RPCs in biomedical applications

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PET: status of the art

- PET generates images depicting the distributions of positron-emitting nuclides in patients
- This technique is used to measure "*in vivo*" biochemical and physiological processes in any organ
- PET provides 2D and 3D images of the living under study
- Improvements have seen a rapid and still ongoing development

The method

Method of administration:

- Injection (appropriate for the organ under study)

How to determine distribution

- Blood volume/flow/organ uptake

What type of radionuclides?

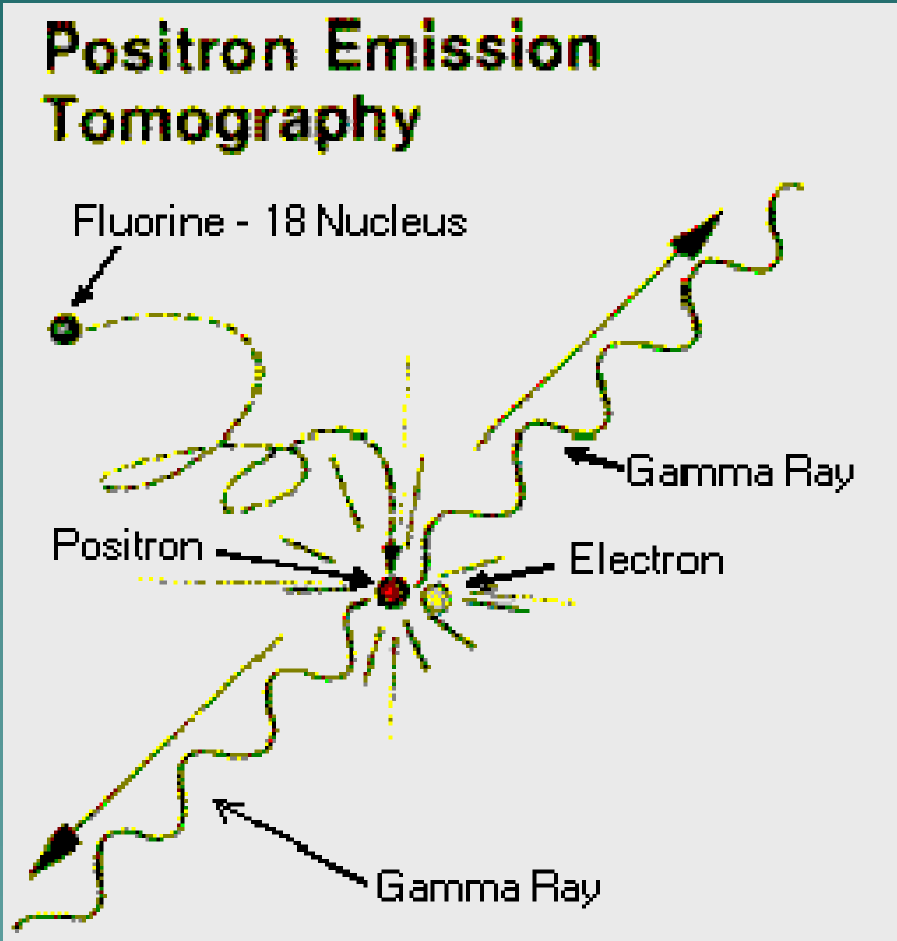
- positron emitters

How to detect?

- Photon detection

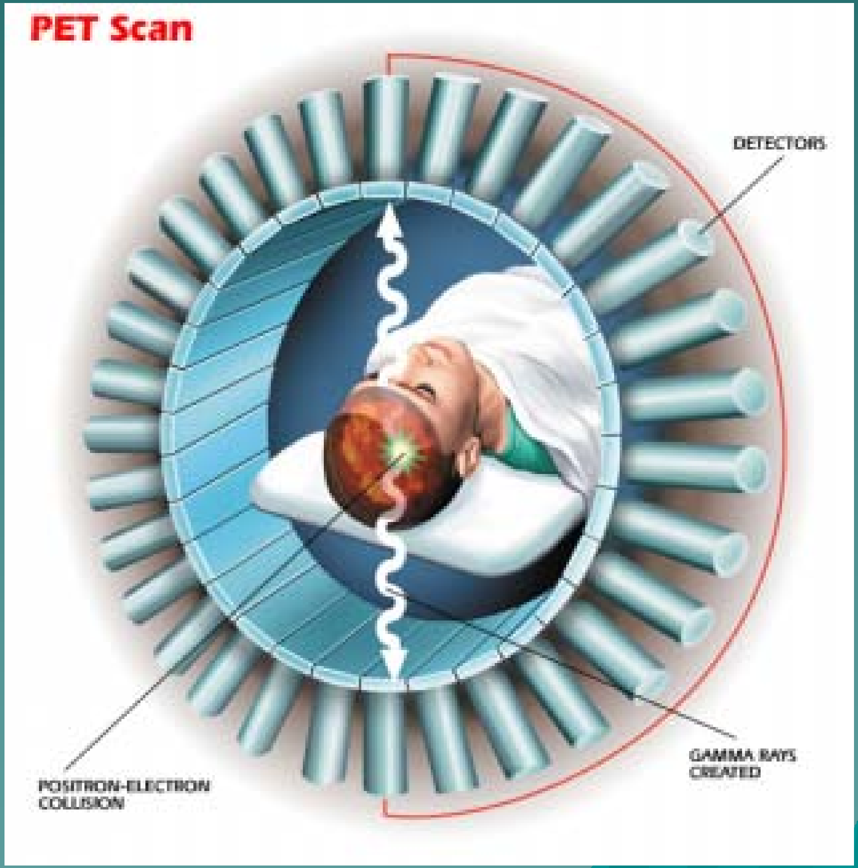
A PET event

- Positron emitters are used for radioactive labeling
- Positrons annihilate with e^- in tissue and two 511 keV γ are emitted back-to-back



Photon detection

- In the typical scanner, several rings of detectors surround the patient
- PET scanners use *annihilation coincidence detection* (ACD) to obtain projections of the activity distribution in the subject



Detectors in PET tomographs

- Scintillation detectors are being used in PET tomographs
- *In the past:* NaI(Tl) crystals
  - Light output: 100
  - Decay time (ns): 230
  - Density (g/cm^3): 3.7
  - Hygroscopic: YES
- *Nowadays:* BGO crystals
  - Light output: 15
  - Decay time (ns): 300
  - Density (g/cm^3): 7.1
  - Hygroscopic: NO
- *New trend:* LSO crystals
  - Light output: 75
  - Decay time (ns): 40
  - Density (g/cm^3): 7.4
  - Hygroscopic: NO

Current PET limitations

The image quality of the current PET is poor because of:

- A short Field Of View (FOV)
- Detector boundary limitations to 2x2 PMT blocks
  → no full energy reconstruction
- Dead time and saturation of the electronics
- Low detector counting rate capability

Current PET captures only 0.2 million pairs per second of the original 1400 million photons pairs per second emitted in the patient body (efficiency order 10^{-4})

