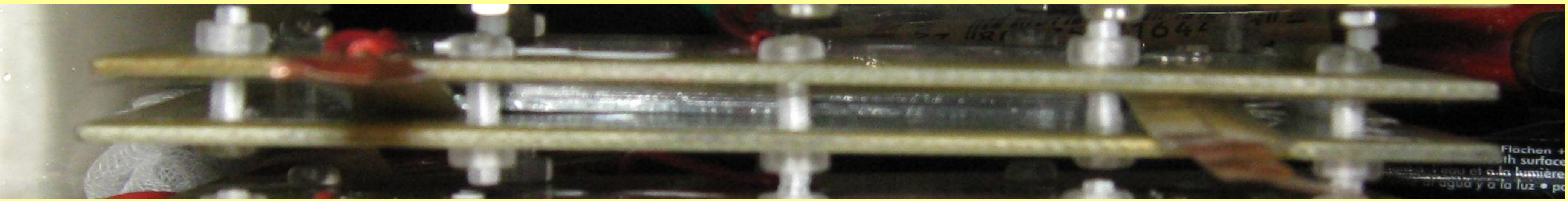
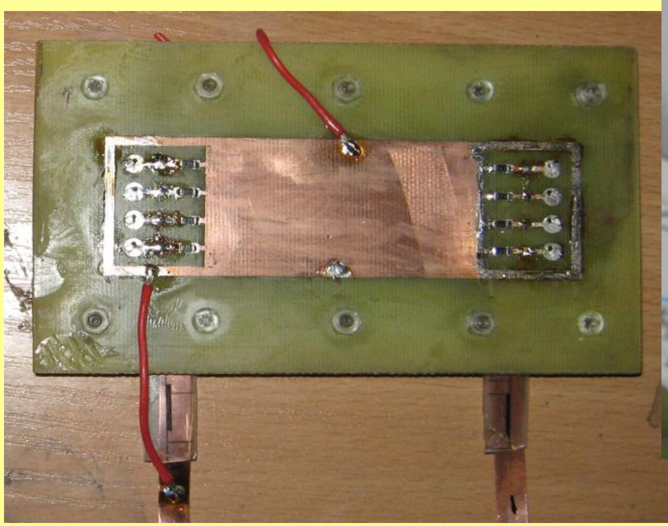
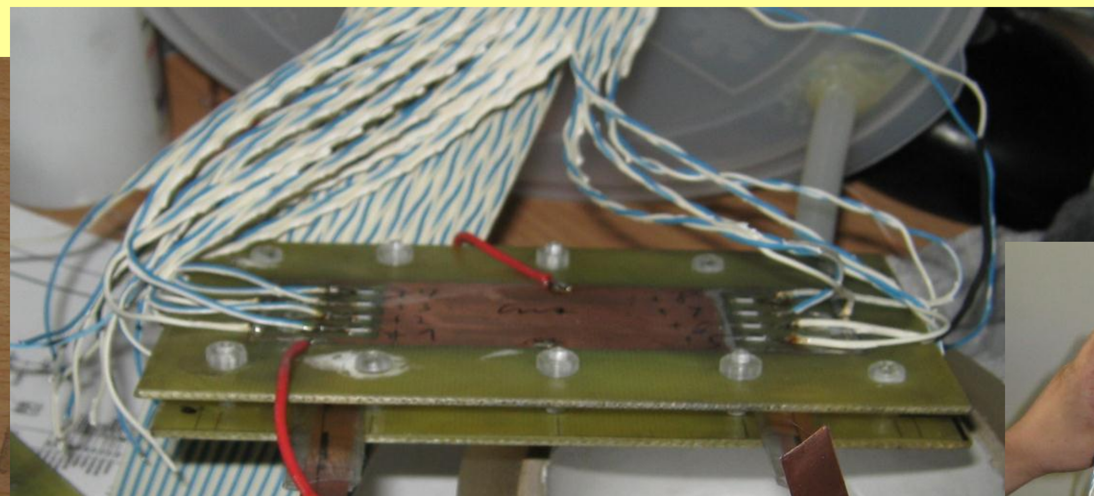


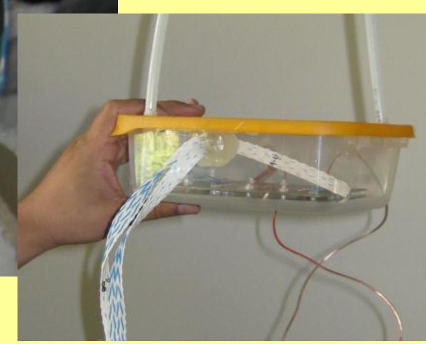
Strips layout and construction of small prototypes (120x70 mm)











