

MPGD Applications Beyond Fundamental Science Workshop

Towards the application of patterned RPCs to very high resolution PET for small animals

P. Fonte

In the framework of the
RD51 collaboration





The RPC-PET team

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Past collaborators

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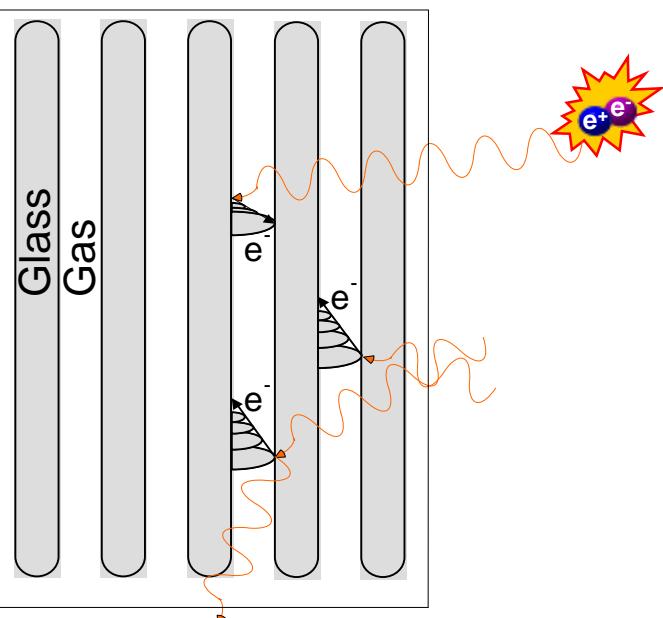
⁵ ISEC, Instituto Superior de Engenharia de Coimbra, 3031-199 Coimbra, Portugal



The basic idea for RPC-based TOF-PET

The converter-plate principle

Stacked
RPCs



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)

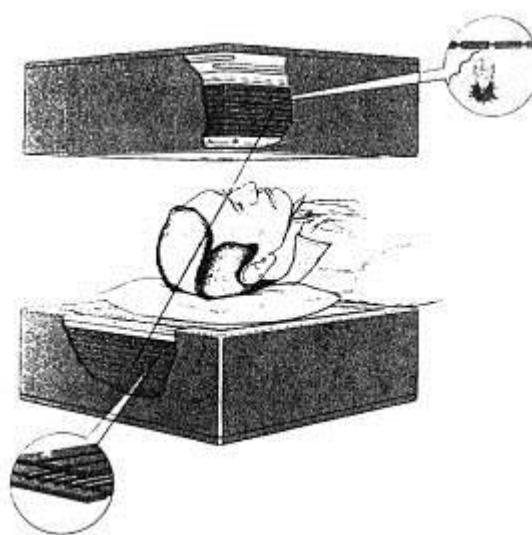
90 ps σ for 1 photon

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”

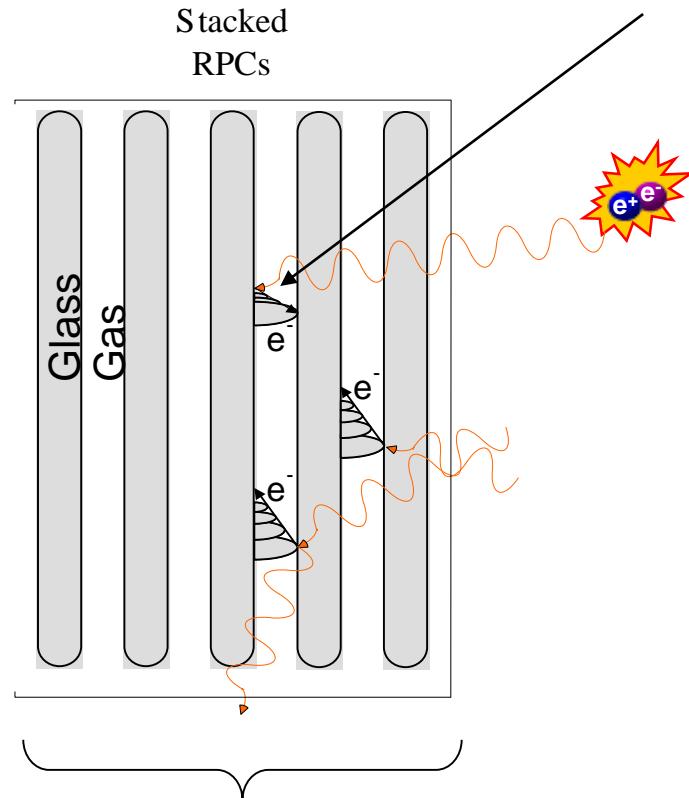
J.E. Bateman et al. NIM 225 (1984) 209-231



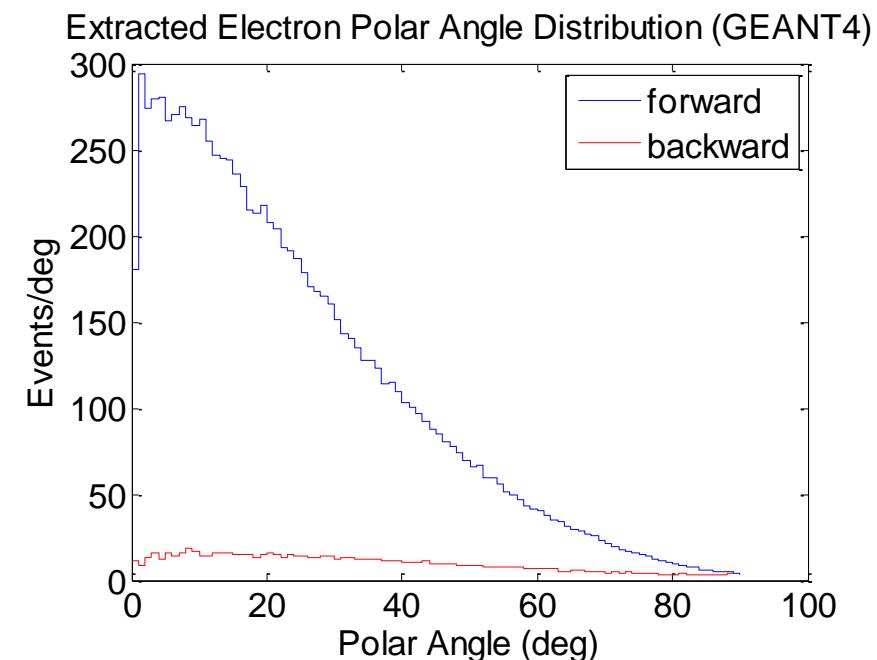


Intrinsic sources of instrumental position error

The converter-plate principle



- Electronic noise
 - Angle of ejection of the electron will shift the baricenter of the avalanche.
- ⇒ Minimized by very thin gas gap