RPCs in PET

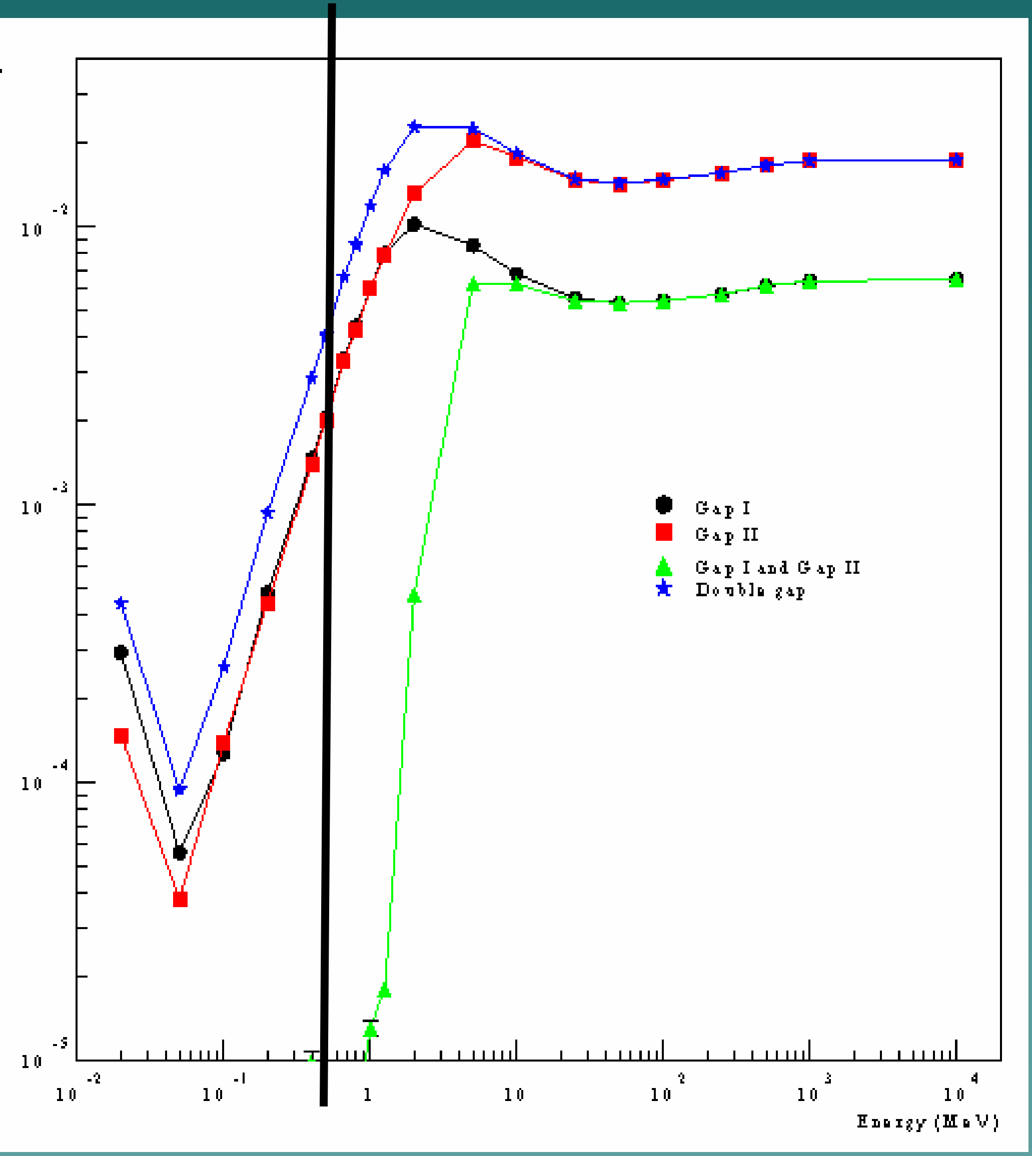
Key features of RPCs:

1. Small reading pads
2. Small time jitter (down to 50 ps)
3. Thin converter plate (tiny parallax)
4. Low cost (about 100 - 200 $/m^2$)

Why should we use RPCs?

- Good spatial resolution (1 + 3)
- Long FOV, high geometrical efficiency, high statistic, high signal/noise (1 + 3 + 4)
- Good time resolution, point-like data, noise reduction (2)
- Affordable price (4)

RPC gamma efficiency



Gamma efficiency of a double gap bakelite RPC in case of isotropic emission

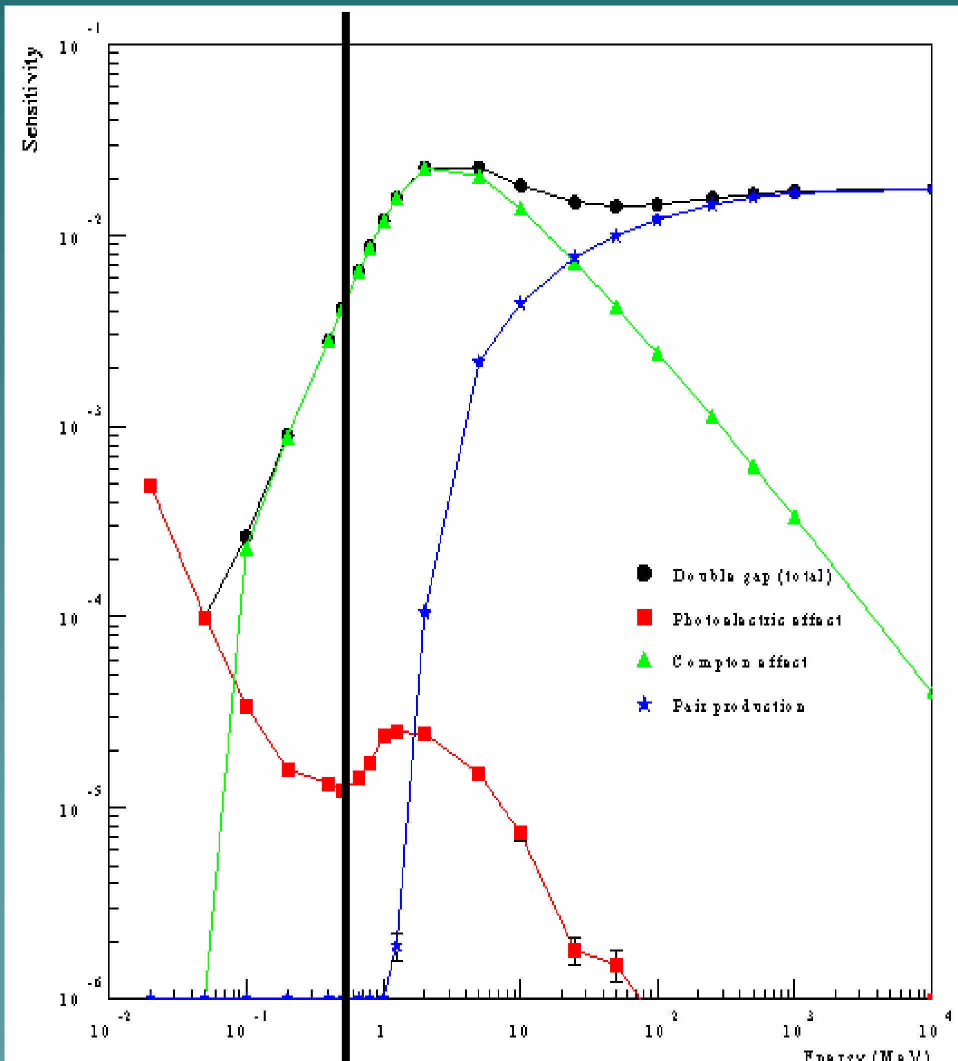
E(γ) = 500 keV

ε (gap I) = 3.5 10^{-3}

ε (gap II)= 2.4 10^{-3}

ε (DG) = 5.9 10^{-3}

Processes involving gamma



E(γ) = 500 keV

Photoelectric effect

→ $1.5\ 10^{-5} \rightarrow Z^{5}$

Compton effect

→ $4.0\ 10^{-3} \rightarrow Z$

How to increase RPC gamma efficiency

- Study of suitable material for the target planes
- Many features of RPCs do not depend on the material they are made of, so we can easily try new ones
- Which materials?
  - High atomic number (Z) → Photoelectric and Compton effects are enhanced
  - Resistive features