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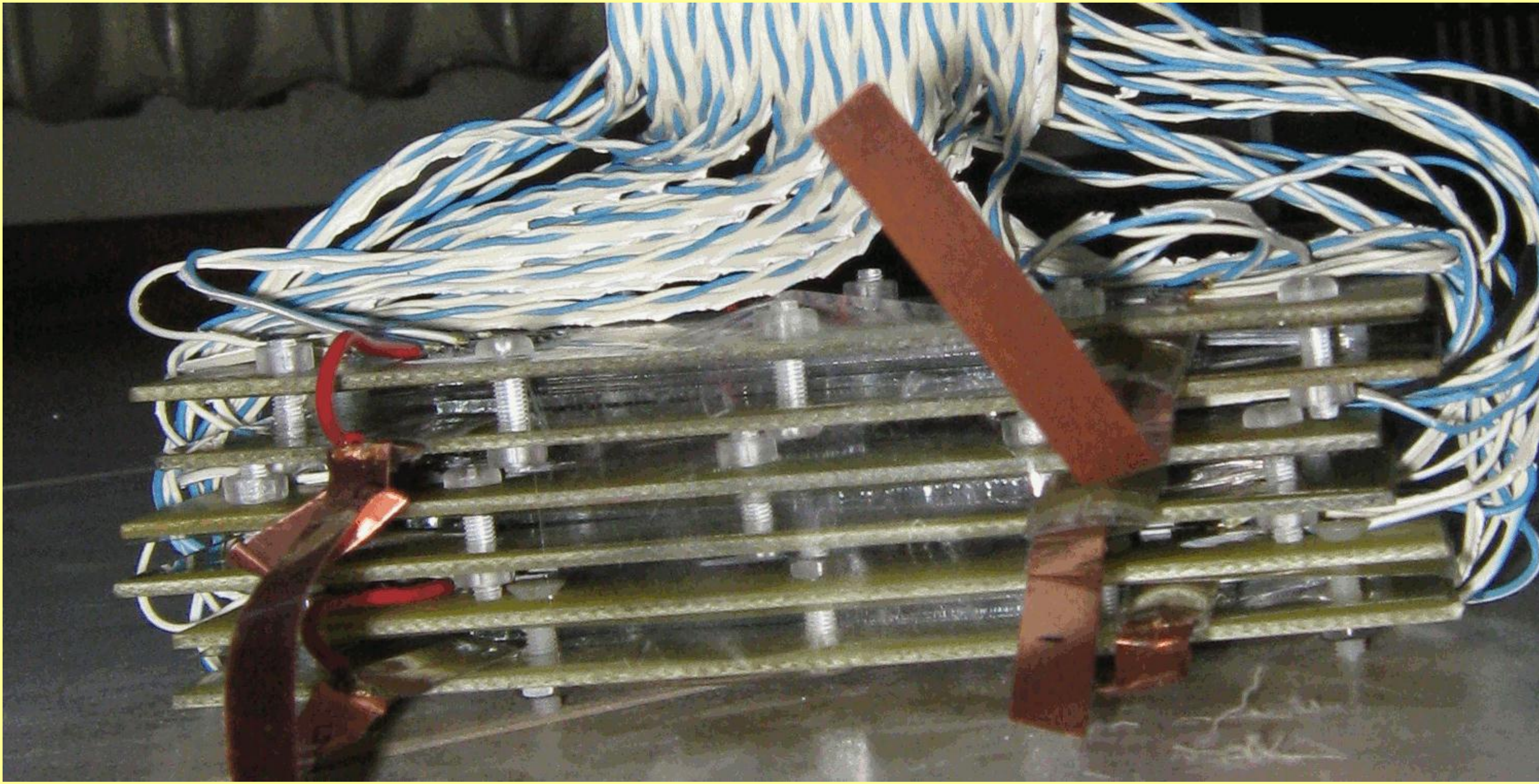