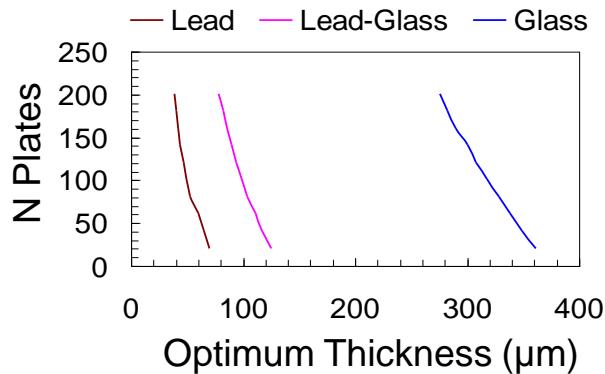
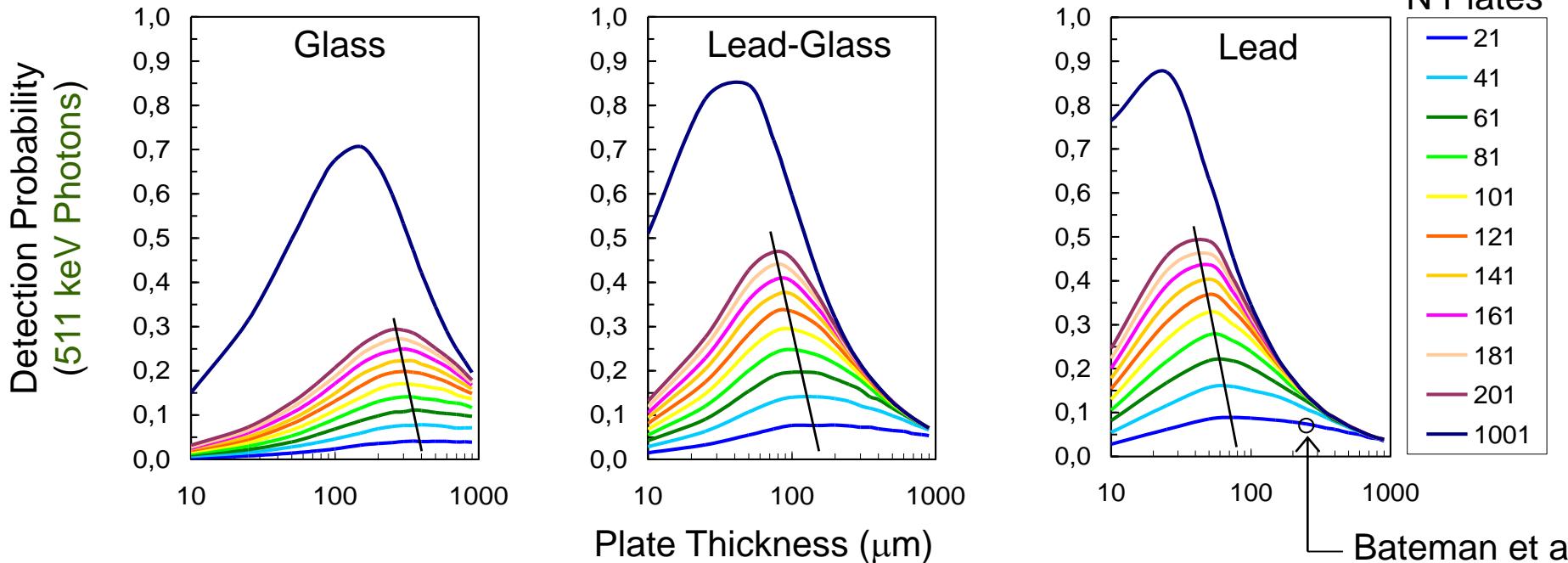
- Different gaps fired along an inclined trajectory cause parallax error (depth of interaction – DOI error)
- ⇒ Identification of the fired gap by analysis of the induced charge pattern



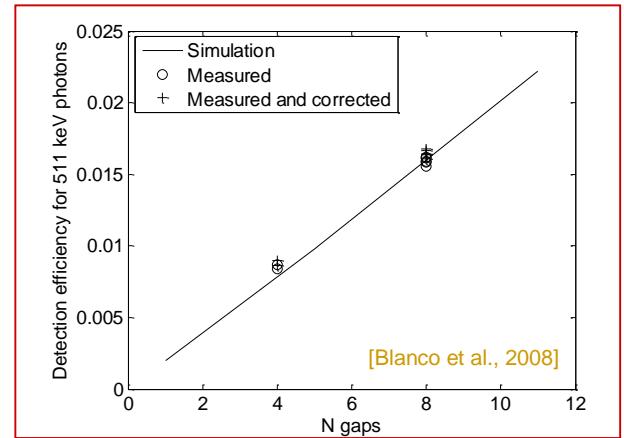
Comparison with GEANT - efficiency

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.