Coating materials

	d (g/cm3)	Electrons 0,5 MeV R (g/cm2)	R (mm)	Gamma 0,5 MeV tot att (cm2/g)	u (1/mm)
Pb	11,3	0,336	0,297	1,61E-01	0,182
Tl	11,9	0,335	0,282	1,58E-01	0,188
Bi	9,7	0,334	0,344	1,66E-01	0,161
Ce	6,8	0,304	0,447	1,04E-01	0,071
Ba	3,5	0,305	0,871	9,92E-02	0,035
PbO	9	0,3268	0,363	1,56E-01	0,140
BaO	5,72	0,2952	0,516	9,80E-02	0,056
Bi2O3	8,55	0,3192	0,373	1,58E-01	0,135
CeO2	7,13	0,2834	0,397	1,01E-01	0,072
Pb3O4	9,1	0,3223	0,354	1,54E-01	0,140
Tl2O	9,52	0,333	0,350	1,55E-01	0,148
Tl2O3	9,8	0,319	0,326	1,51E-01	0,148
Bachelite	1,25	1,85E-01	1,480	9,21E-02	0,012
Vetro	2,4	2,14E-01	0,893	8,71E-02	0,021
Vetro Pb	6,22	2,97E-01	0,477	1,43E-01	0,089
Gd2O3	7,407	2,99E-01	0,404	1,10E-01	0,081

Coating features

- The coating has to be as smooth as possible
- The coating thickness has to be ≤ e^- range in that material

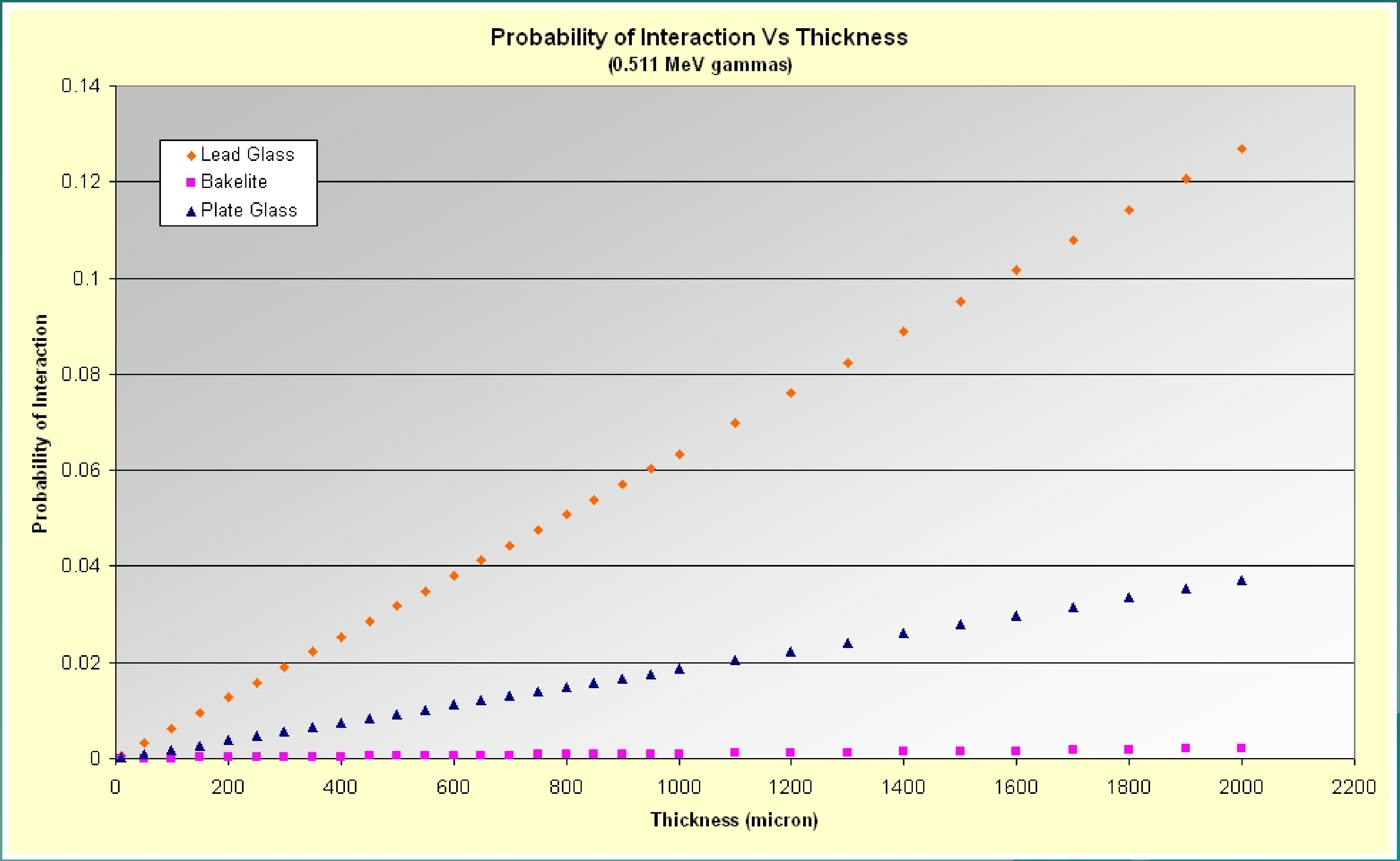
↓

- The proper coating technique seems to be *serigraphy*, since it allows to have homogeneous and smooth layers of deposited mixture in thickness greater than hundreds of microns

