RPC 2022

XVI Workshop on Resistive Plate Chambers and Related Detectors

26–30 Sept 2022
CERN

An RPC-PET brain scanner: first results

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Financed by project
“HiRezBrainPET”
POCI-01-0247-FEDER-039808

Cofinanciado por:

COMPETE 2020

PORTUGAL 2020

UNIÃO EUROPEIA
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Started a long time ago…

RPC2001 VI Workshop on Resistive Plate Chamber

Perspectives in Positron Emission Tomography (PET) with RPCs

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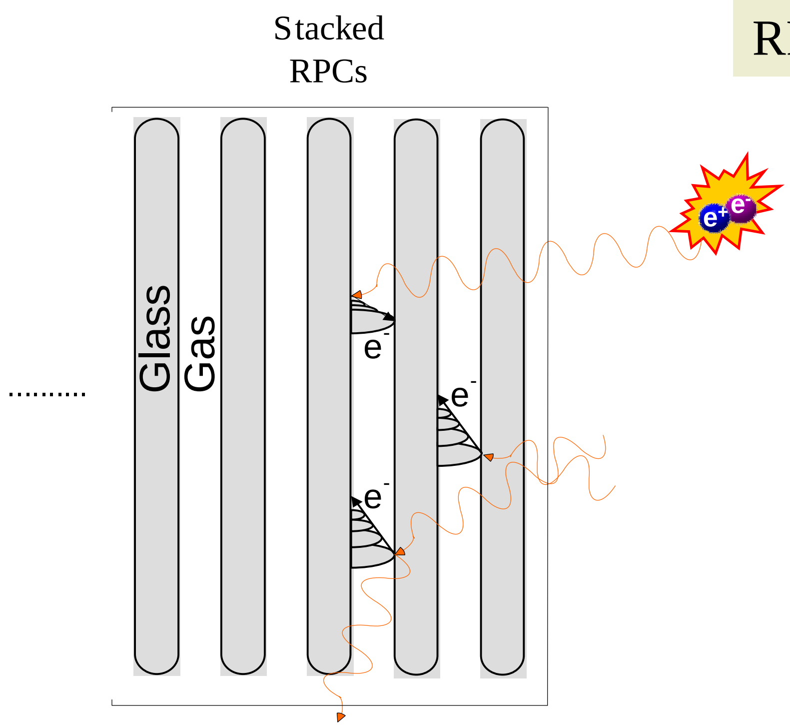
It was a better idea then than it is now, mainly because of the invention of SiPMs and faster crystals ⇒ finer granularity readout ("digital PET") and TOF-PET

The basic idea for RPC-based TOF-PET

[Blanco 2002]

The converter-plate principle



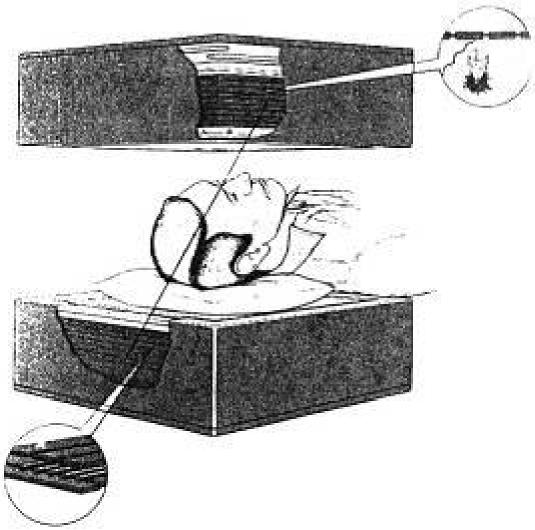
Use the electrode plates as a γ converter, taking advantage of the natural layered construction of the RPCs.

Time resolution for 511 keV photons:
(our routine lab-test tool)

90 ps σ for 1 photon ⇔
300 ps FWHM for the photon pair

A previous work on PET with gaseous detectors
(21 lead plates + 20 MWPCs = 7% efficiency)

"The Rutherford Appleton Laboratory´s Mark I Multiwire Proportional Counter Positron Camera"
J.E. Bateman et al. NIM 225 (1984) 209-231



Comparison with the standard PET technology

Disadvantages

Certainly a much smaller efficiency… it is still to be seen if this is a fatal flaw.

No energy resolution, but there is an equivalent energy sensitivity (more later).

Detector scatter (vs. "misidentified fraction" in crystal blocks)

Possible specialized PET applications

Advantages

Increasing system sensitivity

Inexpensive ⇒ large areas possible ⇒ large solid angle coverage

Excellent timing ⇒ TOF-PET possible

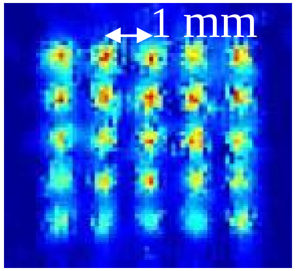
Total body Human PET

Increasing position accuracy

Gaseous detectors routinely deliver 0.1 mm resolution

Full 3D localization possible ⇒ no gross parallax error

The very small gap minimizes intrinsic errors



Small Animal PET

Simulation: 0.51mm FWHM

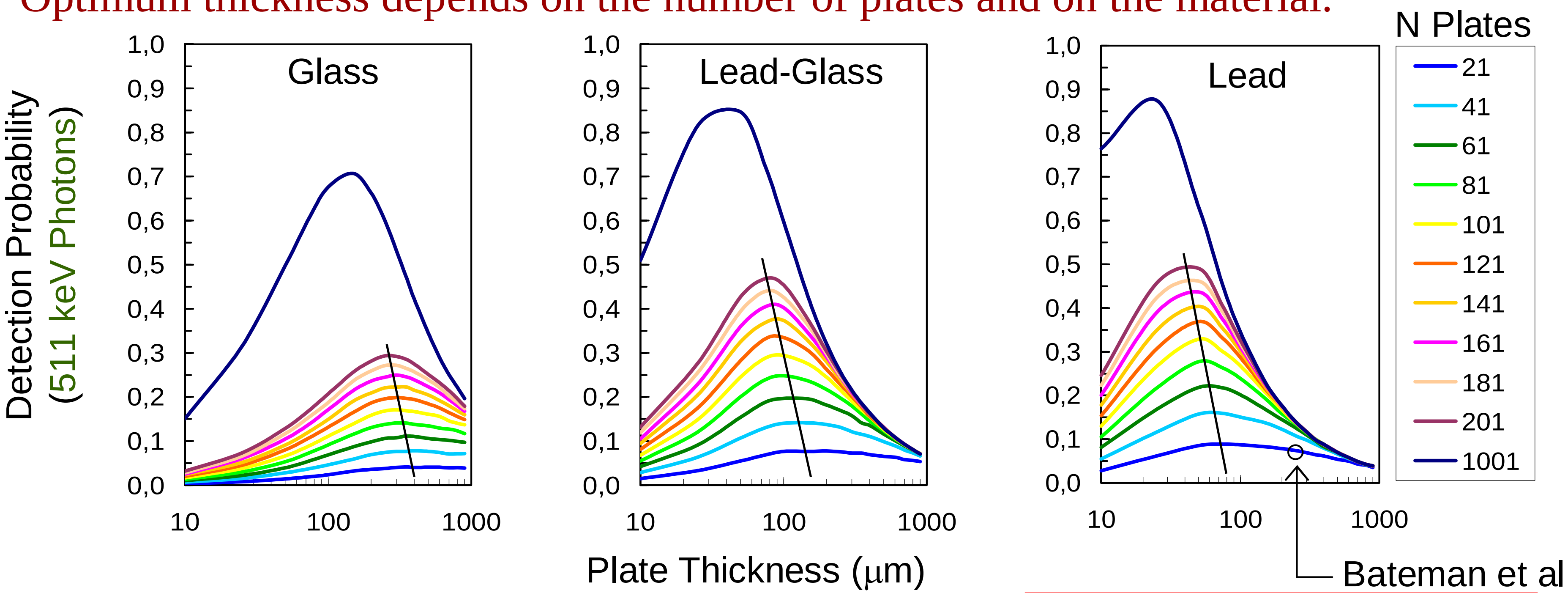
Lowering costs

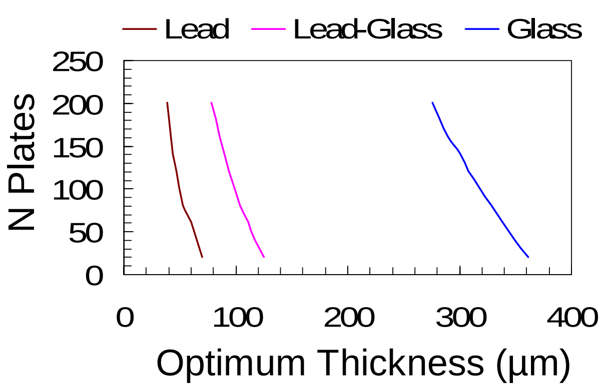
Applications can be also optimized for low cost
at the expense of other characteristics

Comparison with GEANT - efficiency

Optimum efficiency is balanced by beam absorption (thicker plates) and extraction probability (thinner plates)

Optimum thickness depends on the number of plates and on the material.