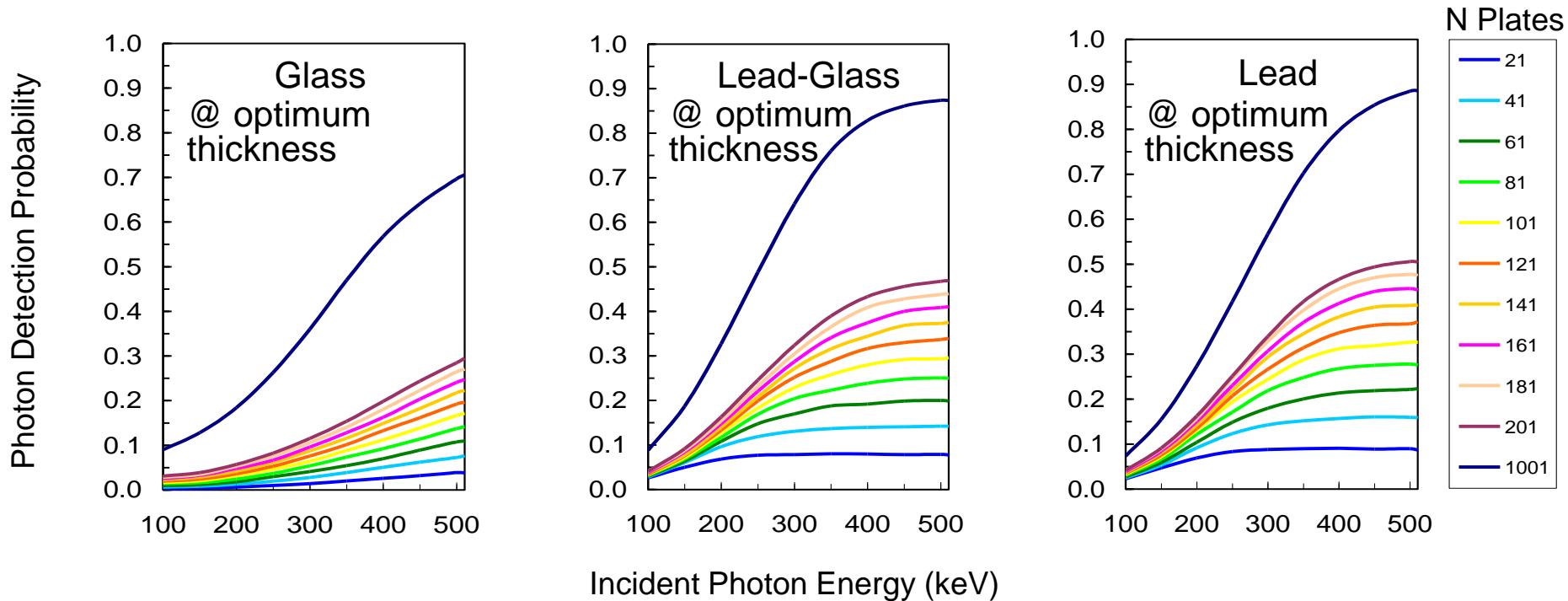


For few gaps
~0.2%/gap
@ 511 keV





GEANT - energy dependence



Strong ENERGY SENSITIVITY
scattered photons statistically rejected

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



Comparison with the standard PET technology

Disadvantages

Certainly a much smaller efficiency: 20 to 50% as compared to 70 to 80%.

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 \Rightarrow large areas possible \Rightarrow large solid angle coverage

Excellent timing \Rightarrow TOF-PET possible + optimum randoms rejection

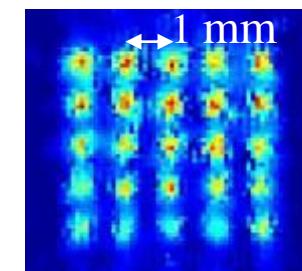
Whole-body
Human PET
[Couceiro 2013]

Increasing position accuracy

Gaseous detectors routinely deliver 0.1 mm resolution

Full 3D localization possible \Rightarrow no gross parallax error

The very small gap minimizes intrinsic errors



Small
Animal
PET

Simulation:
0.51mm FWHM

Other

Simultaneous full body imaging (continuous uptake signal)

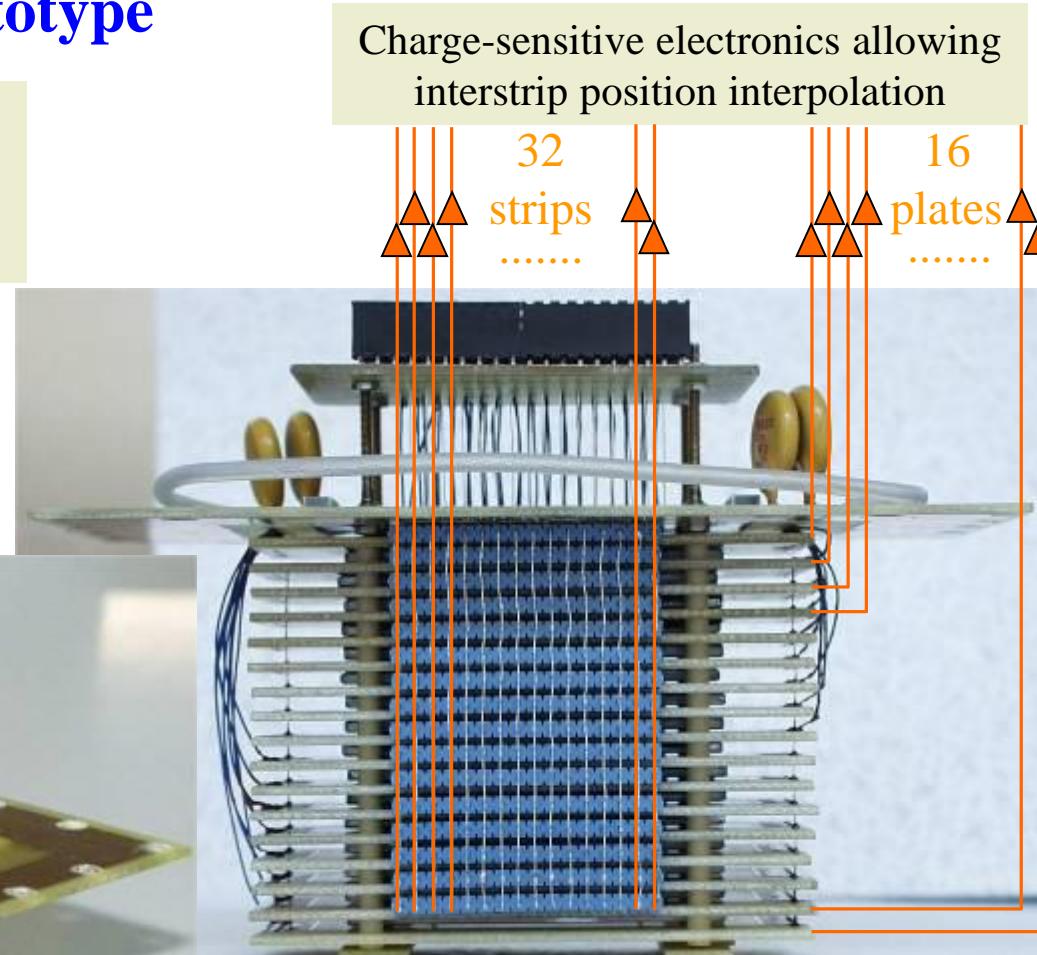
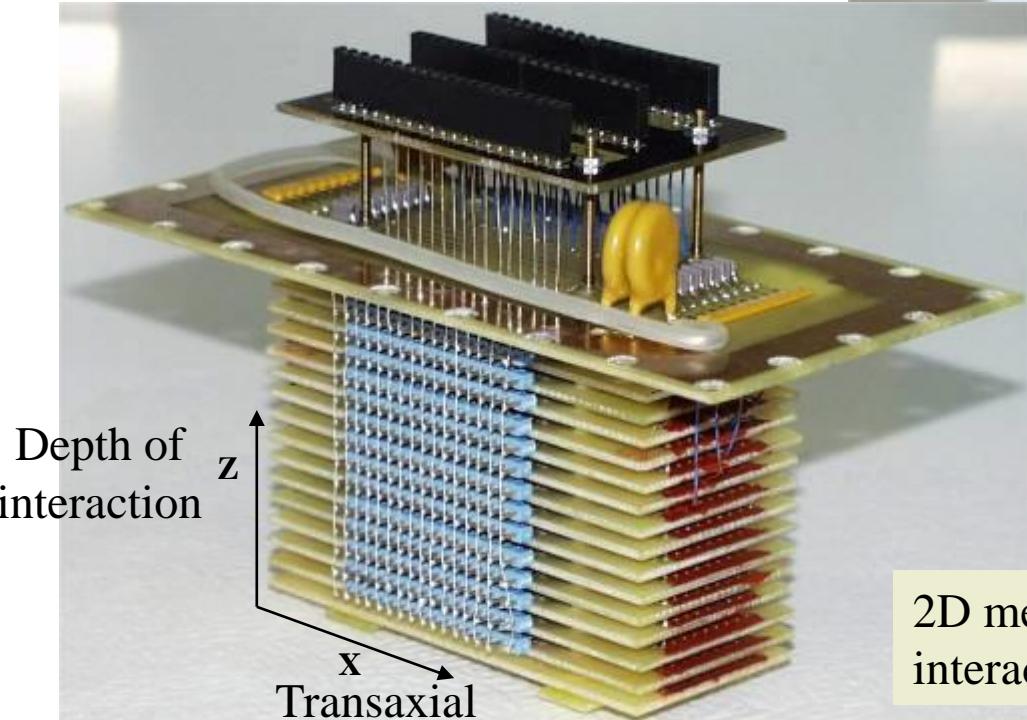
Compatible with magnetic field \Rightarrow PET-MRI can be considered