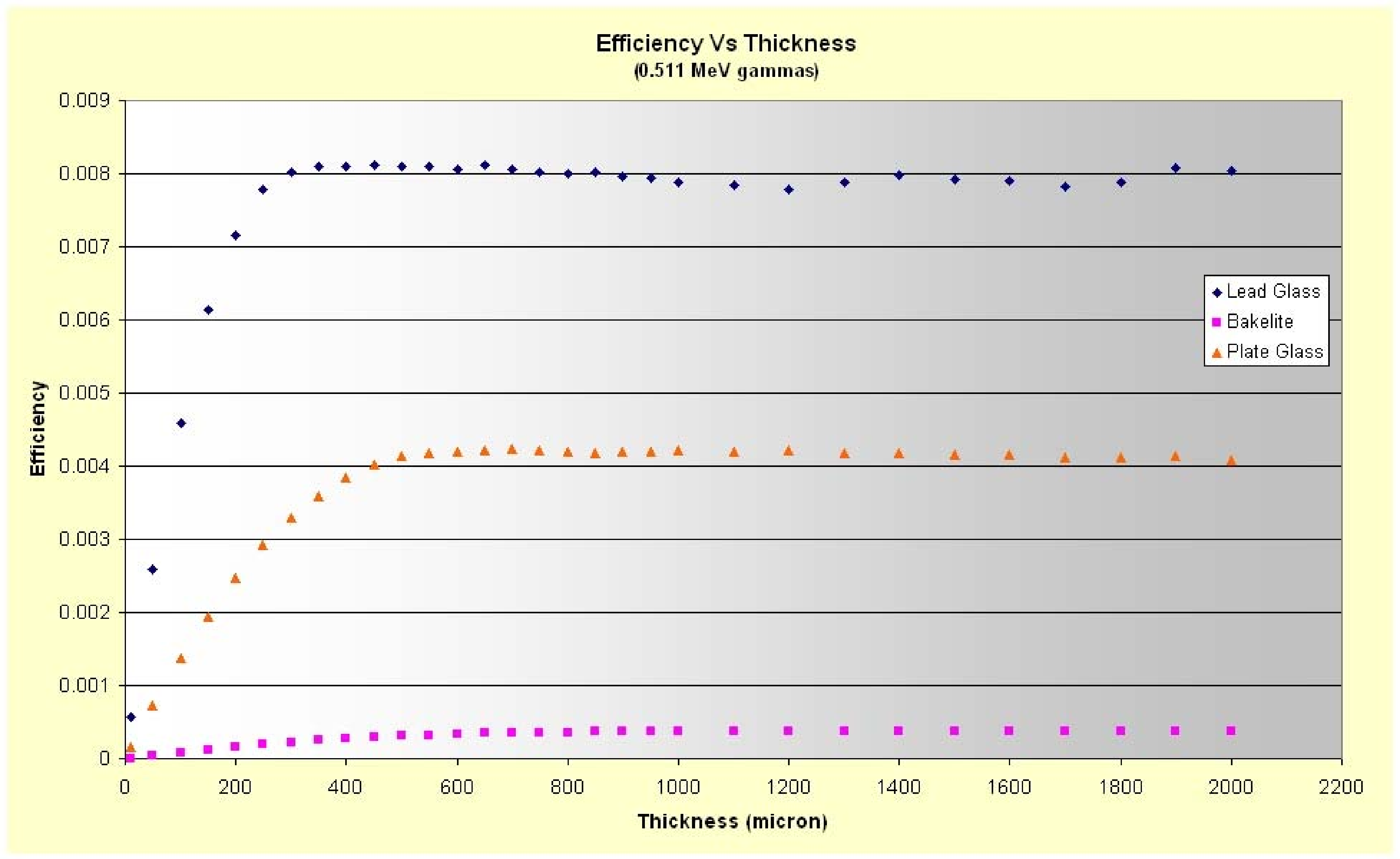
Coating materials under study

- The most promising mixtures seem to be PbO, Bi_2O_3 and Tl_2O. We plan to use Oxide-based mixtures for the resistive properties of the electrodes
- First data from the simulation considered lead glass as target material in a single gap RPC
- Next results showed the importance of employing a high Z material, e.g. a serigraphable “paste” made of PbO
- We are synthesizing a compound, 50%mol SiO_2 – 50%mol PbO: the H.V. electrodes are going to be made by those monoliths (rising questions: the surface roughness)

Materials simulation



Efficiency simulation



To increase efficiency

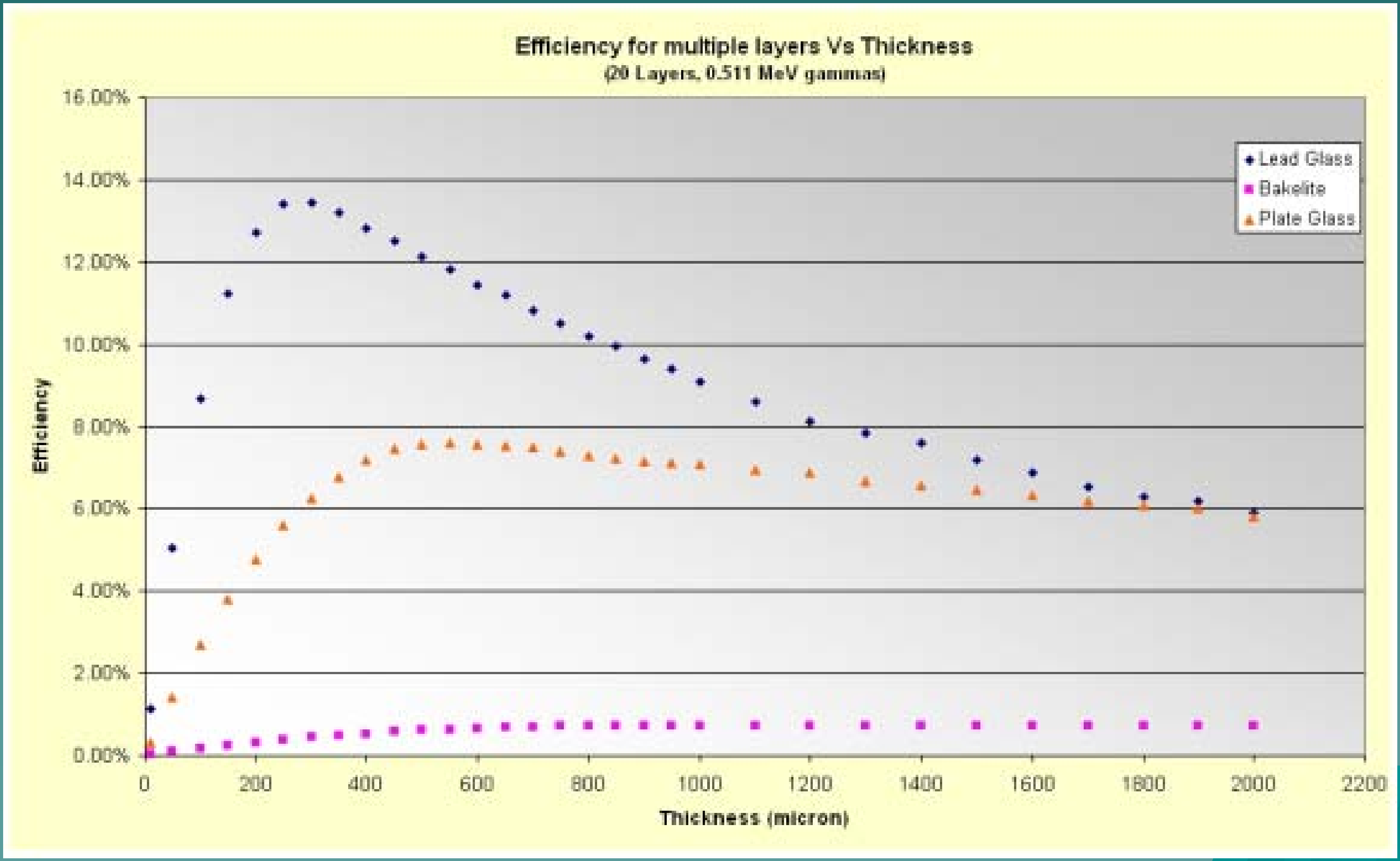
We can employ ***more*** than just one target layer → glass ***multigap RPC***

Multigap I set up

- 5 gas gaps; the spacing is kept by 0.3 mm diameter nylon fishing line
- Electrodes made of thin glasses (1 mm for the outer electrodes, 0.15 mm for the inner ones)
- The detector is enclosed in a metallic gas-tight box, filled with the gas mixture:

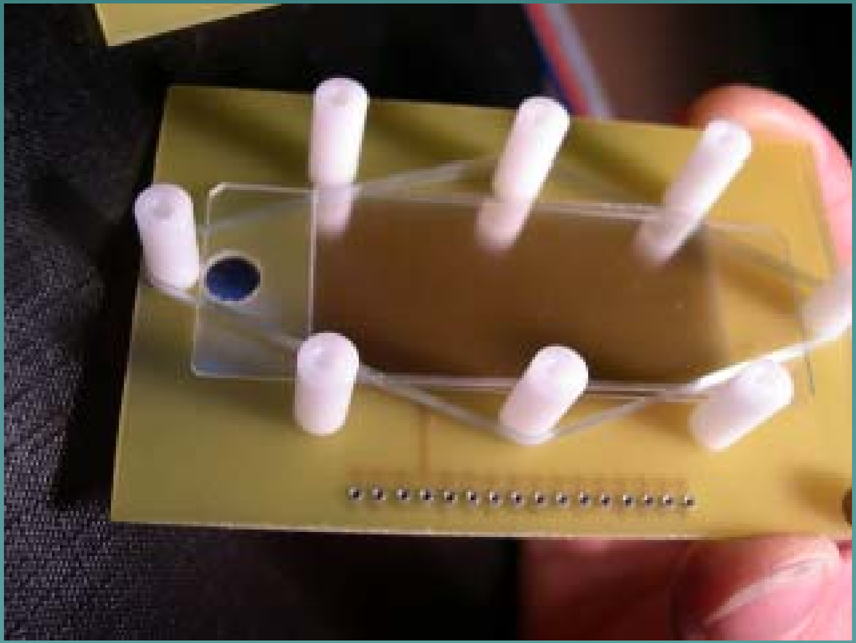
$C_2H_2F_4$ 92.5%, SF_6 2.5%, iC_4H_{10} 5%

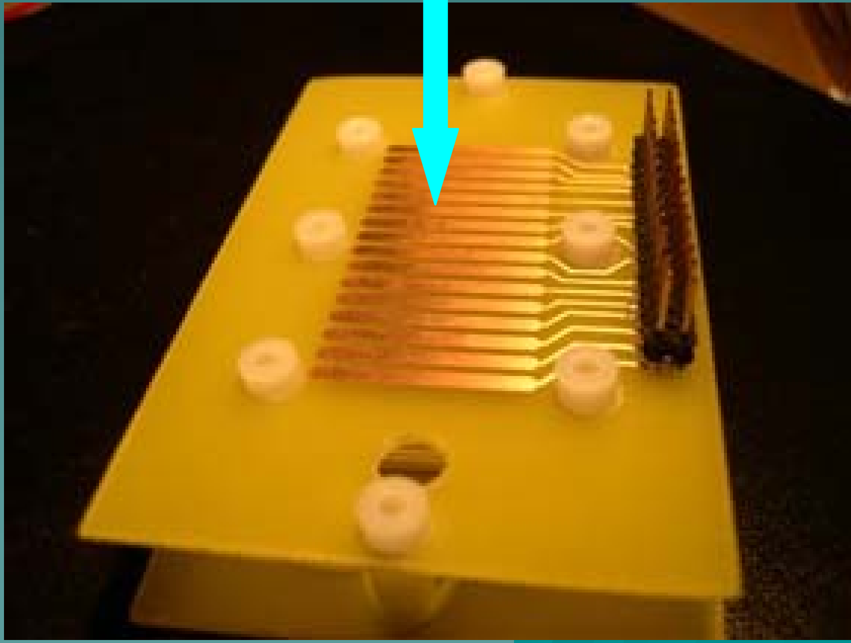
Multigap gamma efficiency (simulation)



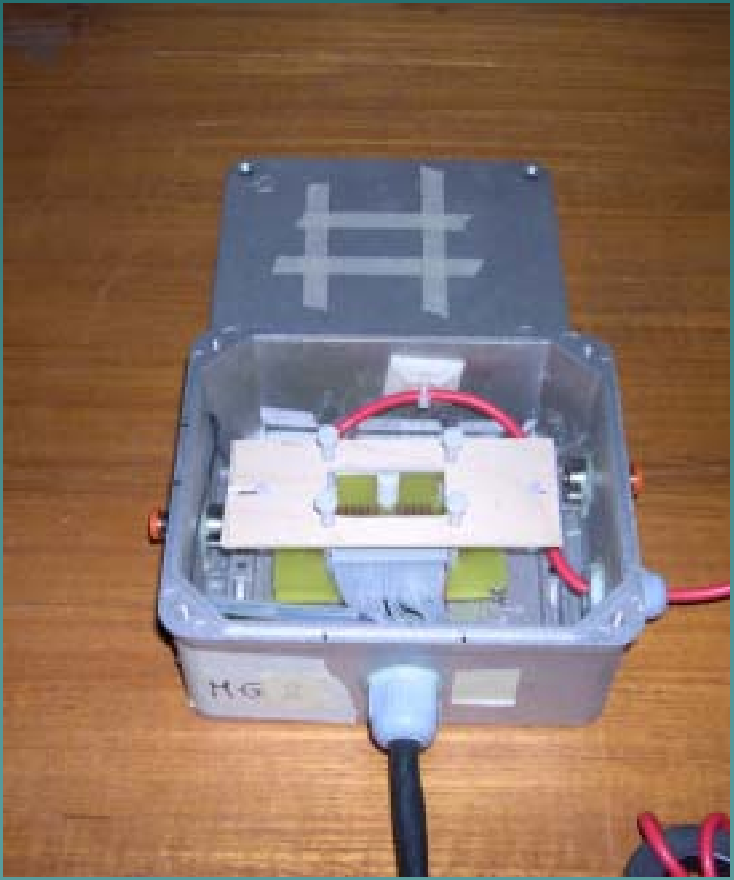
Multigap prototype I

MG I has a pad on the lower PCB layer and strips (2 mm wide, 1mm spaced) on the upper layer





The box with the multigap

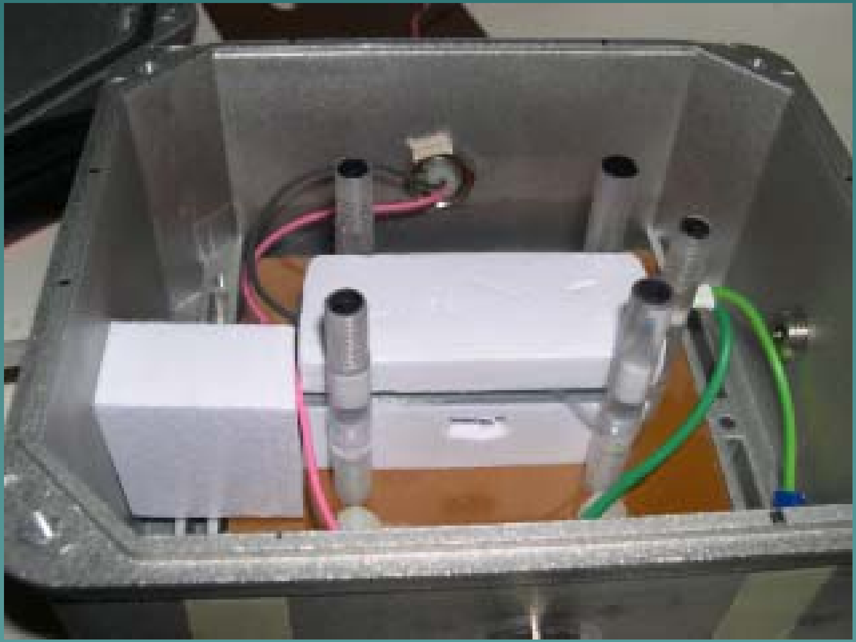


The metallic gas tight box with H.V. and signal cables; signal is picked up by a flat cable