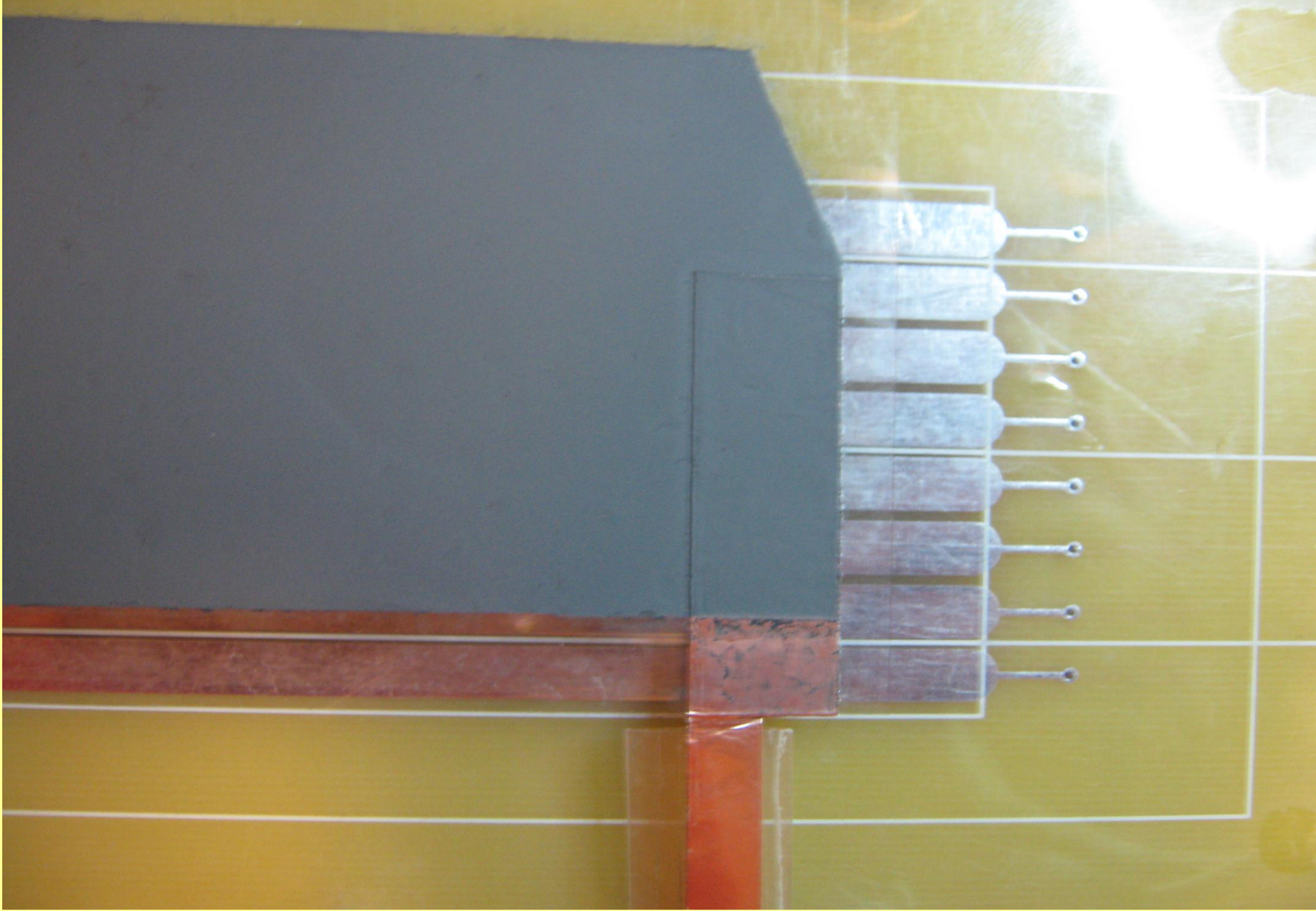
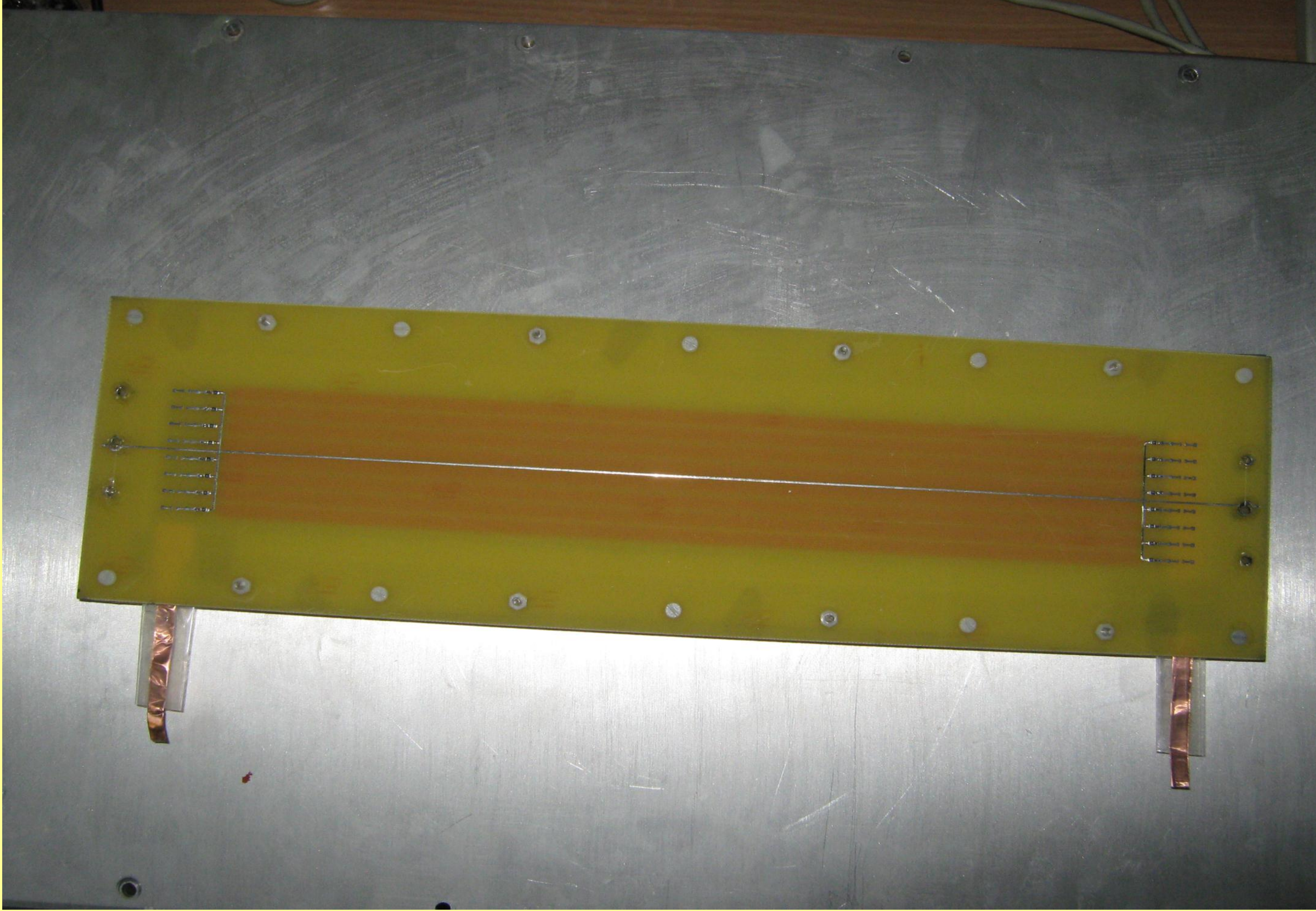
3 modules in a stack