Small animal PET - a first prototype

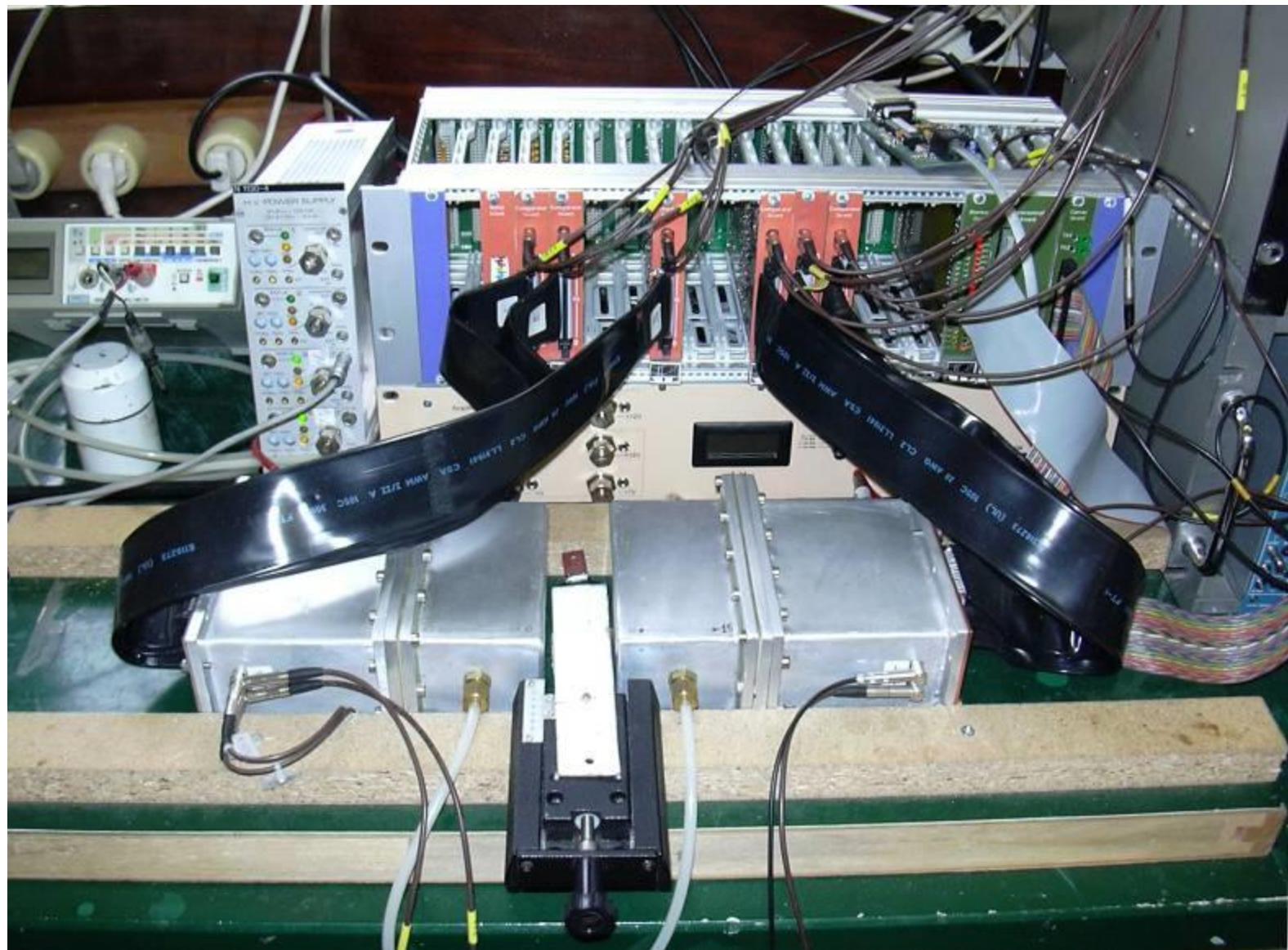
Aimed at **verifying** the concept and show the **viability** of a **sub-millimetric spatial resolution**.