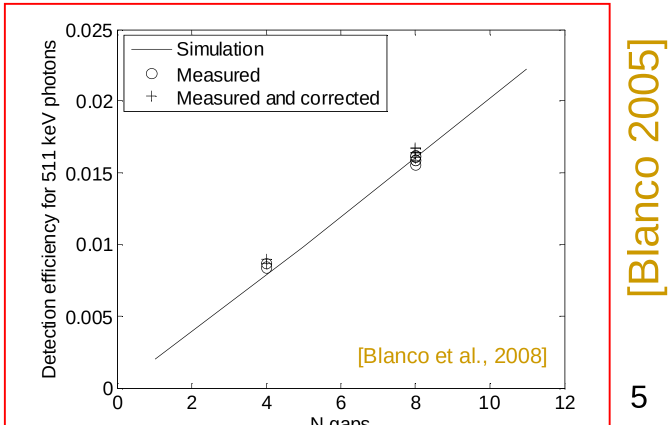


Our measurement:

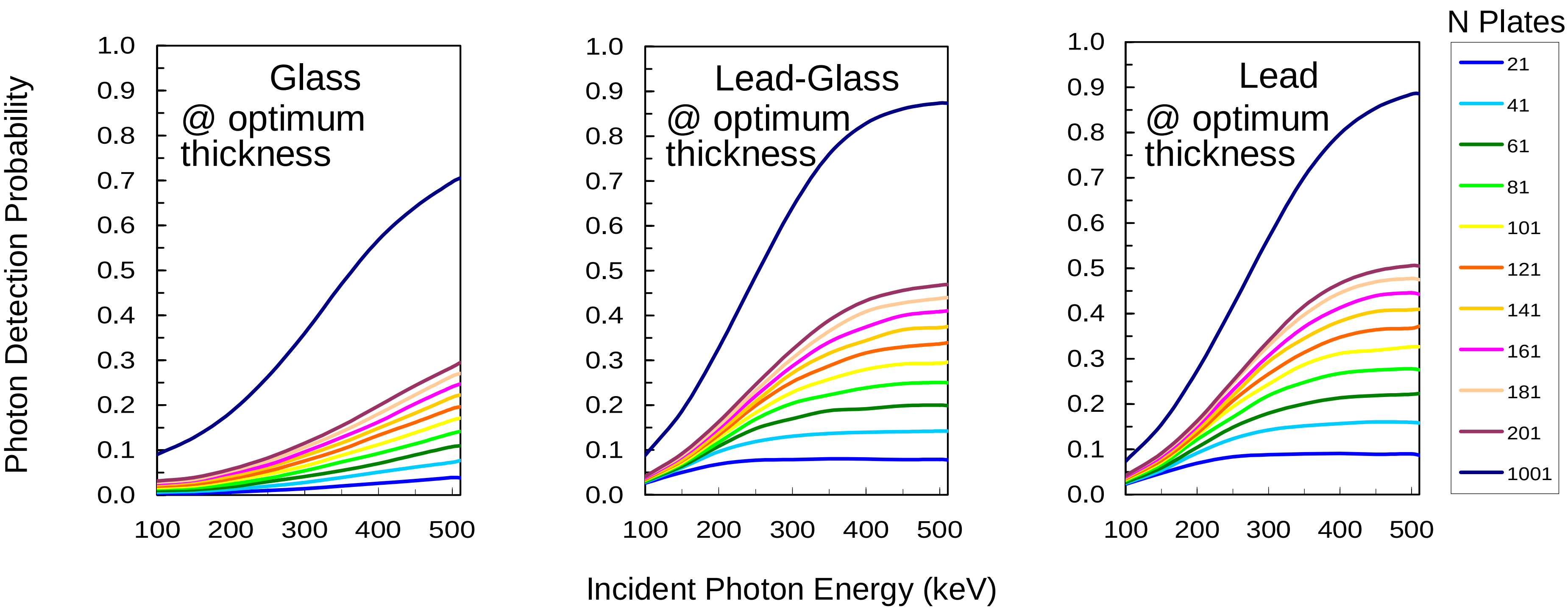
for few gaps

~0.2%/gap

@ 511 keV



GEANT - energy dependence

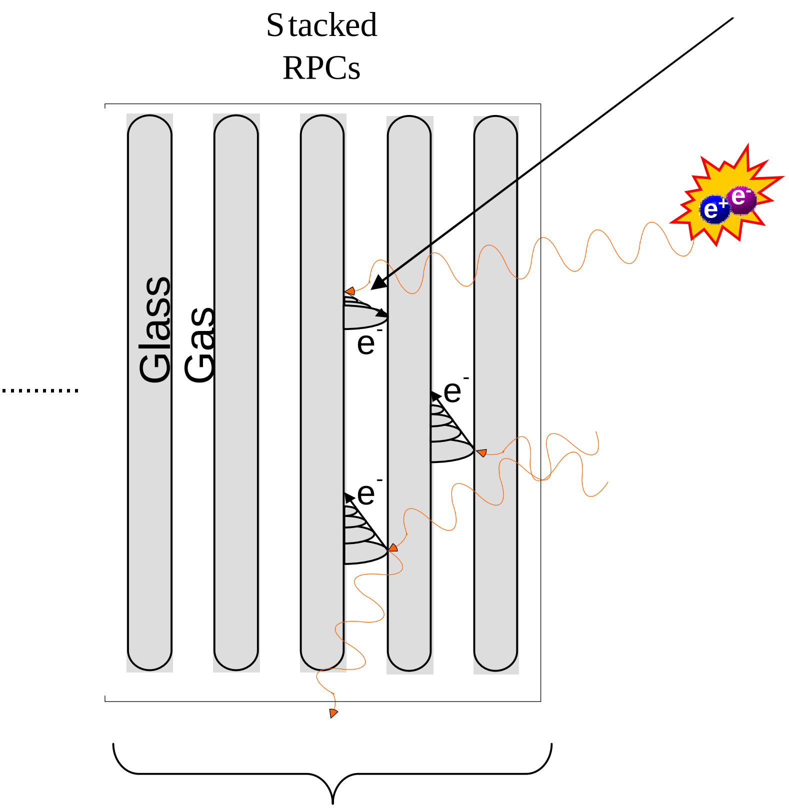


Strong ENERGY SENSITIVY
scattered photons statistically rejected

		Material		
	ε_{max}	Glass	Lead-Glass	Lead
N Plates	101	*17%*	*29%*	*31%*
	201	*29%*	*47%*	*50%*

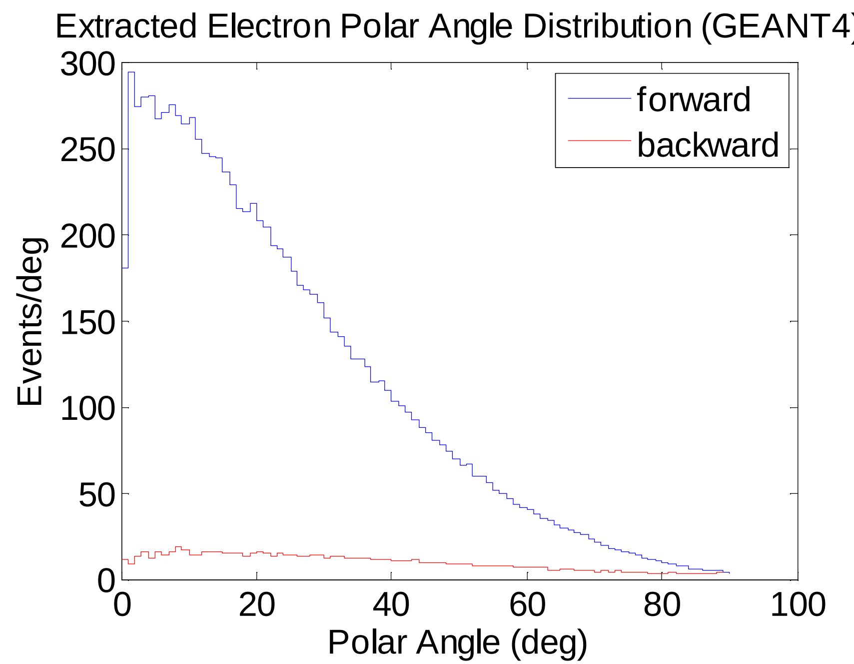
Intrinsic sources of instrumental position error

The converter-plate principle



- Electronic noise
- Angle of ejection of the electron will shift the baricenter of the avalanche.