Multigap prototype II

- ***Multigap II set up:***
  - 5 gas gaps; the spacing is kept by 0.3 mm diameter nylon fishing line (like the first one)
  - Electrodes made of thin glasses (1 mm for the outer electrodes, 0.4 mm for the inner ones)
  - With thicker glasses we expect a greater counting rate
  - The detector is enclosed in a metallic gas-tight box, filled with the gas mixture: $C_2H_2F_4$ 92.5%, SF_6 2.5%, iC_4H_{10} 5%

Multigap prototype II



Signal is picked up on the upper pad

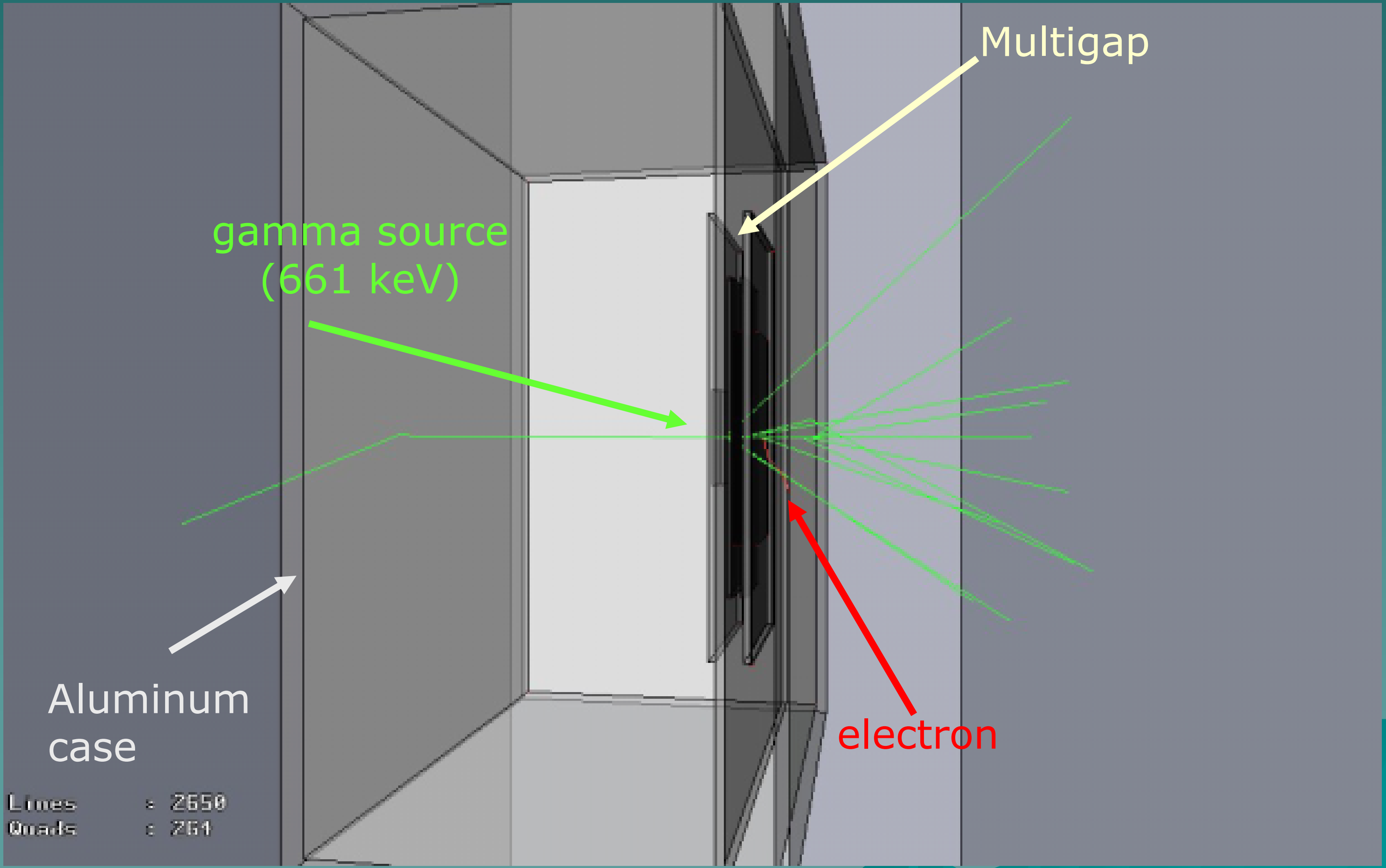
Simulation data

- Geometry, materials, gas, gamma and electron generation and transport using *Geant4*-based frame work
- Minimum detector physics simulation

→ $$Q_{ind}(x) = \frac{E_W}{V_W}\frac{e_0}{(\alpha-\eta)}\left(e^{(\alpha-\eta)x}-1\right)$$ + saturation

- Preliminary MC data for multigap I
- Optimization of MC simulation
- Simulation of SiO_2-PbO monoliths as multigap electrodes