16 stacked RPCs

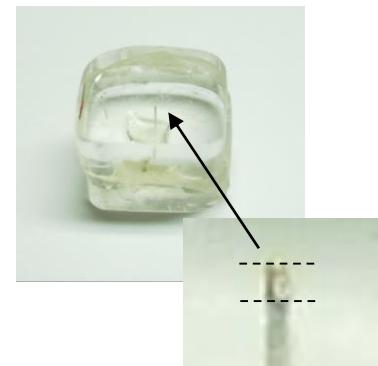
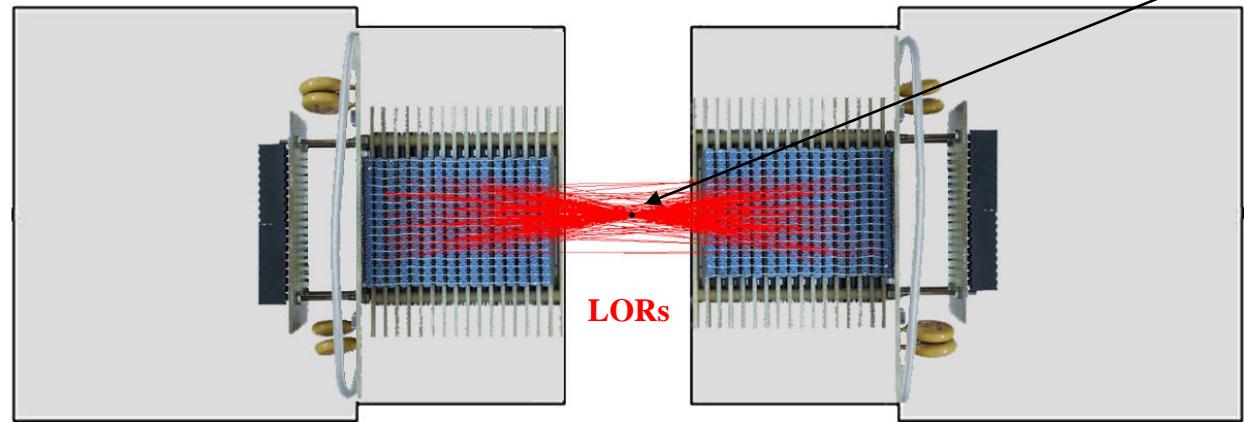




System



Intrinsic spatial resolution



Custom-made
 ^{22}Na source
 $0.22 \varnothing \times 0.5 \text{ mm}$

Red lines correspond to real data acquired with the ^{22}Na source

LOR = Line of Response. Connects the interaction points of the photons.

D = Distance between each LOR and the center of the system

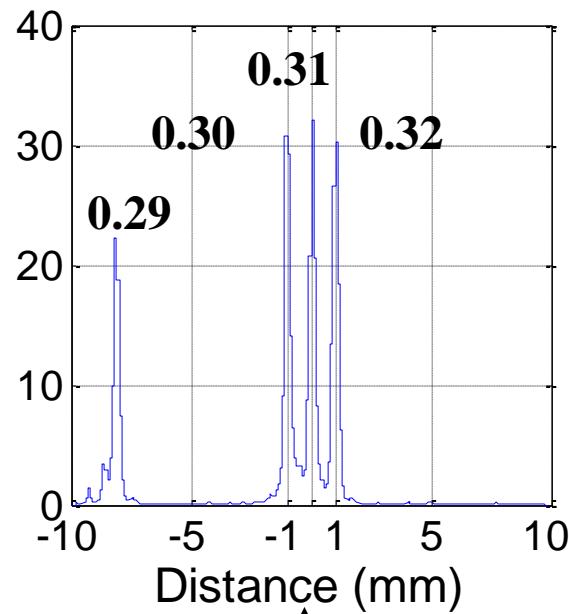
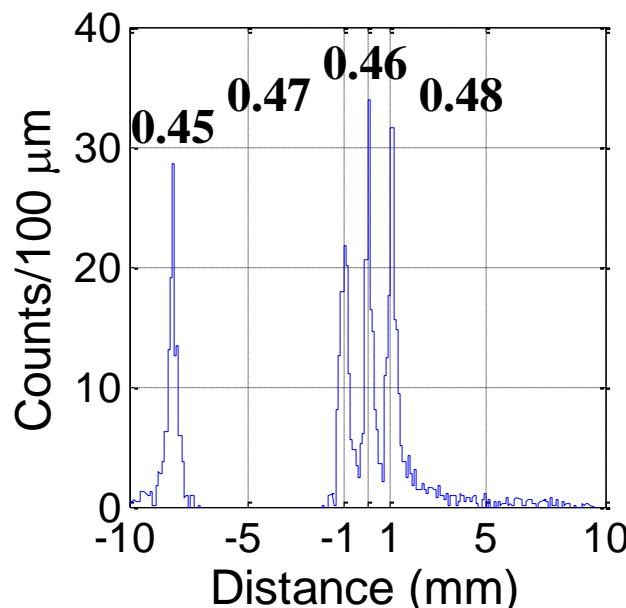
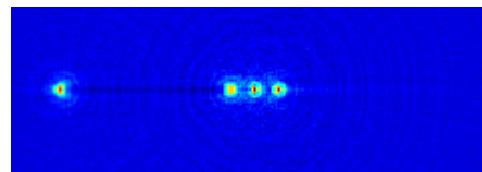
Image spatial resolution (gaussian fitting)

Filtered Back Projection FBP

~ 465 μm FWHM

Maximum likelihood-expectation
maximization with resolution
modeling (ML-EM)