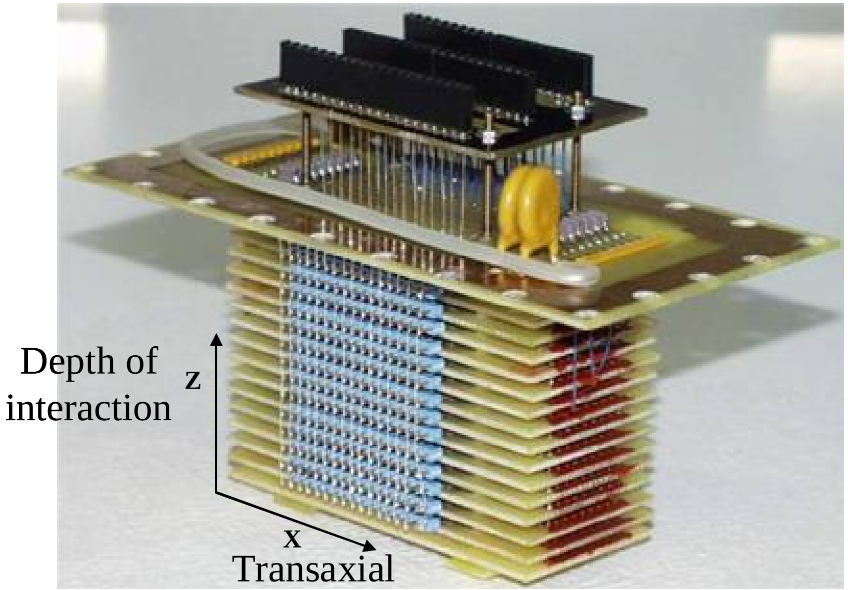
⇒ Minimized by a very thin gas gap

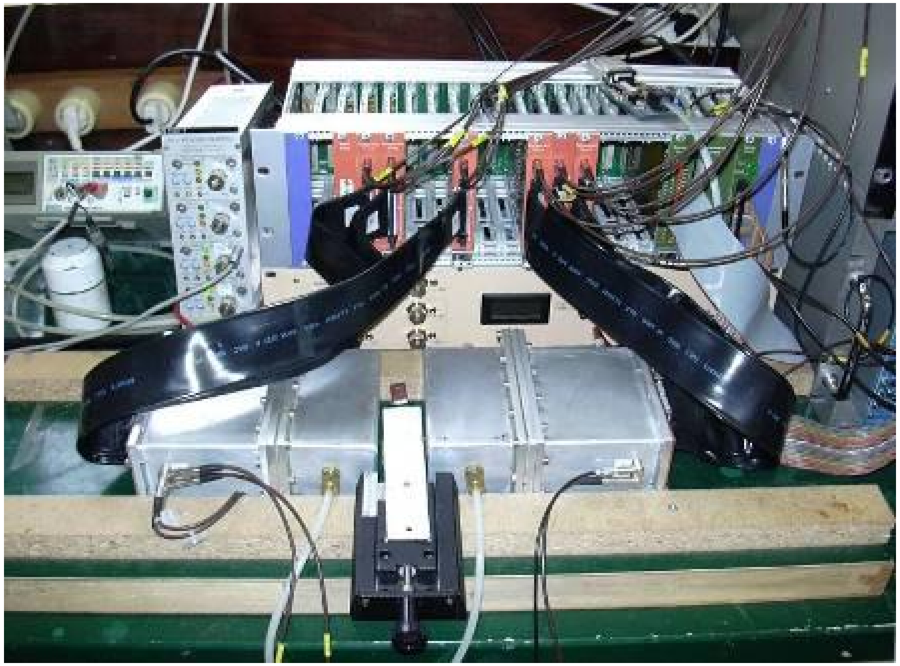


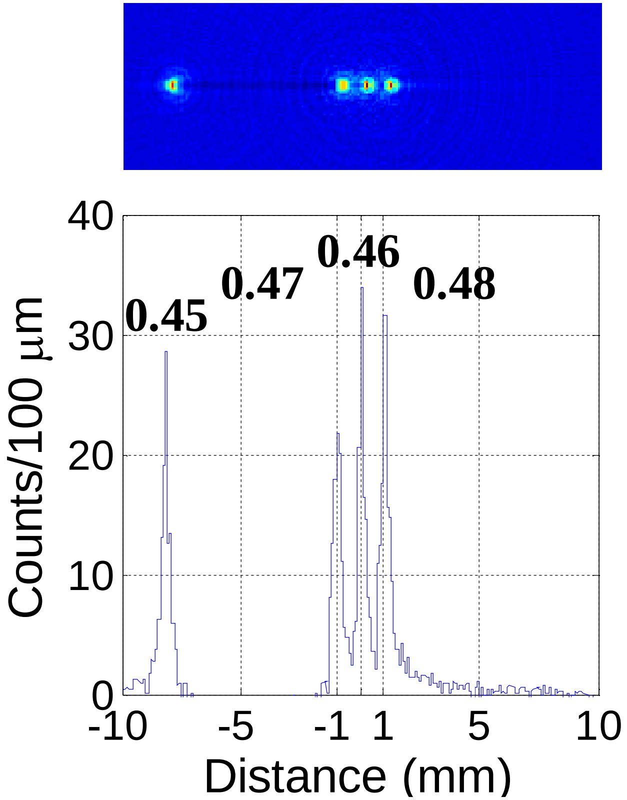
- Different gaps fired along an inclined trajectory cause parallax error (depth of interaction – DOI error)

⇒ Identification of the fired gap by analysis of the induced charge pattern

Along the way…





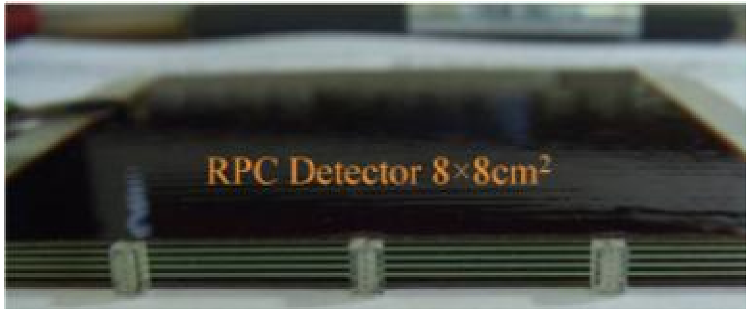


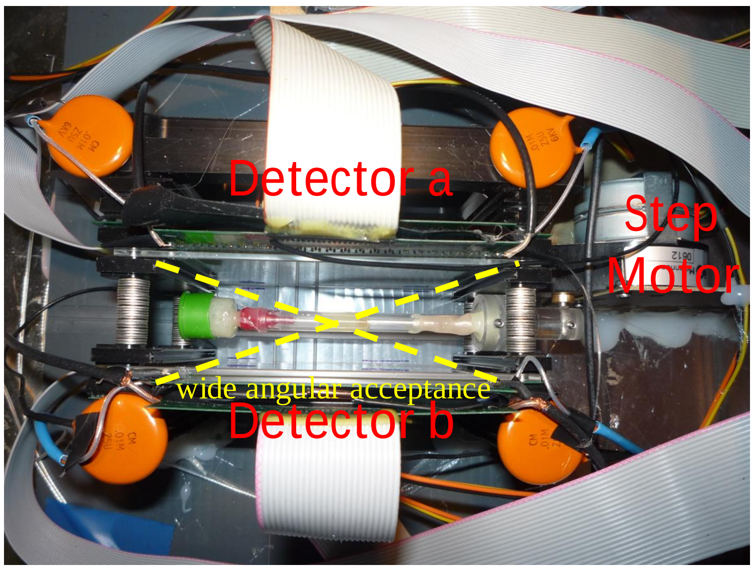
2D readout

0.47 mm FWHM
over the transaxial FOV

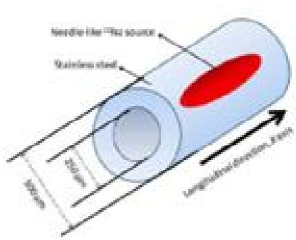
[Blanco NIM 2004]

Along the way…

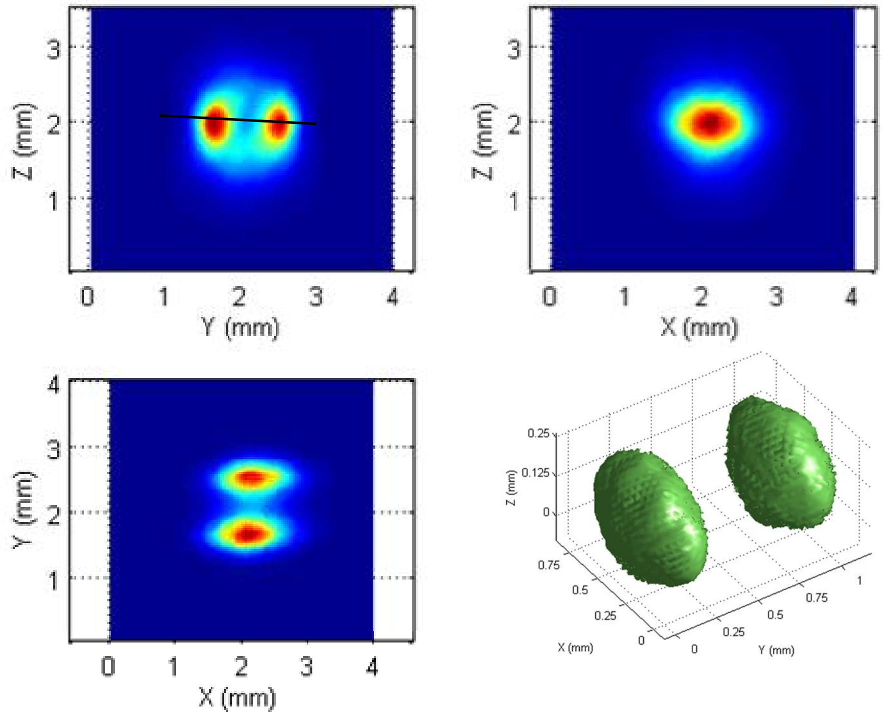


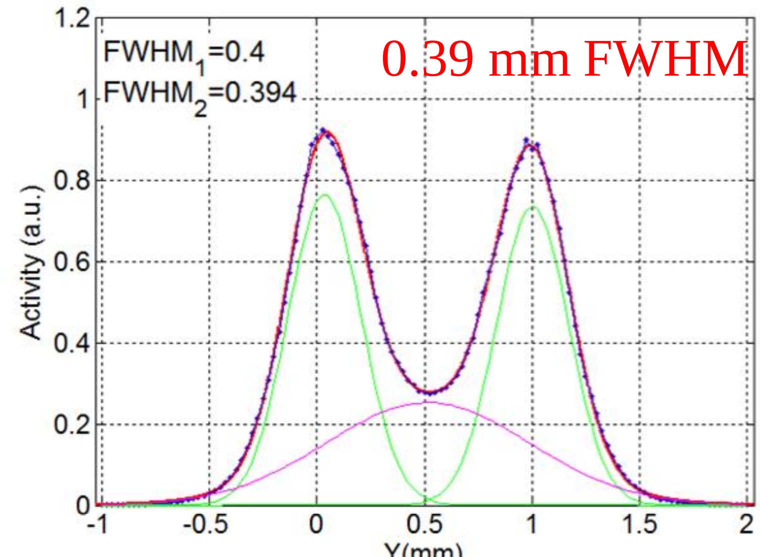


Needle source, 0.2 mm ∅ int.