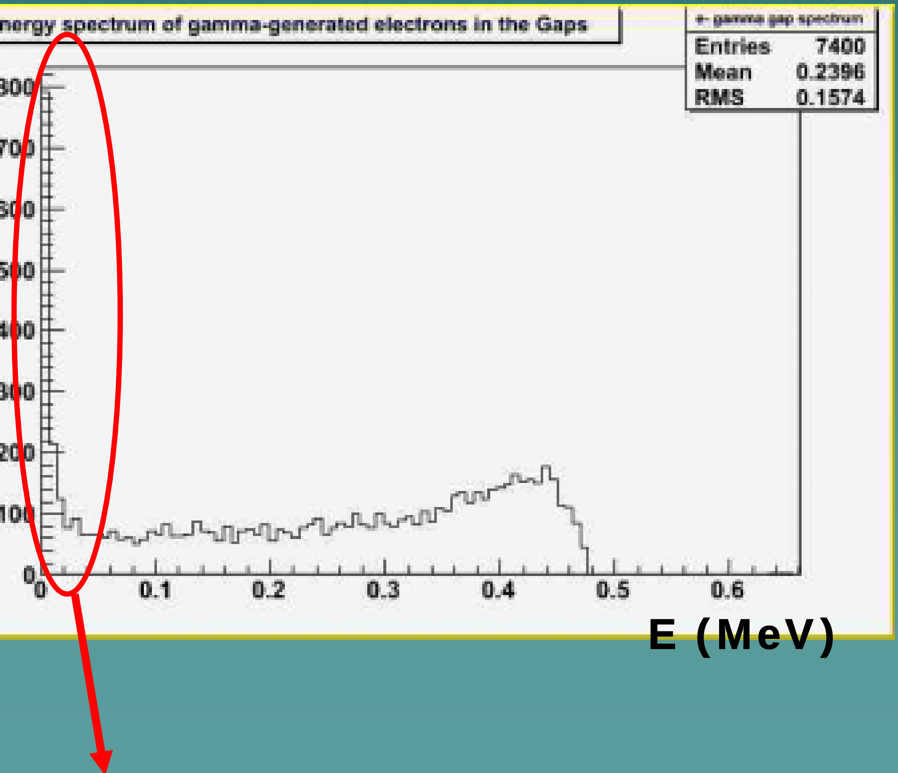
Multigap simulation



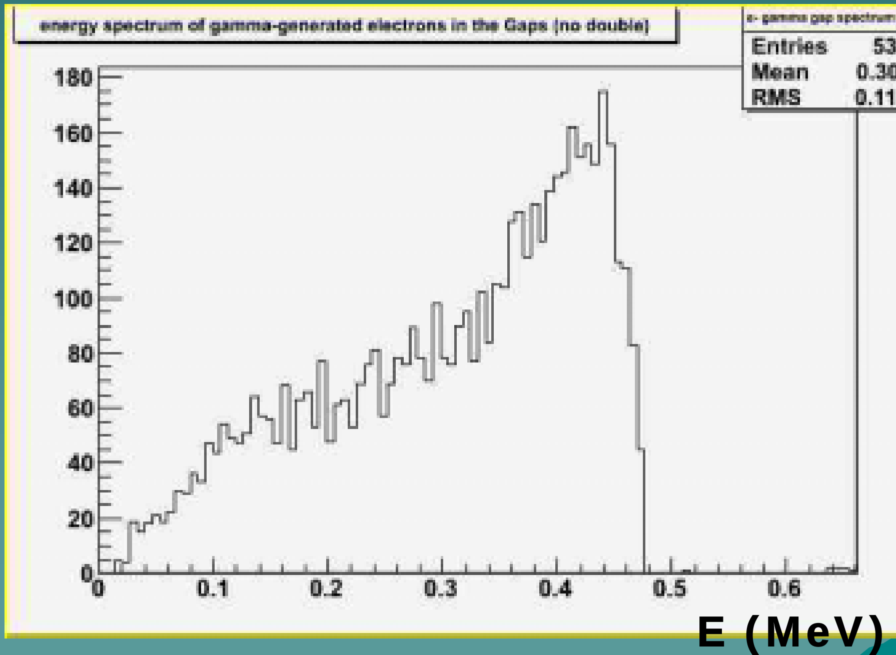
Examples of Geant4 output

Energy spectrum of gamma-electrons in the gas gaps

With secondary Compton



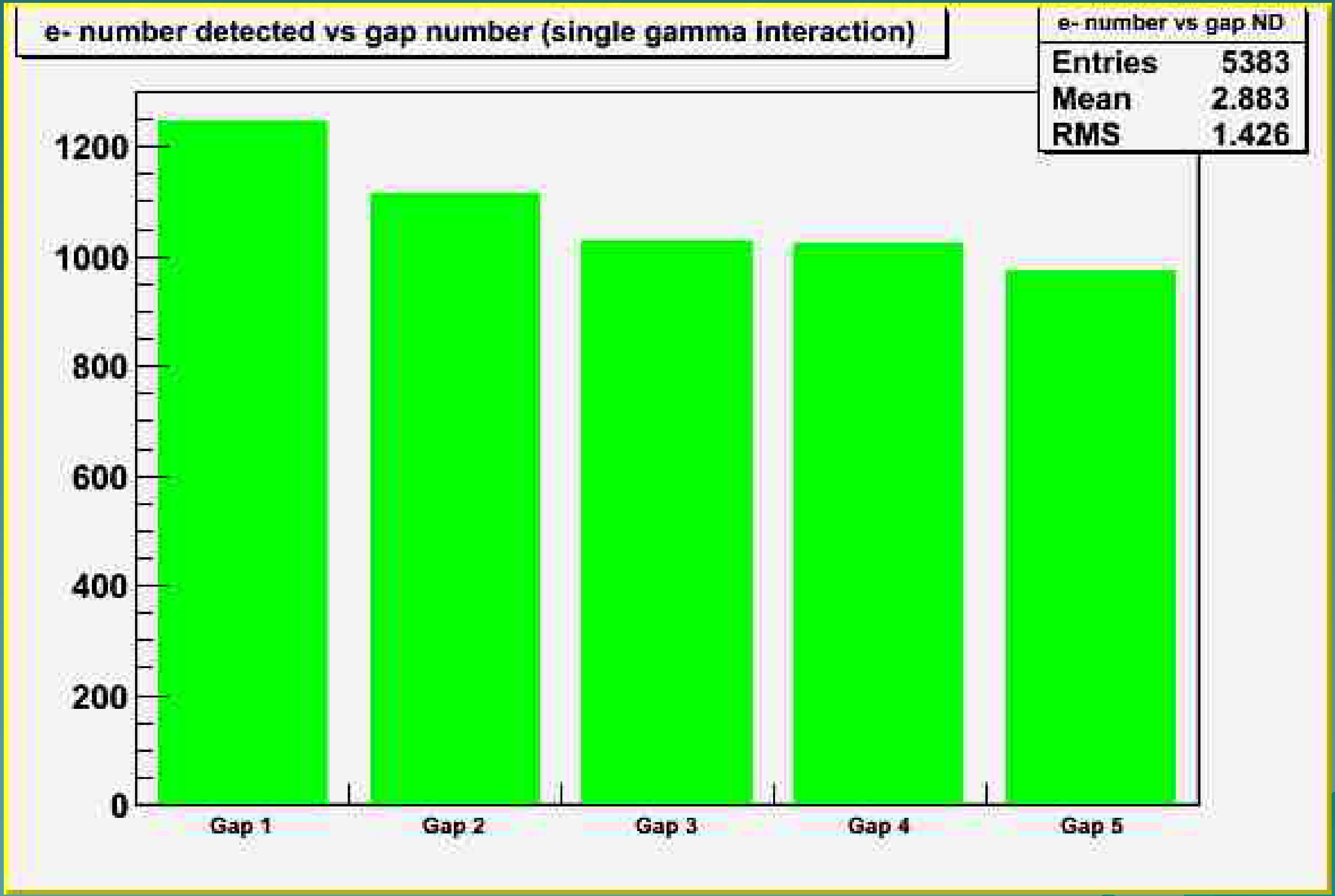
Without secondary Compton



Secondary Compton electrons only at low energies

Electrons in the gaps

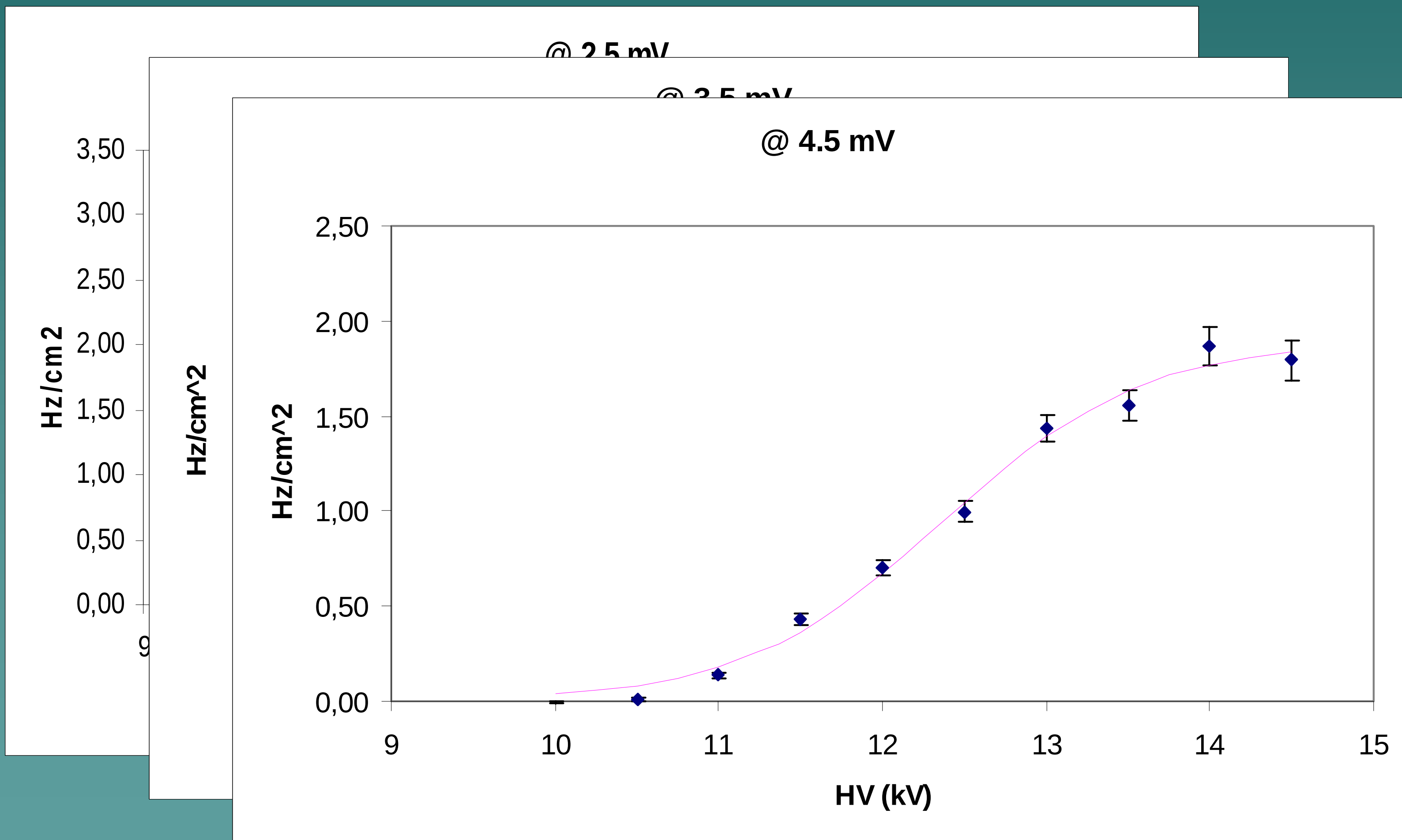
Multigap I simulation



Decreased geometrical acceptance

Multigap I

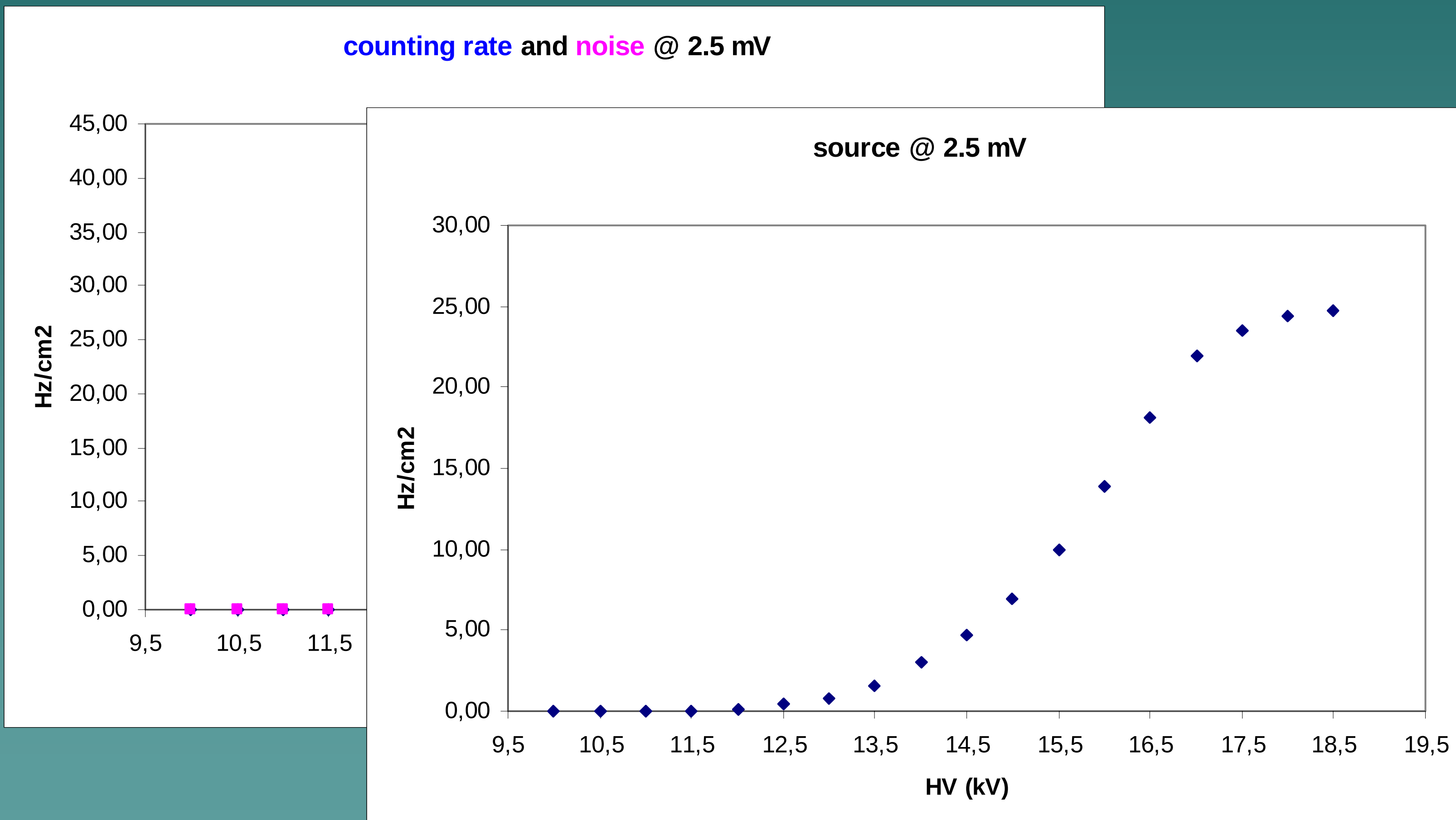
Counting rate at different thresholds: 2.5 mV, 3.5 mV and 4.5 mV
Counting with a γ source, ^{137}Cs, whose activity is 5 μCi



Noise subtracted plots

Multigap II

icker glasses → greater counting rate



Simulation vs. experimental data

- Primary and secondary Compton are seen as one by the electronics
- Limits on cluster simulation with *Geant4*
- 46% of electrons cross two adjacent gaps (in MGI)

Outlook

- A multigap prototype made of proper materials ready within a couple of months
- Increasing efficiency using a stack of multigaps and new materials
- Study of image reconstruction techniques

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