~ 305 μm FWHM



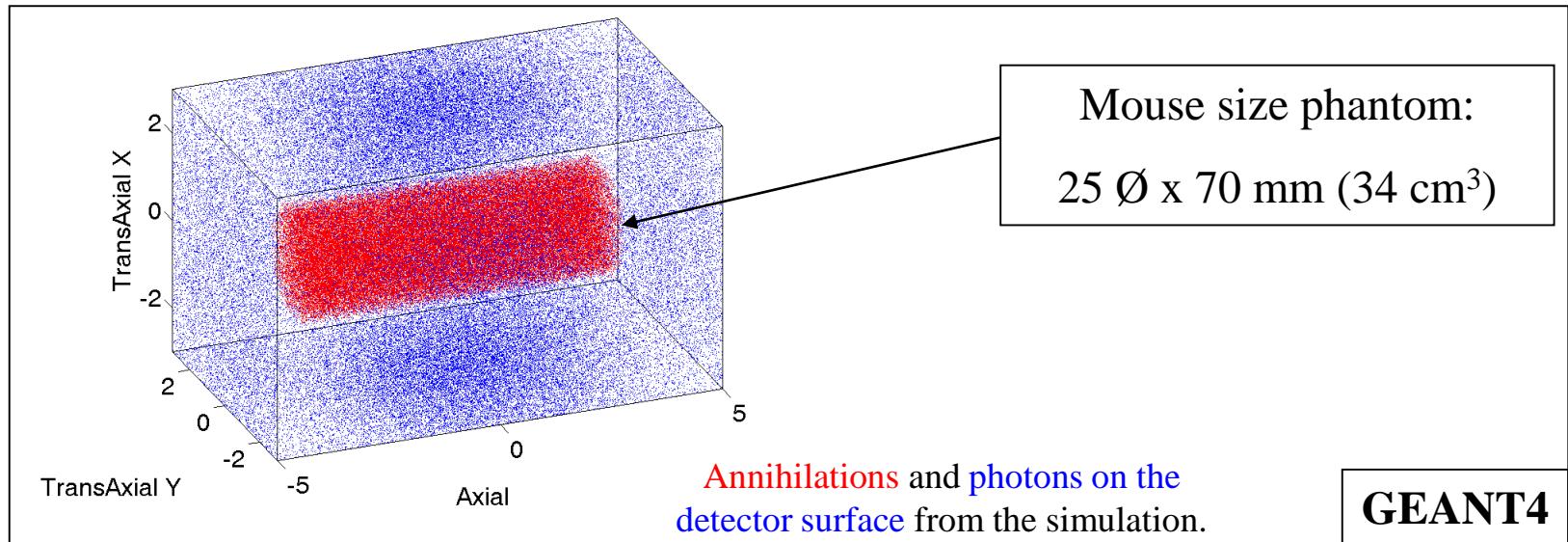
Proceeding IEEE MIC (2004) M2-177

Homogeneous spatial resolution over the entire field of view



Simulated count rate performance

Evaluation of the count rate performance Prompts, Randoms, and NECR



Characteristic of the simulated system:

- **90% Solid angle coverage** => defining a FOV of 60 Ø x 100 mm axial.
- Narrow **coincidence window 1 ns. (Timing resolution 300 ps FWHM)**
- **Dead time ~ 100 ns.**
- **10% - 15% detection efficiency.**



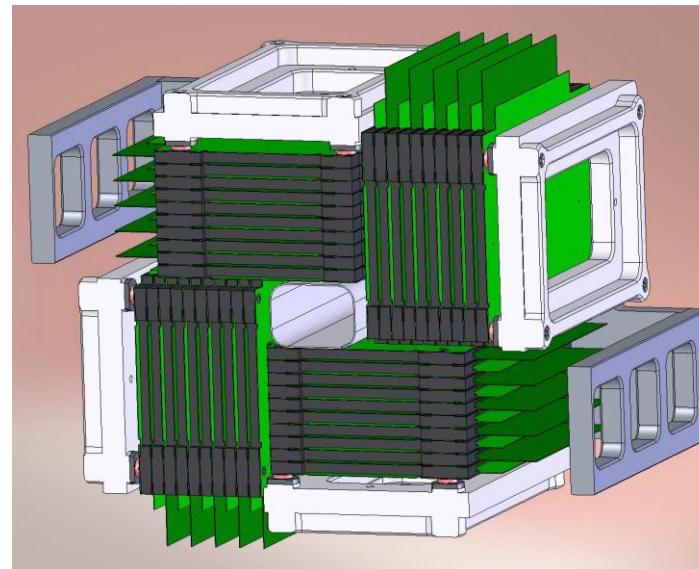
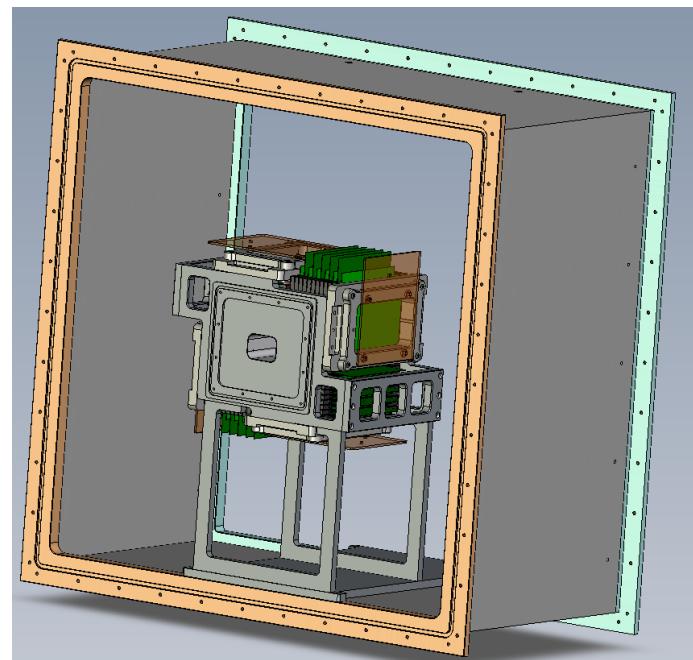
Performance – small animal PET

Comparison between different small animal PET parameters and the expected parameters of the RPC-PET.