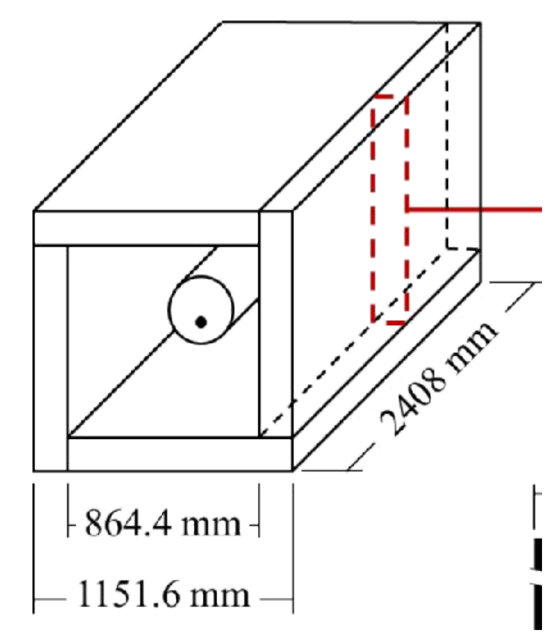
3D readout
+
fast trigger

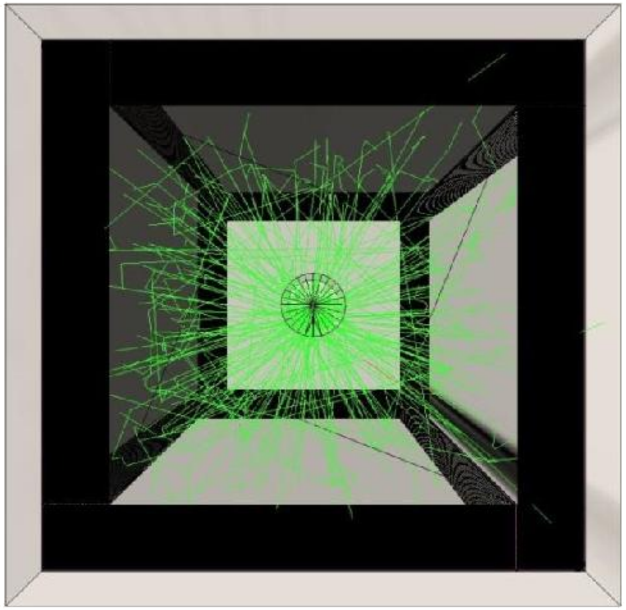




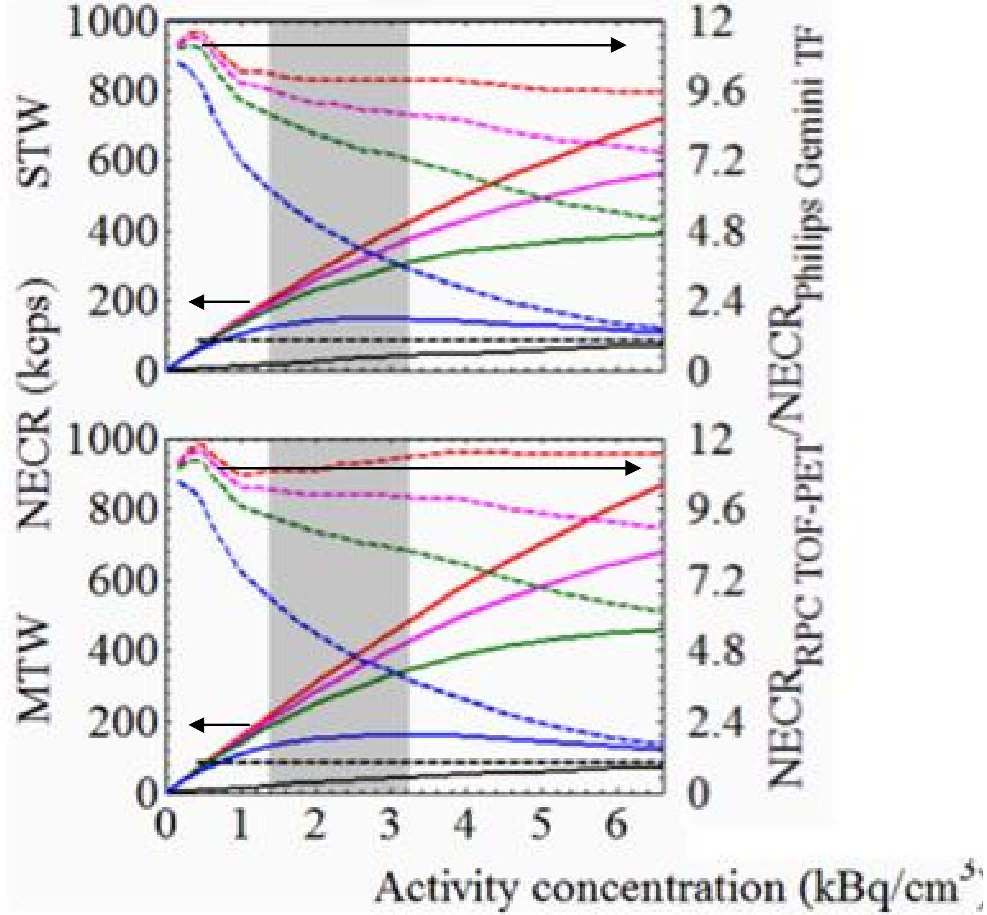
[Martins JINST 2014]

Along the way…





Detailed simulations of human total-body RPC-PET



<u>No TOF advantage considered</u>
<u>No single-bed advantage</u>

Factors 5 to 11 NECR advantage over GEMINI TF
(depending on the assumed electronics dead time
⇒ the different lines)

[Couceiro IEEE-TNS 2014]

RPC-PET brain scanner

30×30×30 cm^3 field of view

Acceptance solid angle = 66%

Installed at ICNAS Pharma

Motivation:

- Resolving the smaller brain structures, often involved in severe neurological disorders (e.g. Parkinson, Huntington, addictions)
- Better characterization of the lesions from strokes
- Improve the oncological therapeutic planning by better detection and characterization of tumors

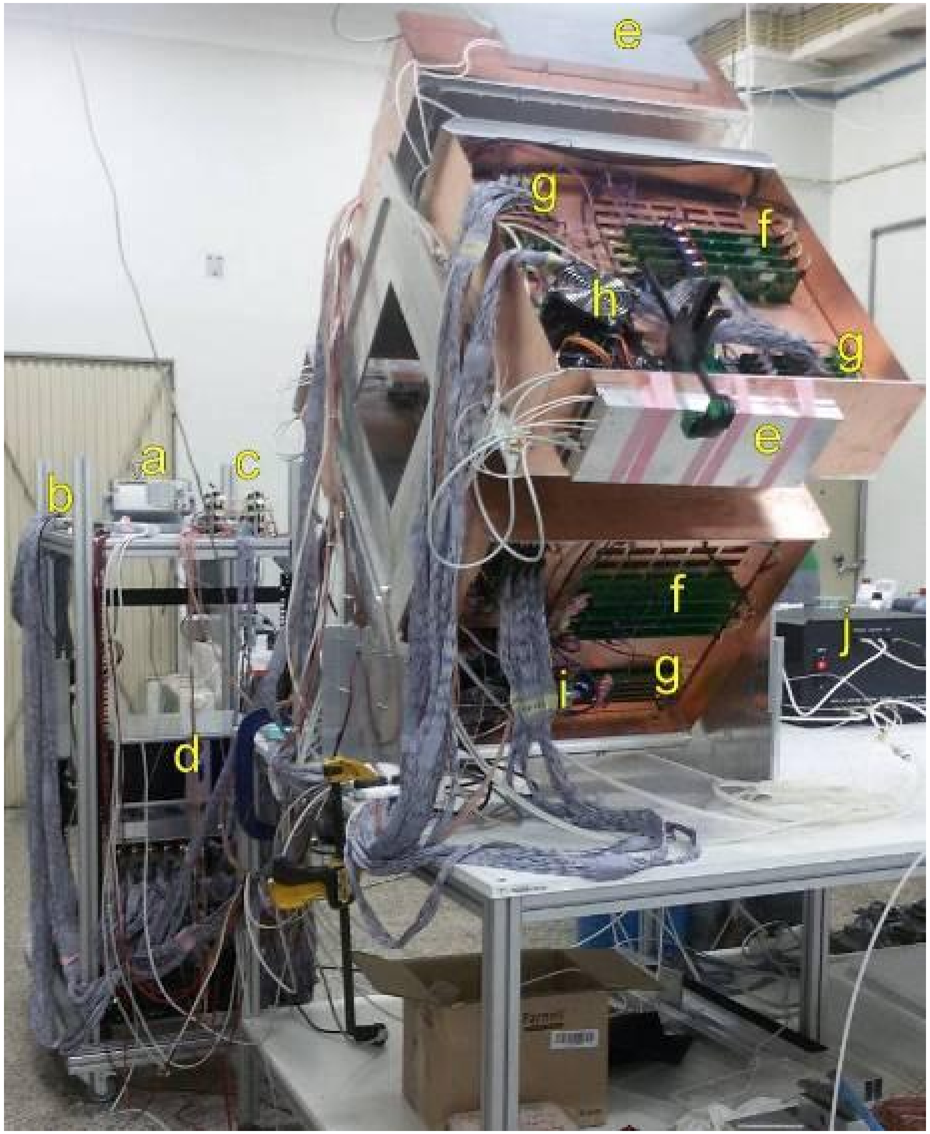
Specific project goals:

1 – best image resolution possible

2 – modest sensitivity of 0.1 % (this is a demonstrator)

3 – fit the budget and the schedule (2.5y)

Instrumentation overview

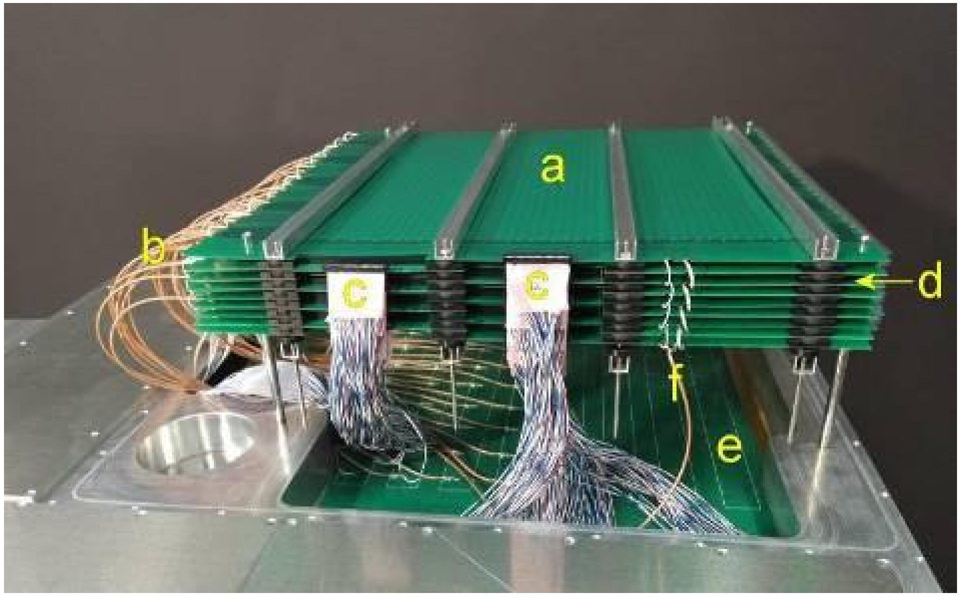


a) Pulse generator
b) Slow control main unit
c) Auxiliary comparators for trigger
d) DAQ system
e) HV power supplies
f) Timing amplifiers/comparators
g) Charge amplifiers
h) LV power supply
i) Local slow control
j) Gas system