Голямо стъкло
Голямо стъкло
Малко стъкло


Малко стъкло
Голямо стъкло



The Lab @ Sofia University

- **Gas system**
- **HV system**
- **LV system**
- **Front-end electronics (from CMS and ALICE)**
- **DAQ system**
- **Trigger system**

The Lab @ Sofia University

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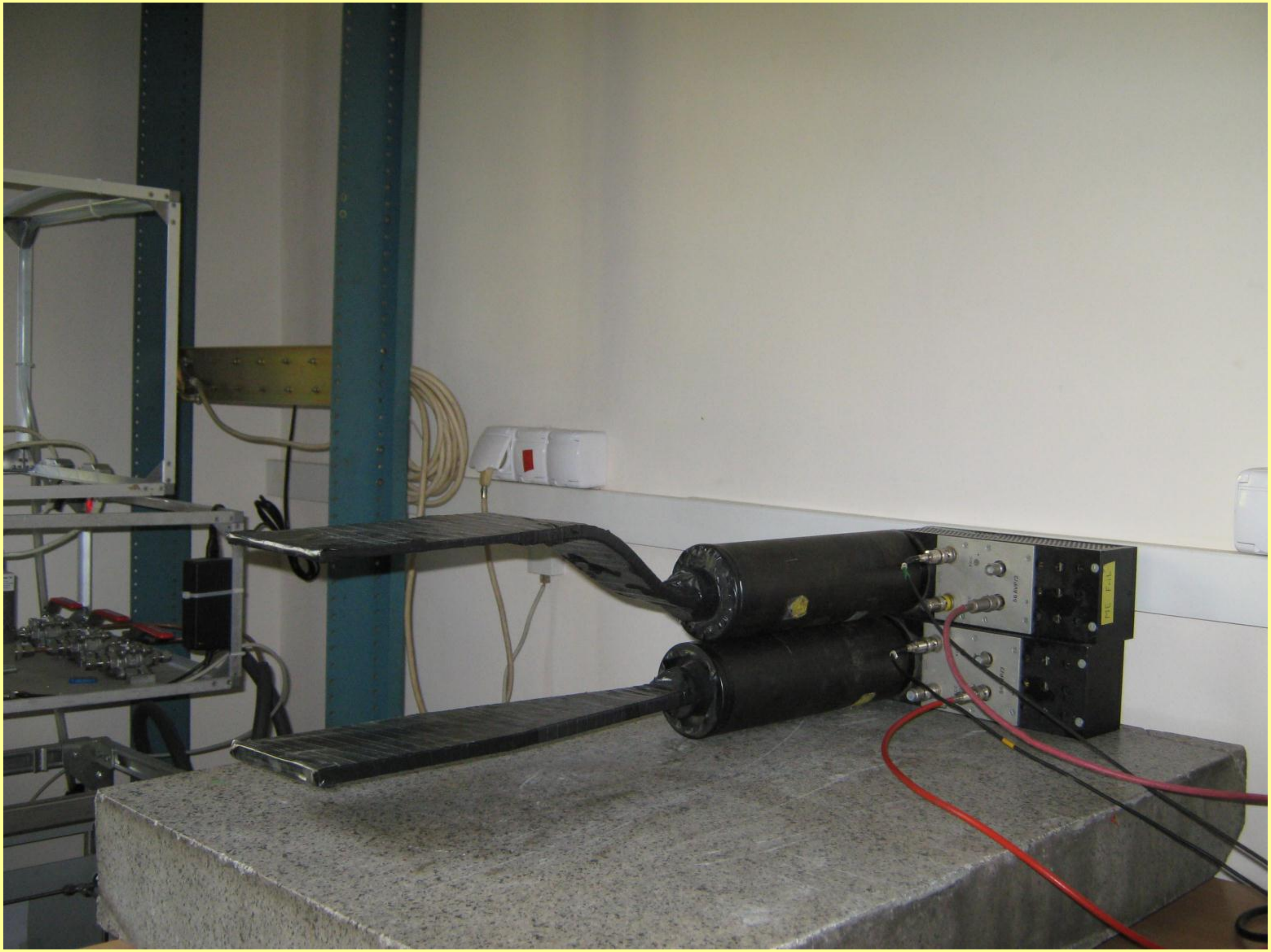
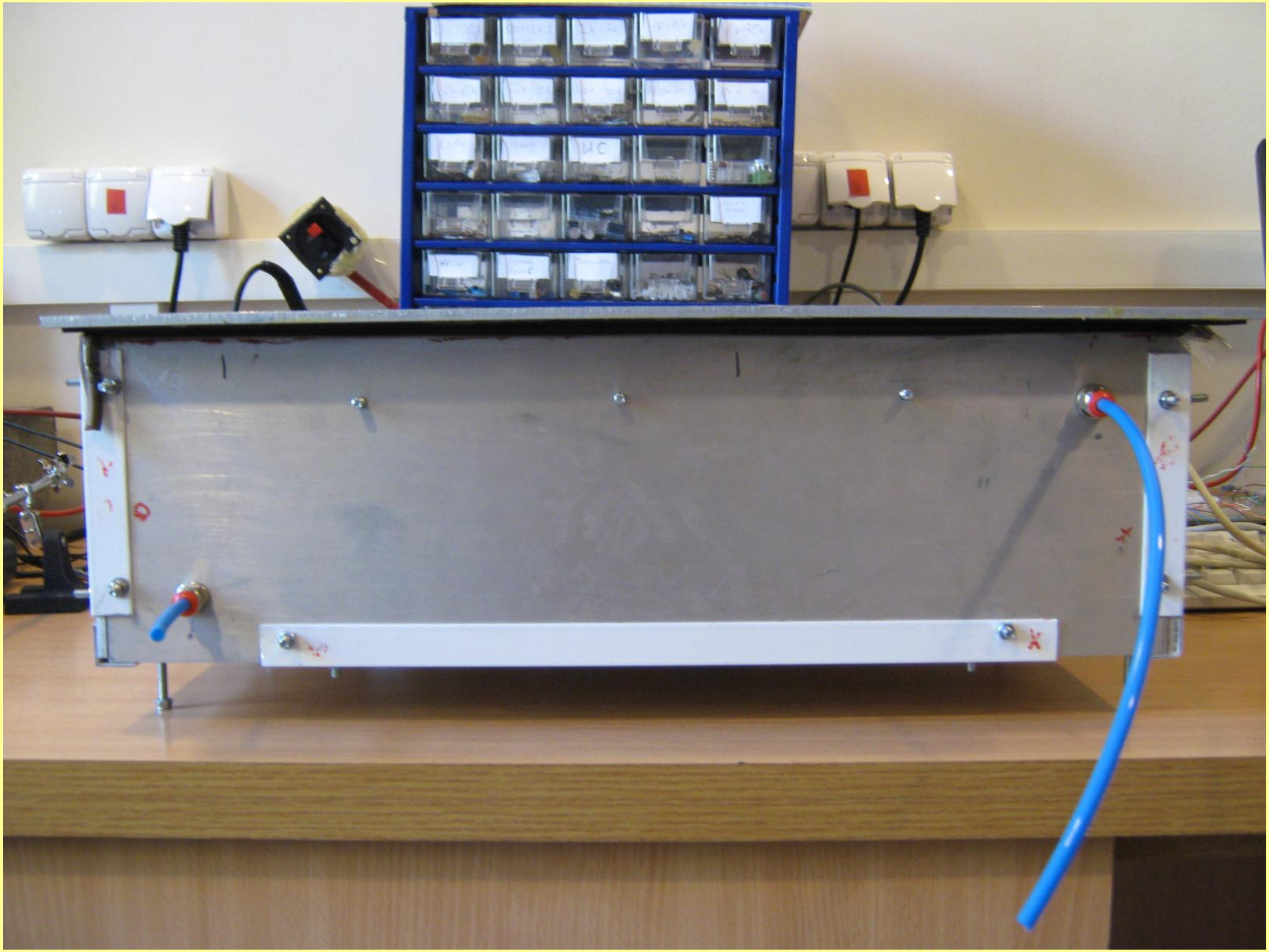
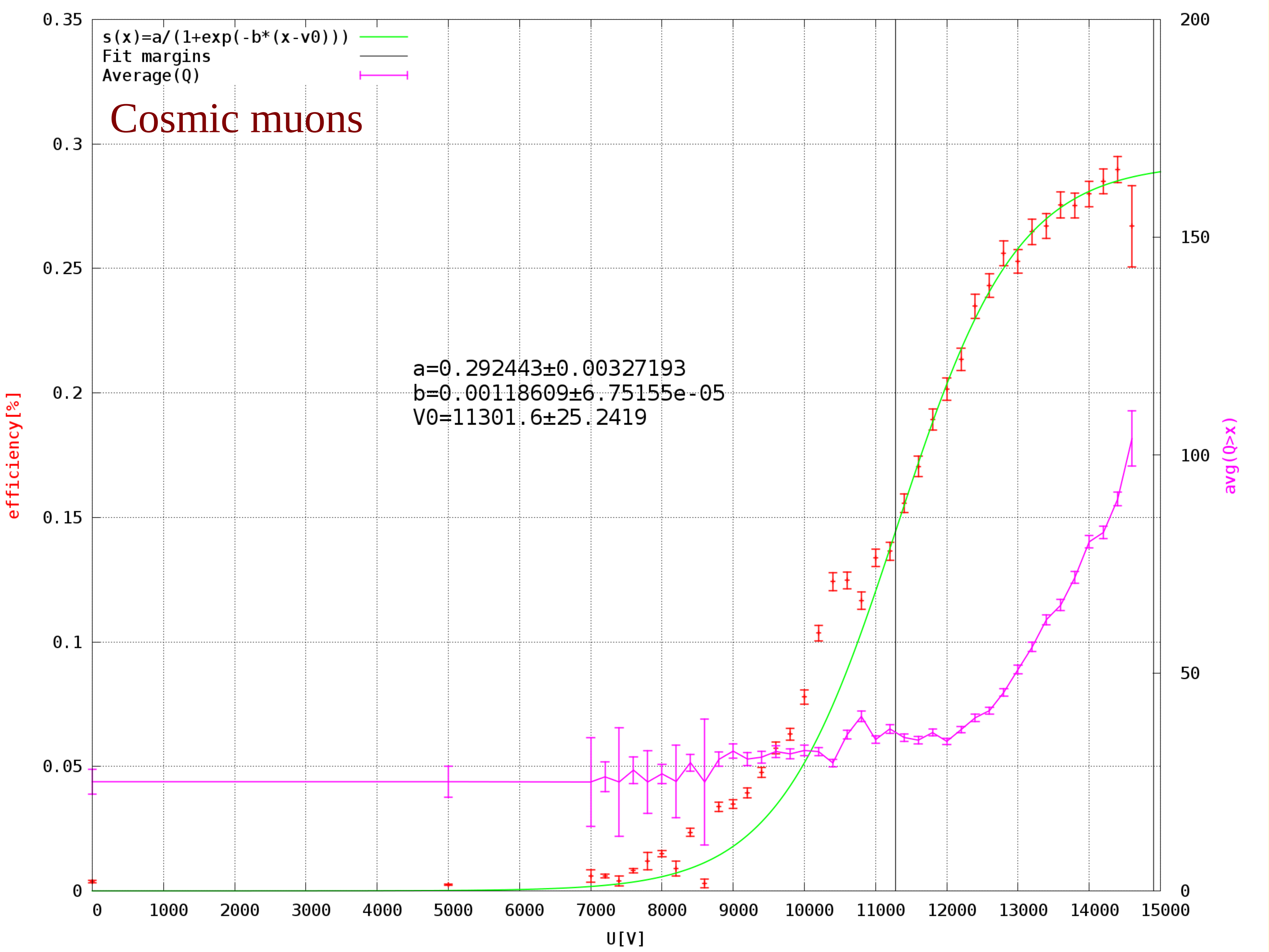