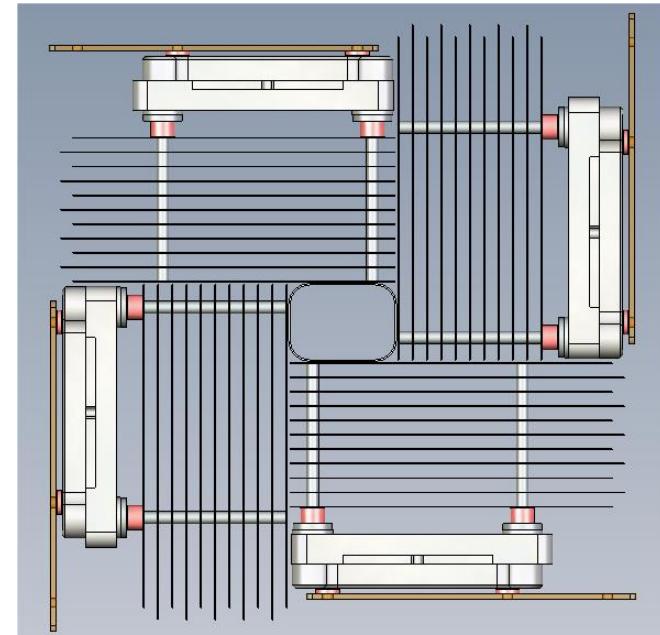
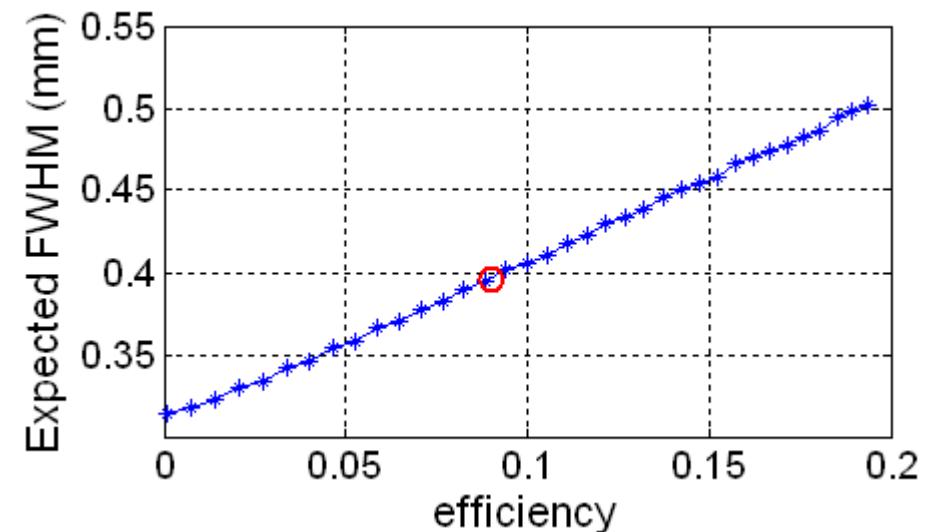
Scanner	Image spatial Resolution, FBP (mm)	Time resolution (ns FWHM)	FOV (mm Ø x mm)	Central point absolute sensitivity (cps/kBq)	Source (mm Ø x mm)	Peak NEC (Kcps)
microPET II® [1],[2]	1.1	3	160 x 49	23 - 33	25 x 70 mouse size	235 at ~2.35 MBq/cm ³
microPET Focus F120 [6]	1.75	6	147 x 76	71	mouse size	809 at ~88 MBq
YAP-PET [3],[4]	1.6	2	40 x 40	18 at ($\varnothing = 150$ mm)	-	90 (not peak) at ~16.6 MBq
Quad HIDAC (32 modules) [5]	0.95	-	170 x 280	18	-	100 at ~0.2MBq/cm ³
RPC-PET	0.51	0.3	60 x 100	21	25 x 70 mouse size	318 at ~ 2.63 MBq/cm ³ (simulated)

1. Yuan-Chuan Tai et al., "MicroPET II: design, development and initial performance of an improved MicroPET scanner for small-animal imaging", *Phys. Med. Biol.* 48 (2003) 1519-1537.
2. Yongfeng Yang, et al., "Optimization and performance evaluation of the microPET II scanner for in vivo small-animal imaging", *Phys. Med. Biol.* 49 (2004) 2527-2545.
3. A. del Guerra, G. Di Domenico, M. Scandola, G. Zavattini, "YAP-PET: first results of a small animal Positron Emission Tomograph based on YAP:Ce finger crystals", *IEEE Trans. Nucl. Sci.*, vol 45, No. 6 December 1998, 3105-3108.
4. G. Di Domenico et al., "Characterization of the Ferrera animal PET scanner", *Nucl. Instr. And Meth. A*, 477 (2002) 505-508.
5. A.P. Jeavons, R.A. Chandler, C.A.R. Dettmar, "A 3D HIDAC-PET Camera with Sub-millimetre Resolution for Imaging Small Animals", *IEEE Trans. Nucl. Sci.*, vol. 46, No. 3, June 1999, 468-473.
6. Richard Laforest et al. "Performance Evaluation of the microPET – Focus F120", presented at IEEE NSS/MIC Rome 2005.