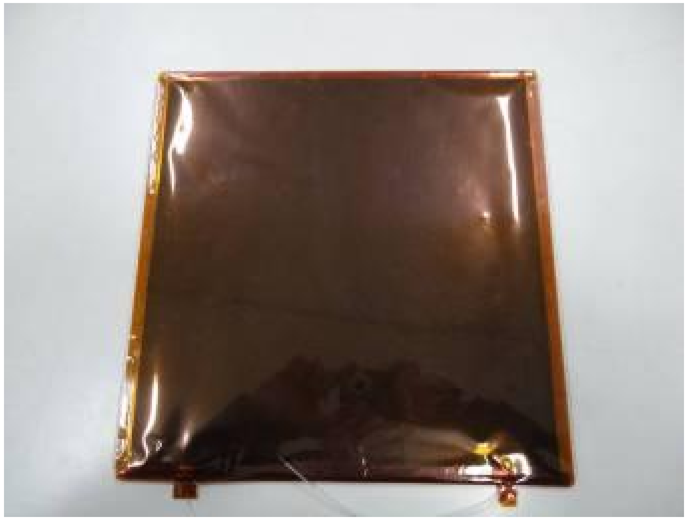
DAQ system was developed by the TRB collaboration (trb.gsi.de)

All other hardware developed at LIP

Detector

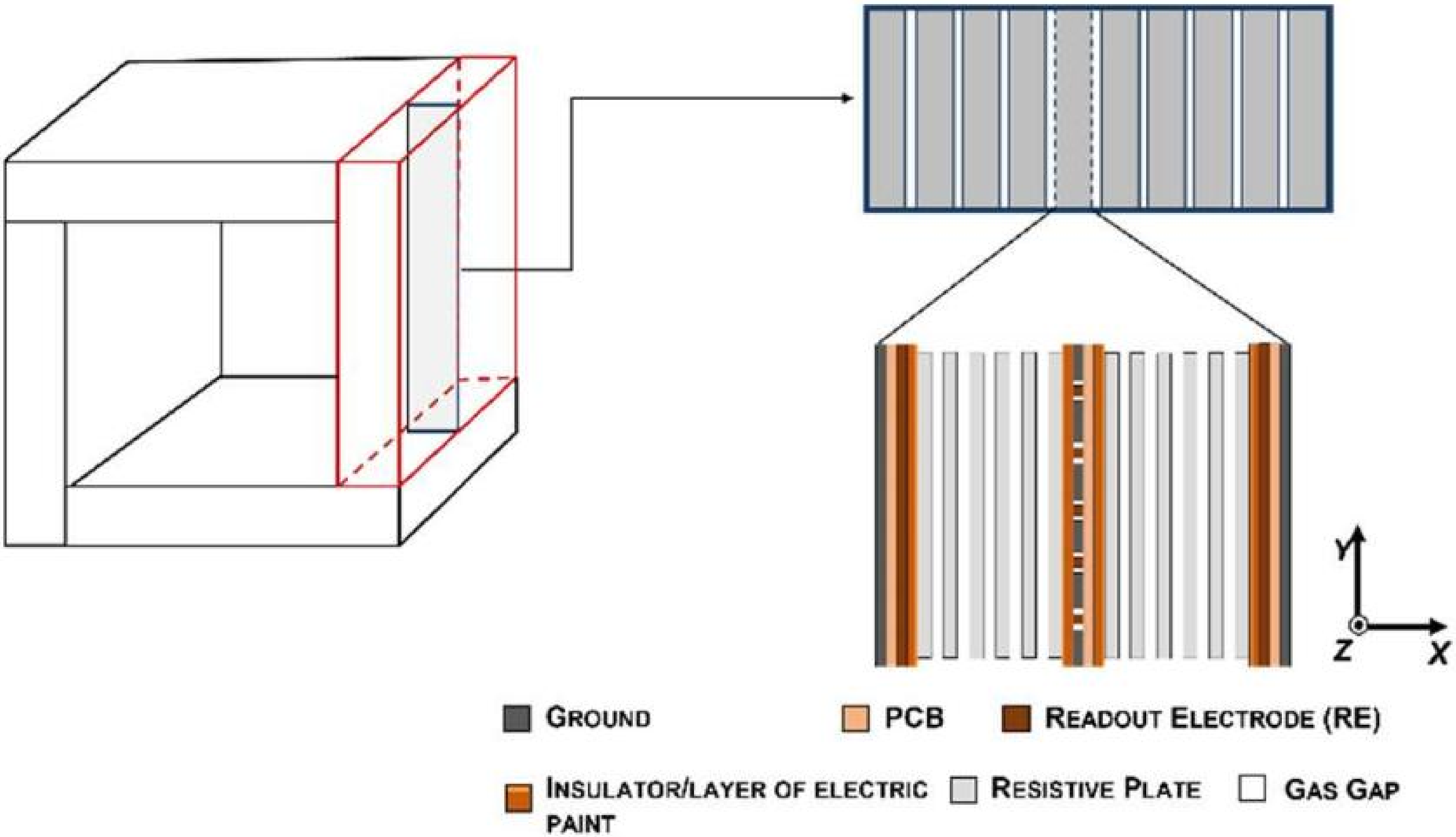


a) Readout electrodes
b) Cabling towards fast amplifers
c) Cabling towards charge amplifiers
d) RPCs (8 = 40 gaps total)
e) Empty space for twice more RPCs
f) Pulser cable



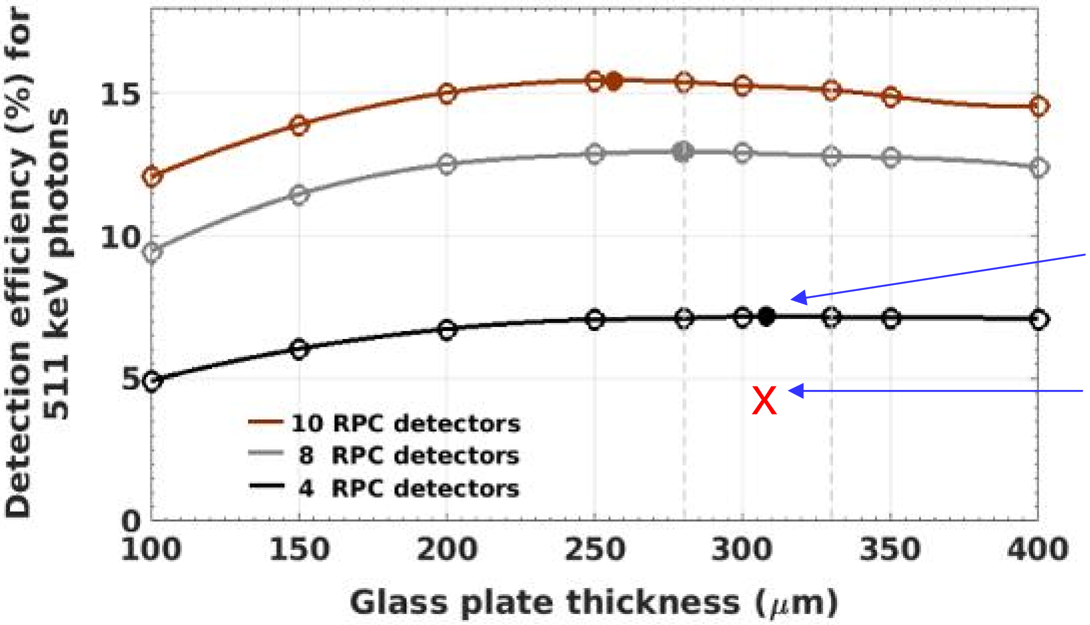
5-gaps MRPC: 30×30 cm^2 active area
Glass 0.33 mm, 0.35 mm gaps, ~4.5 mm thick

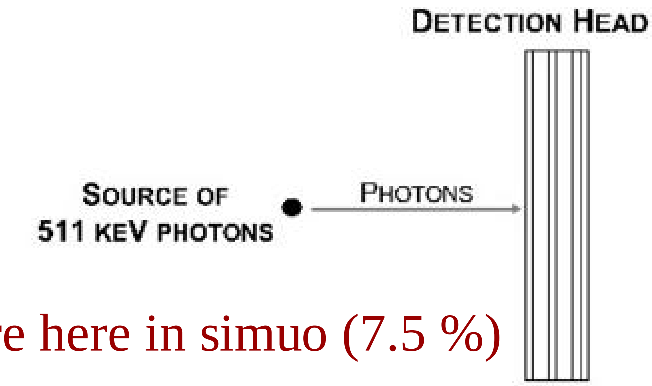
Simulation of the scanner



Realistic model, with materials, etc.

Simulation of detection efficiency





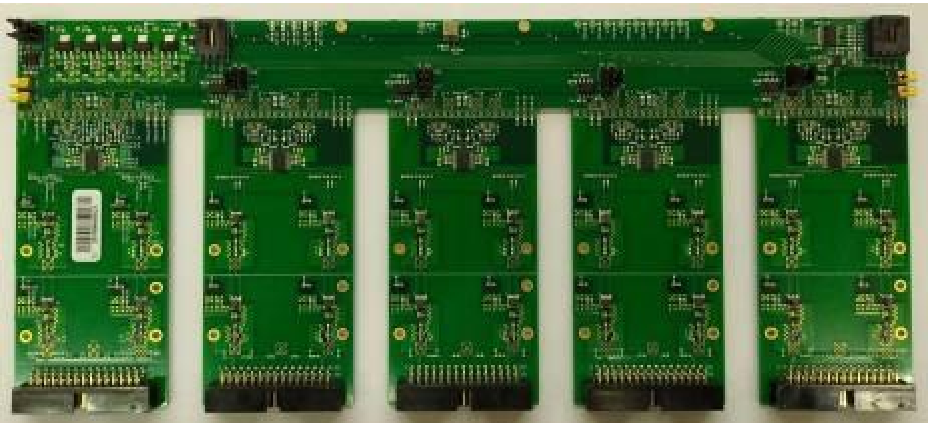
We are here in simuo (7.5 %)

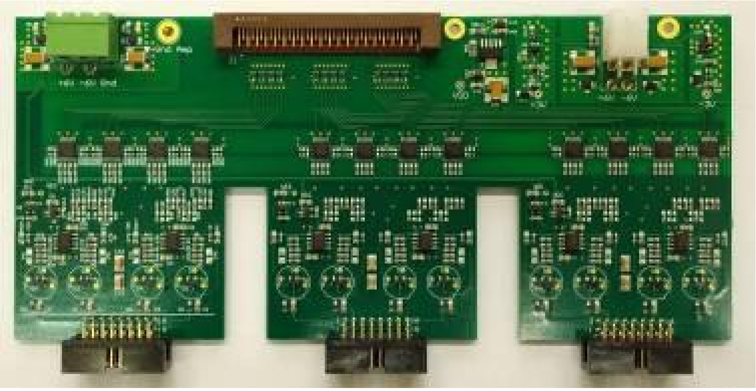
But here in reality (3.7 %), as determined by the observed sensitivity (more later)