The Lab @ Sofia University





s(x)=a/(1+exp(-b*(x-v0)))
Fit margins
Average(Q)
Cosmic muons
a=0.292443±0.00327193
b=0.00118609±6.75155e-05
V0=11301.6±25.2419
efficiency[%]
avg(Q>x)
U[V]
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0
50
100
150
200
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
14000
15000

Prin

The efficiency

The measured efficiency > 29 %

The measured efficiency = (RPC efficiency)x(Geometrical Acceptance)

The Geometrical acceptance is ~ 30 %,

so the RPC efficiency is > 95 %

Only an ADC is used (no dedicated front-end electronics, amplifiers, etc. !!!)

Conclusions

- Model investigations towards the design of an RPC-based PET detector is performed

Multi-gap Gas-Insulator-Converter design. In the multi-gap GIC design, the yield increases with the number of gaps. For 100 gaps the RPC efficiency seems to be comparable with the typical PET scintillator efficiency.

Optimized in the context of PET purposes parameters:

100 gaps; 50 *μm* Bi converter between 50÷100 *μm* glass plates

the electron yield in the gas increases to 24%

sensitivity 511 *KeV* photons / 307 *KeV* photons ~ 2:1;

About 86% of the registered in the PET process photons are with energies above 380 *KeV*.

- First few detector prototypes are ready and are under study.
- The efficiency for muons is very high as expected (95+%), even without dedicated front-end electronics. Tests with photons are the next step.