Supporting Layer Material	Copper Strips Thickness (µm)	Efficiency (%)	Relative Gain (%)
FR4 (400 µm)	35	15.37	-------------
	17	15.50	0.85
	5	15.57	1.30
	0 (no strips)	15.69	2.08
Air	35	16.04	4.36
	17	16.23	5.60
	5	16.36	6.44
	0 (no strips)	16.33	6.25

The electrodes seem to matter little for efficiency
~6% relative loss only

Front-end electronics (custom, discrete)





Charge amplifiers:

- 24 channels
- bipolar
- 50 mV/pC
- 20 μs integration time
- readout by streaming ADCs
- digital pulse proccessing

Timing amplifiers:

- 10 independent channels
- selectable polarity
- two-stage wideband amplification
 (2 × SPF5043Z ⇒ gain 60 @ 1GHz)
- comparator MAX9601 as 200 ns one-shot
- individual VLDS outputs
- wired OR output for trigger
- noise floor ~20 μA at input (50 ohm) ⇔ 50 mV on the comparator

DAQ

Developed by the TRB collaboration (trb.gsi.de)

- two independent systems (1/crate = 1 head pair)
  - 8 × 48ch streaming ADCs
  - 8 × 1GbE links
  - central trigger processor
- switch for data aggregation into 2 × 10GbE links
- server for event building and storage (~2 h)
- acquisition rate limited only by the 1GbE links

DAQ

TRB3sc

- base module for numerous addon boards
- 1GbE link
- many firmware options
    - 48 ch 10 ps TDC
    - central trigger processor
    - digital pulse processing for ADCaddon
    - etc.

ADCaddon

- 48 ch 40 MHz streaming ADC

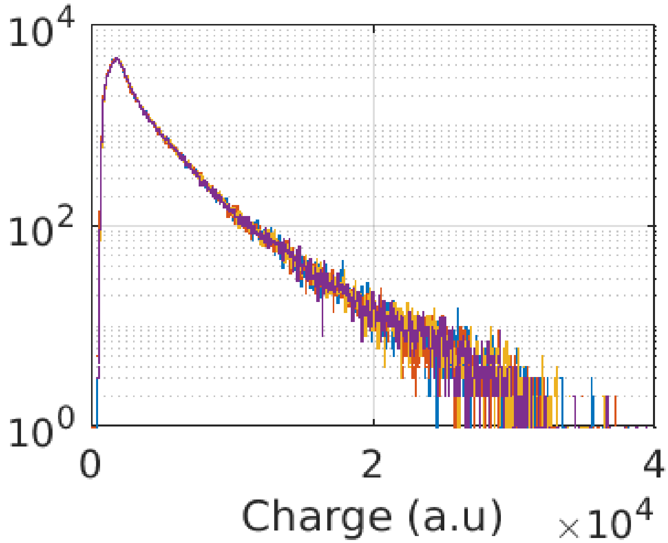
Gas system

Very nice gas system:

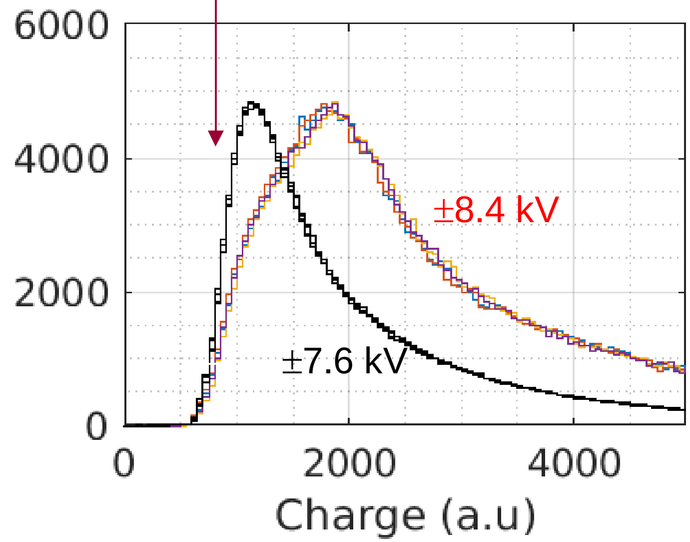
- flow splitted equally between the 4 heads
- separate exit bubblers
- flow and humidity measurement in each bubbler
- temperature, etc.
- local RPI for control & measurement

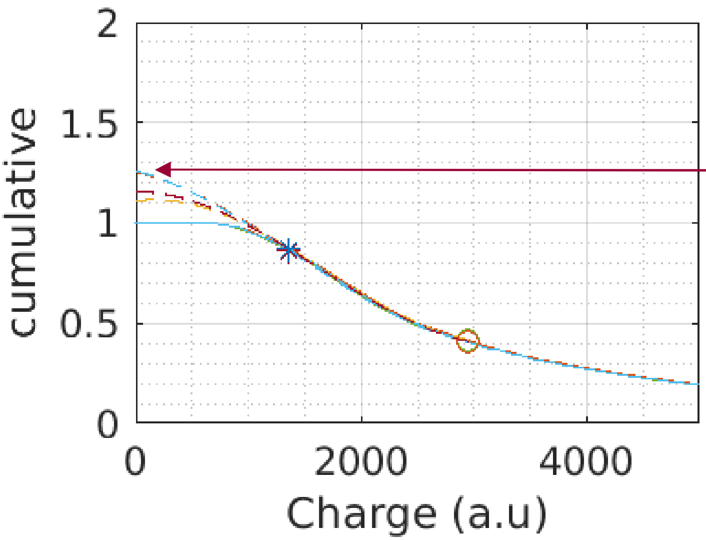
Charge spectrum

Unfortunately ~ exponential



Cut from the trigger amplifier





Efficiency reduced by 1/1.3 = 0.77

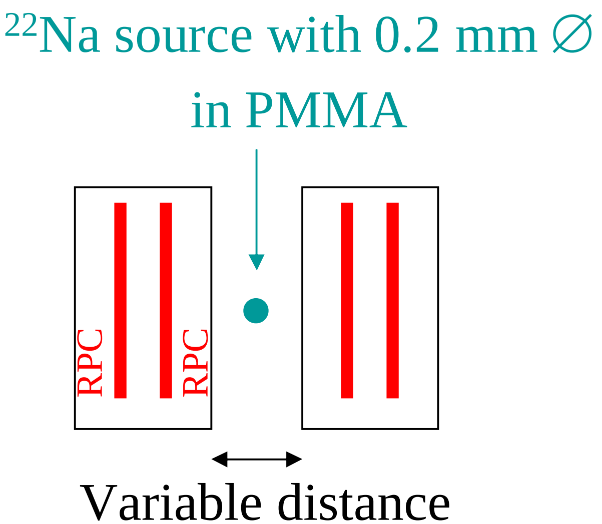
This doesn't fully explain the difference between the simulated and the measured efficiency…

3D event localization – in plane with photons

<u>This is not image resolution</u>

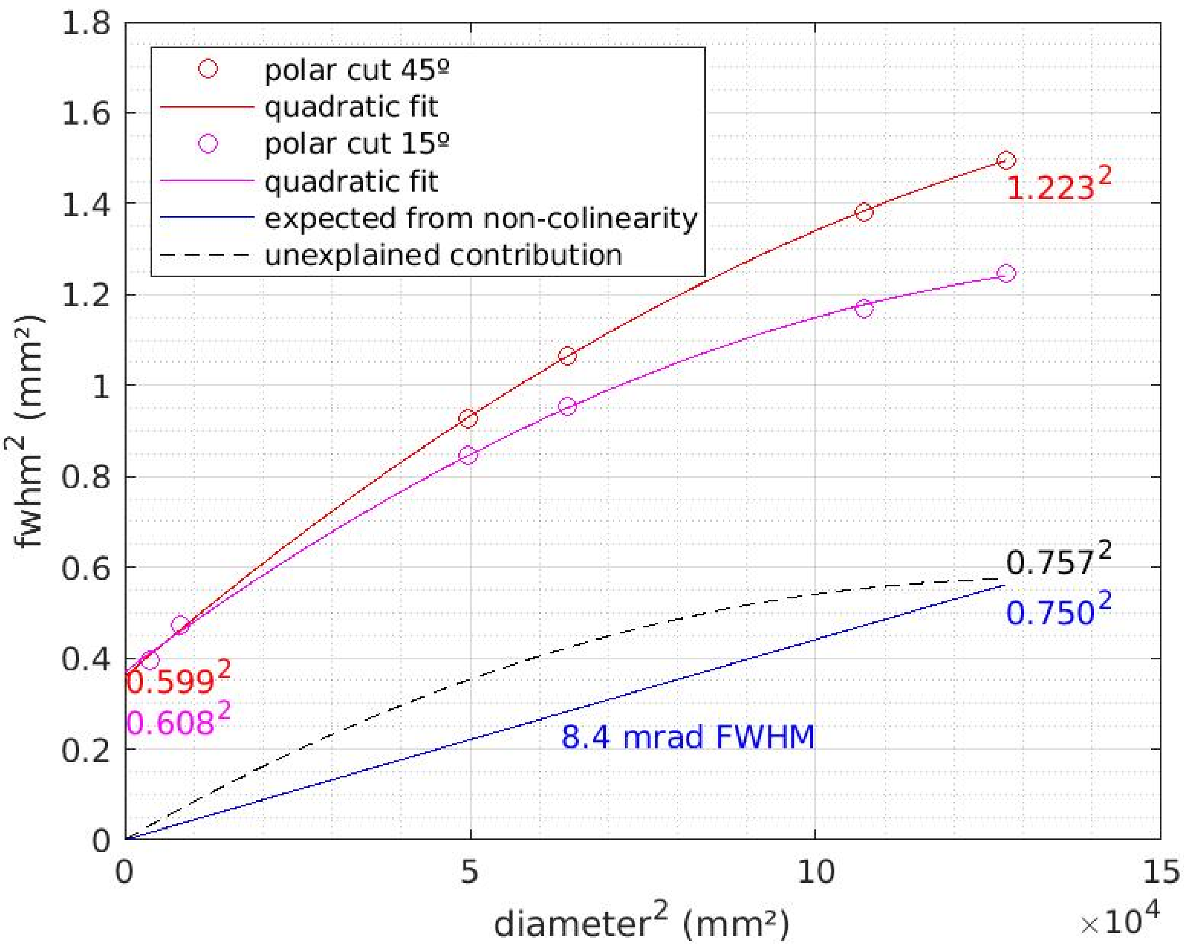
(but it is related)

Complication: the 2 photons are not emitted exactly collinear
- This causes a distance-dependent jitter
- Depends on the material where the positrons annihilate



The intrinsic resolution seems to be 0.60 mm FWHM for the line of response ⇒ 0.85 mm/plane

There is a distance-dependent unexplained contribution of ~0.76 mm

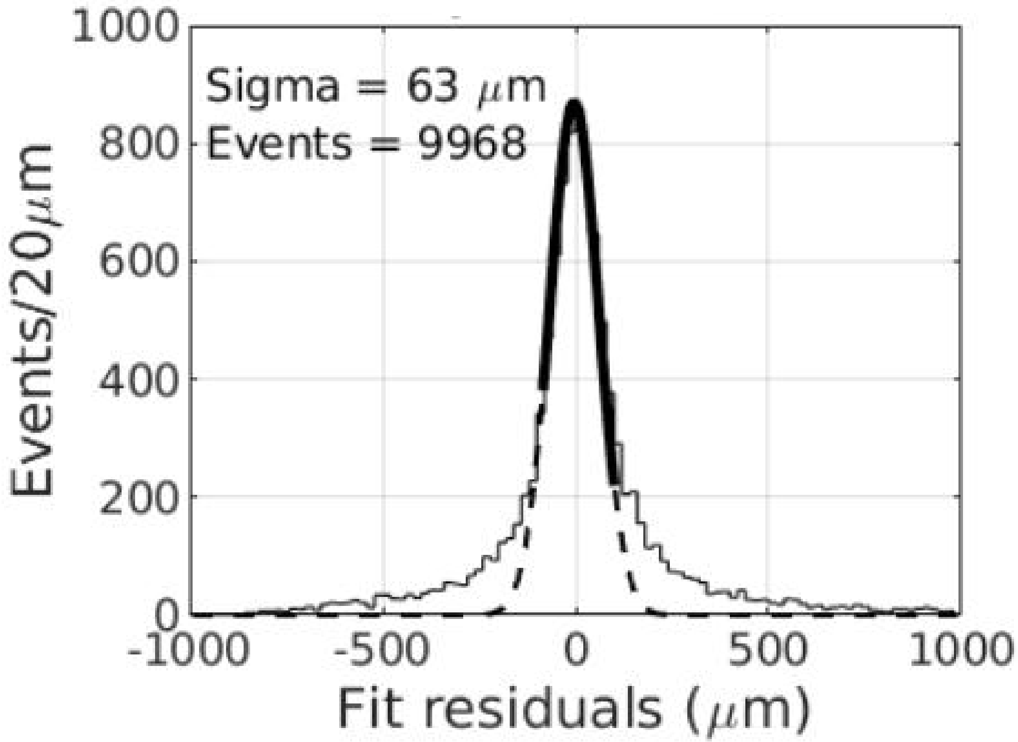


Non-colinearity data for PMMA taken from ACAR measurements in Y.C.Jean et al.(1990), Phys.Rev.B 42,15-9705

3D event localization – in plane electronic contribution

Difficult to determine with photons because there is always a parallax effect on the emitted electrons

Cosmic ray test with 3 full planes (all systematics in)

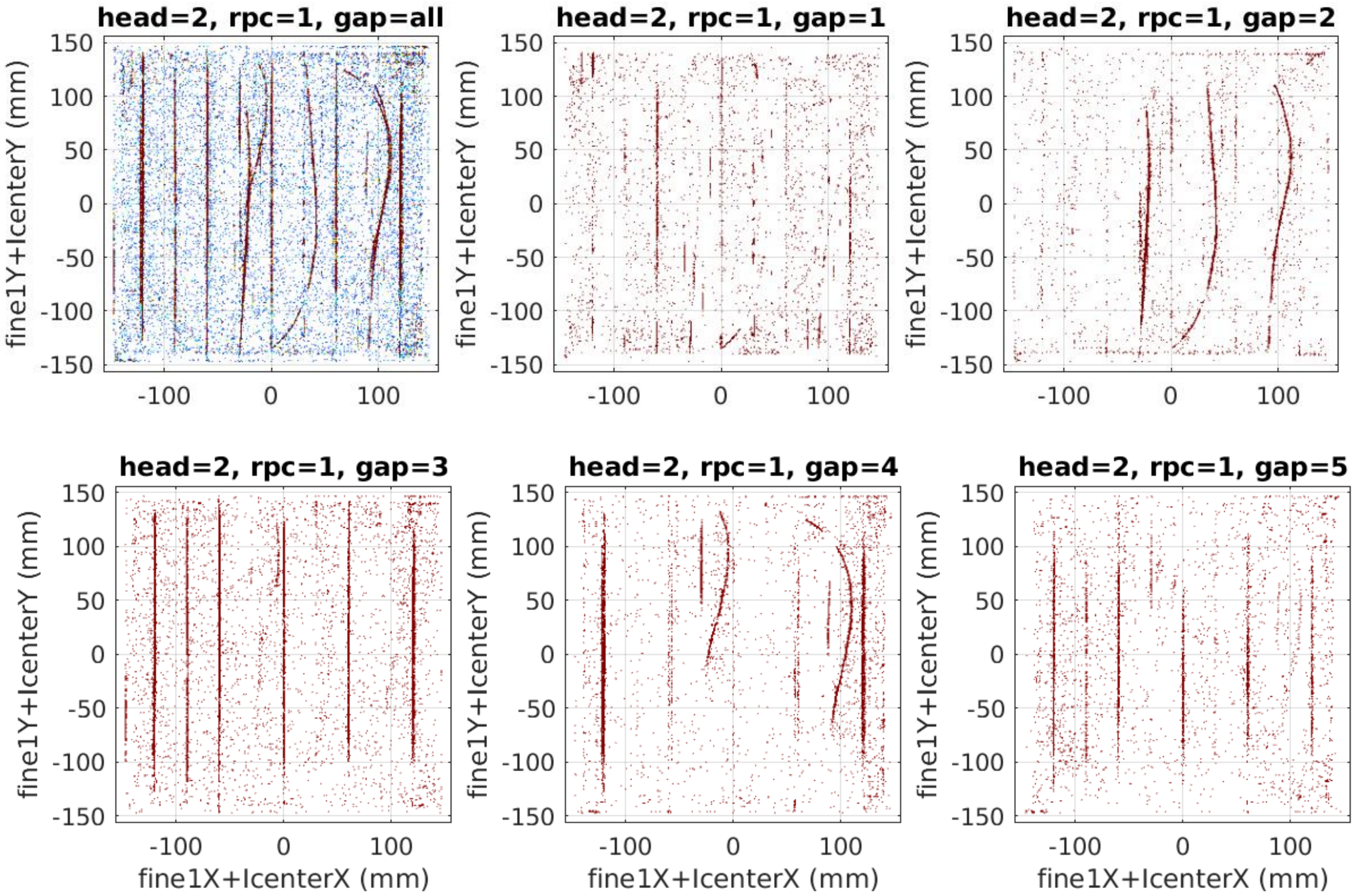


Fit of the residuals = 63 μm σ ⇒ 272 μm FWHM/plane

(61 ps σ time resolution)

3D event localization – gap identification (depth of interaction)

Via analysis of the induced charge profiles, which depend on which gap has fired



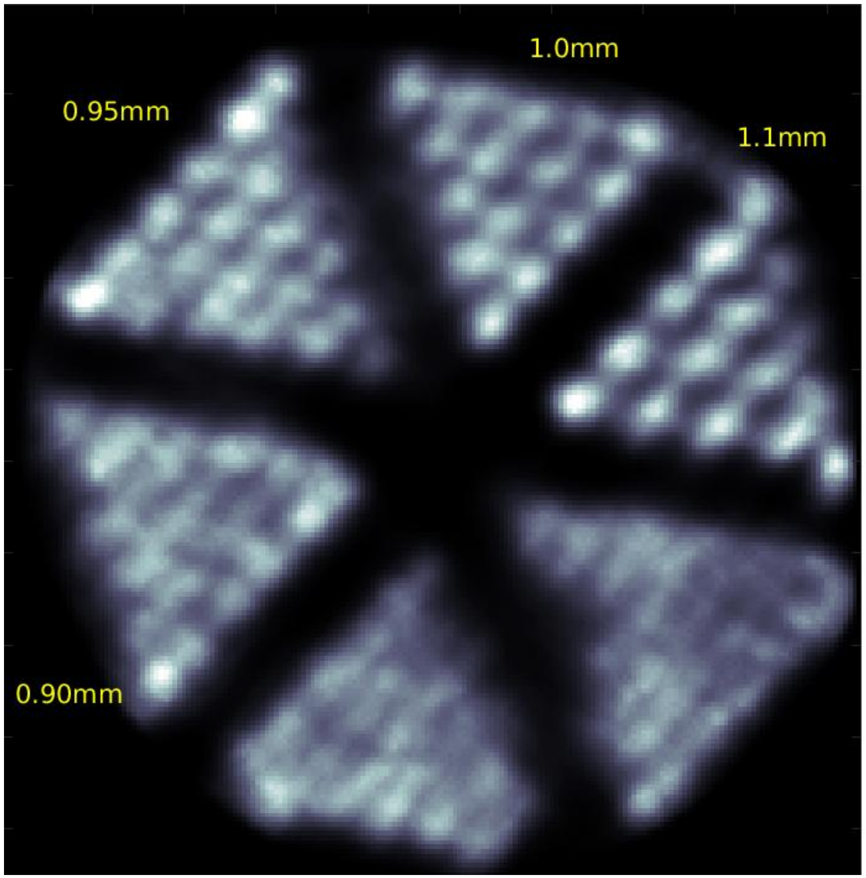
Self-trigger image of a chamber with loose spacing lines and deficient pressing