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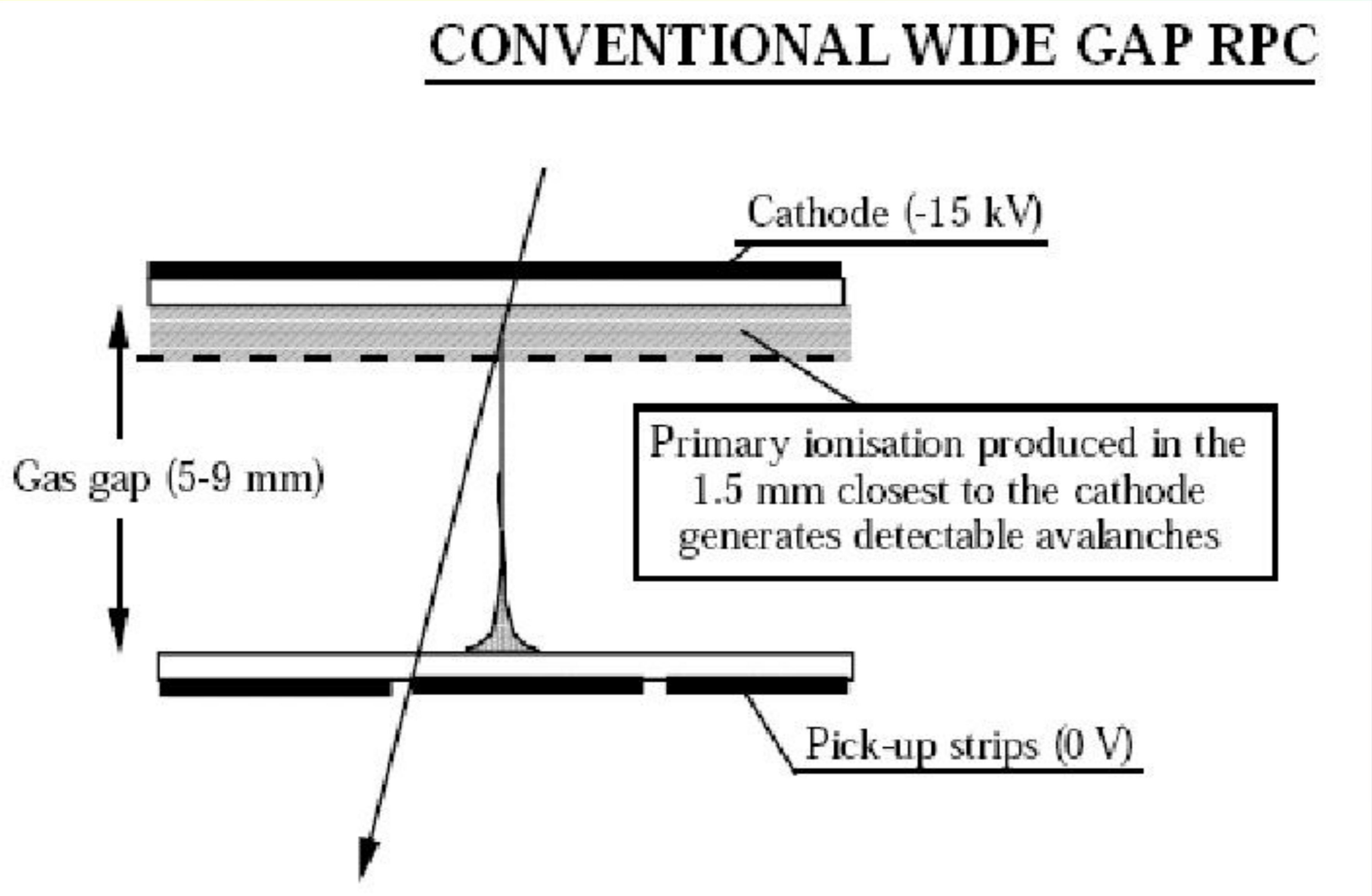
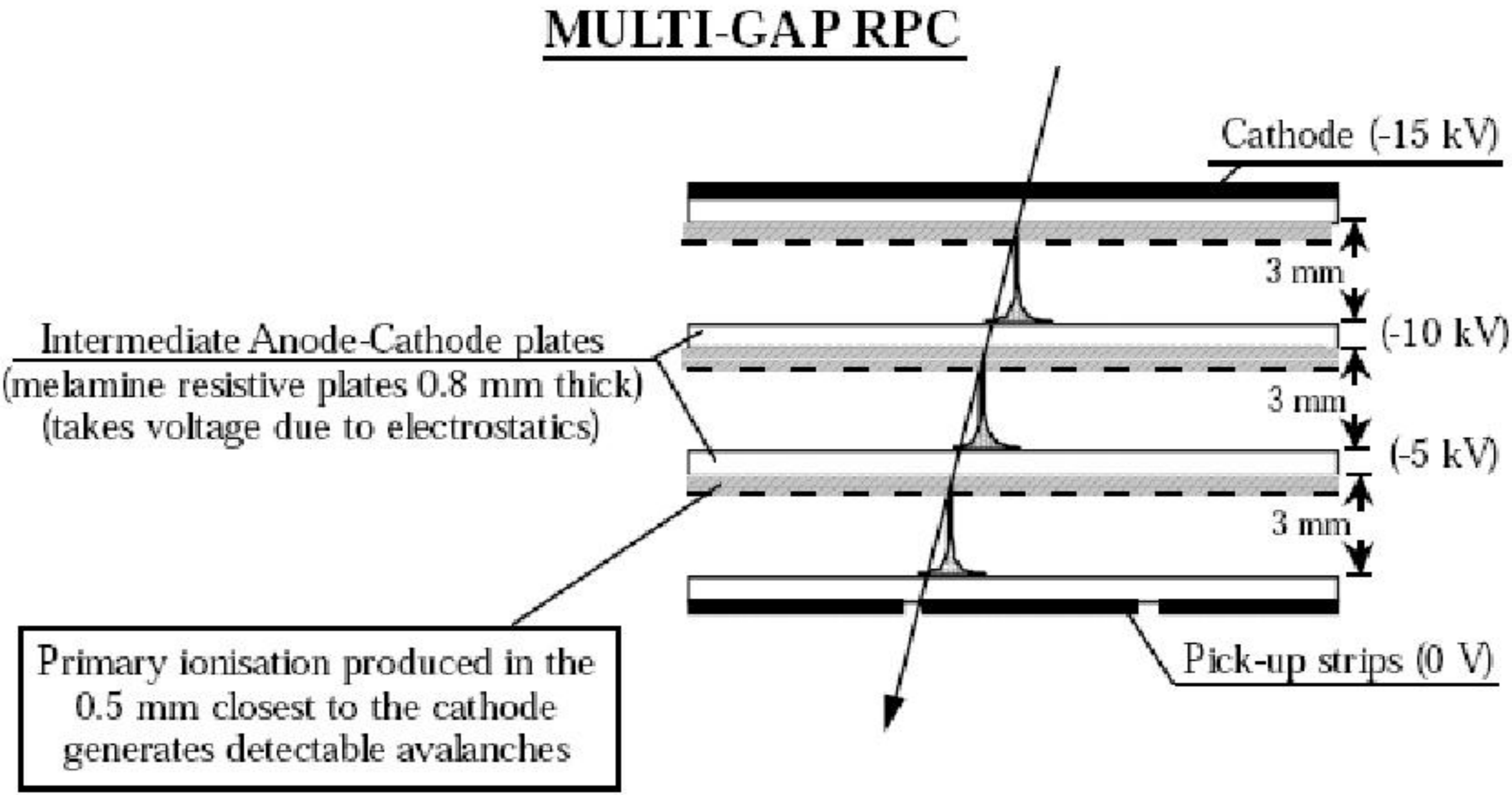
Thank you !!!

Backup slides

Single vs Multigap RPC



Single vs Multigap RPC



Дози при PET

При PET се налага излагане на пациента на действието на йонизиращо лъчение.

Пълната доза е малка, обикновено около **7 mSv**.

За сравнение:

- средногодишната доза, дължаща се на фонова радиация във Великобритания е **2.2 mSv**
- **0.02 mSv** е дозата при Рентгенова снимка на гръдния кош
- **8 mSv** за CT (компютърна томография) на гръден кош
- **2-6 mSv** на година за въздушен персонал (пилоти и стюардеси)
- **7.8 mSv** от фонова радиация в областта Cornwall във Великобритания