There is little mixture between the line images on the different gaps

Image resolution

Data taken on the final scanner with a “Derenzo” or “hot-rod” phantom with ^{18}F

Radial resolution < 1mm (above the state-of-the-art)



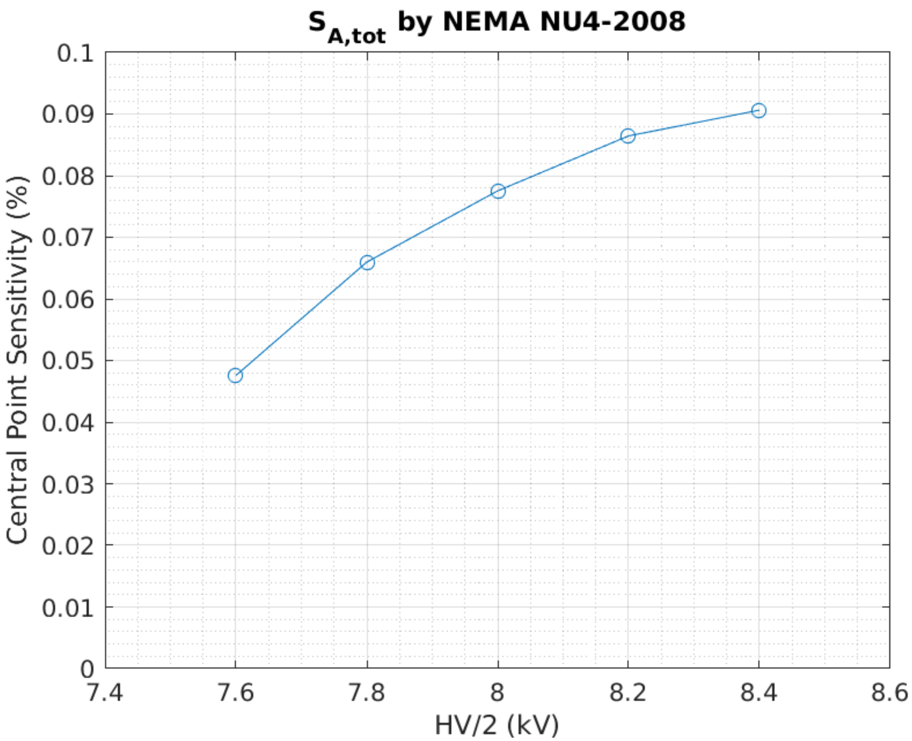
Moliner, L. et al., Sci Rep 9, 15484 (2019)
https://doi.org/10.1038/s41598-019-51898-z

PET Name	Algorithm	Isotope	10 mm FWHM radial	tang.	axial
Celestion	SSRB+FBP	^{18}F	4.5	4.7	4.4
Biograph mCT flow	FORE+FBP	^{18}F	4.33	4.33	4.25
Biograph mCT	FORE+FBP	^{18}F	5.0	5.0	6.4
Biograph mMR	FORE+FBP	^{18}F	4.0	4.0	4.1
Vereos	3DFRP	^{18}F	3.99	3.99	3.99
Ingenuity TF	3DFRP	^{18}F	4.84	4.84	4.73
Ingenuity PET/MR	3DFRP	^{18}F	4.7	4.7	4.6
Geminity		^{18}F	5.06	4.84	4.73
SIGNA PET/MR	FBP	^{18}F	4.4	4.10	5.34
Discovery MI	FBP	^{18}F	4.02	3.97	4.39
Discovery IQ	OSEM (VPHD)	^{18}F	4.2	4.7	4.8
Dedicated PETs					
CareMiBrain	SSRB+2DFBP	^{22}Na	1.72	1.66	1.71
CareMiBrain	SSRB+2DFBP	^{18}F	2.34	1.93	1.94
BrainPET-4layer MPPC	2DFBP	^{22}Na	1.8–2.1	1.8–2.1	1.8–2.1
NeuroPET	FBP	^{22}Na	3.2	3.2	3.5
Human Brain Insert	OP-3DOSEM	^{18}F	1.8	2.9	2.7
G-PET	3D-FRP		4.2	4.2	5.2
ECAT HRRT	2D FBP	^{18}F	2.6	2.7	3.0
jPET-D4	SSRB+2DFBP	^{18}F	3.1	3.1	3.1
GAPD-PET		^{22}Na	3.0	3.0	—
PET-HAT	SSRB+2DFBP	^{22}Na	4.0	4.0	—
MB-PET (simulation)	MLEM	^{22}Na	1.02	1.21	1.27

Table 6. Spatial resolution (center axial

Sensitivity

Moliner, L. et al., Sci Rep 9, 15484 (2019)
https://doi.org/10.1038/s41598-019-51898-z



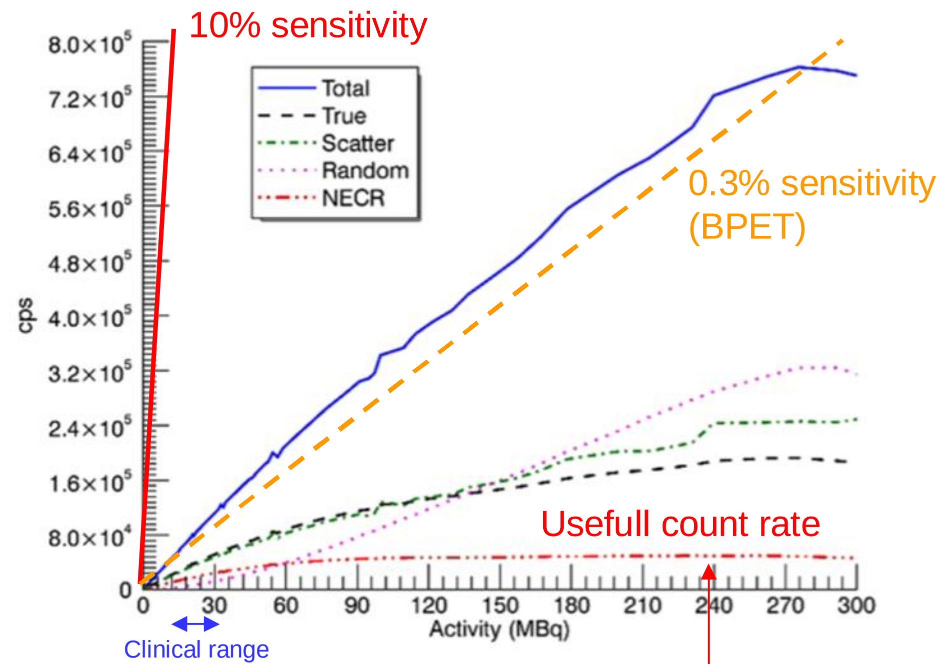


Figure 4. Count rate curves NU 2-2012.

Sensitivity (probability of pair detection at low count rate) of 0.09%

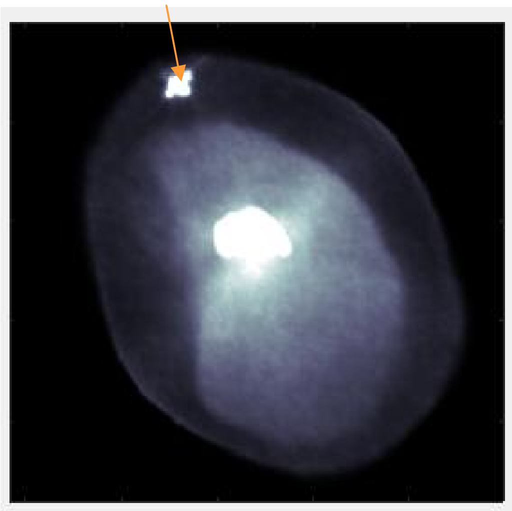
But only half of the RPCs were installed. If all ⇒ > triple the sensitivity.

Sensitivity is not so important. What matters is the noise-equivalent count rate (not yet)

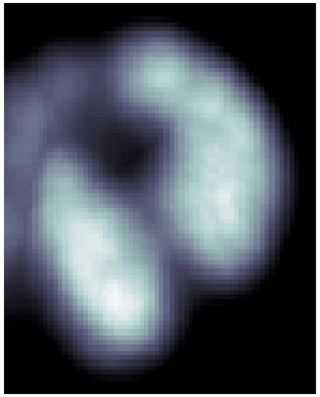
Brain phantom imaging

Phantom of cranium, brain and striatum nuclei

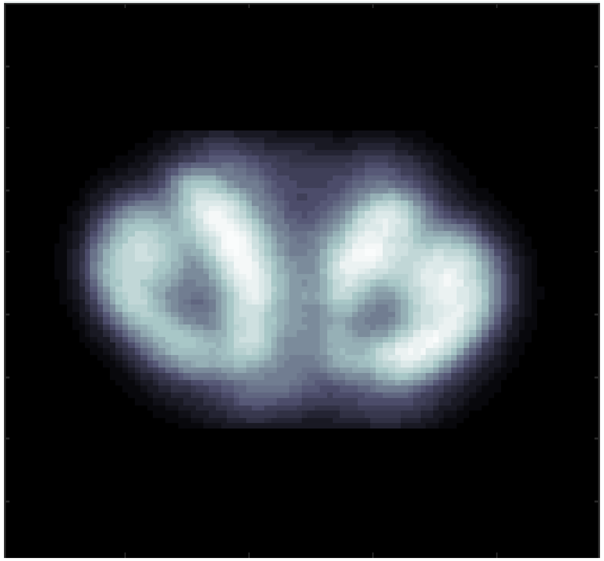
Striatum was filled with 8-fold more activity concentration than the brain



Global image of the brain (6 kBq/mL)



Detail showing the separation between chambers, which are externally touching



Striatum (50 kBq/mL)

Conclusion

An RPC-PET demonstrator scanner dedicated to human brain imaging was developed.

First results include

- Radial resolution better than 1 mm by hot-rod phantom (above the state-of-the-art)
- Sensitivity of 0.09 %
- Successful imaging of a realistic brain phantom
- Relatively inexpensive

Outlook

- Full evaluation according to the NEMA standards (inc. time resolution)
- Imaging of human subjects
- Investigate and demonstrate clinically interesting applications
- Upgrade for full sensitivity?
- Still room for some improvement in:
    - Calibration (0.76 mm of unexplained position jitter)
    - Sensitivity of the trigger/time channel (factor up to ~2)