Full scanner for mice

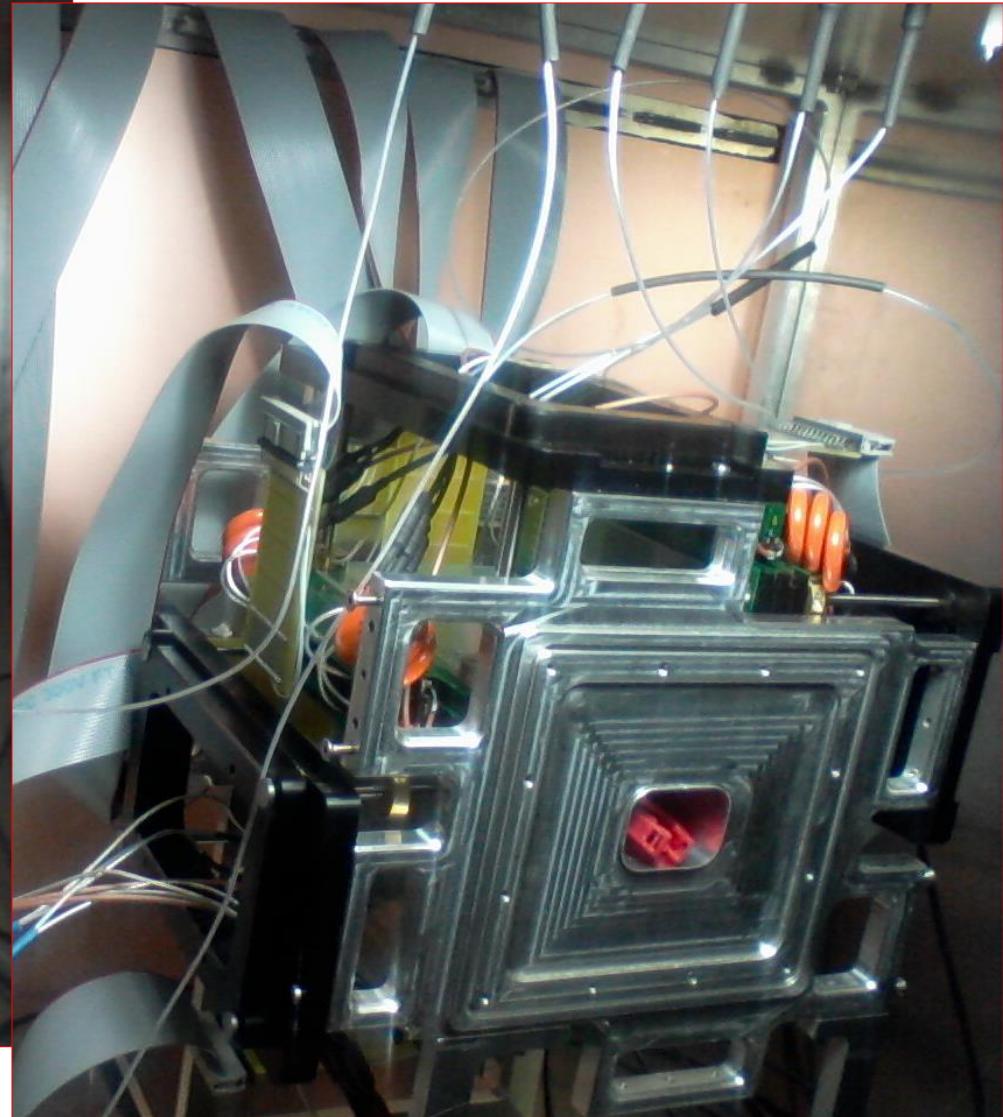
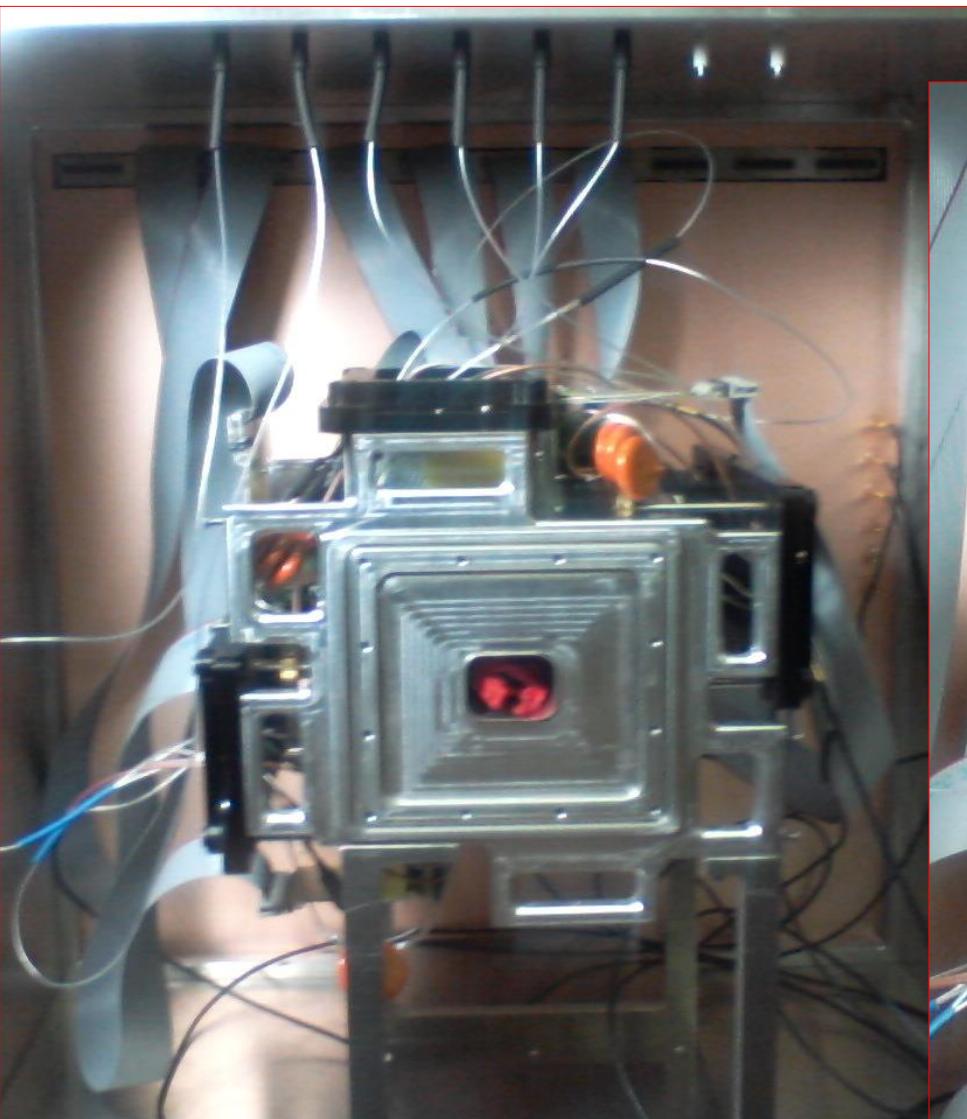


Expected quantum efficiency
and resolution

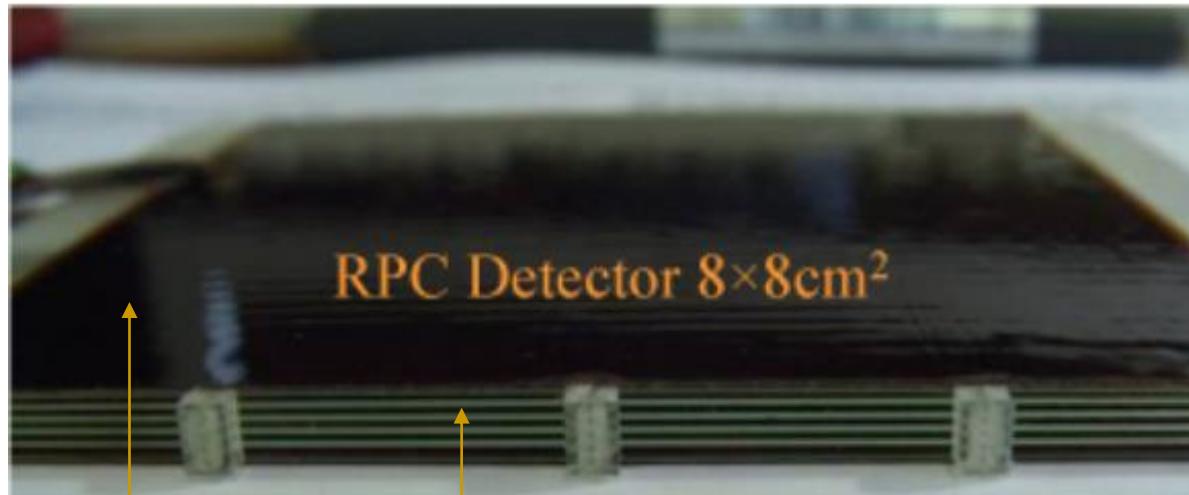




Full scanner for mice (almost finished)

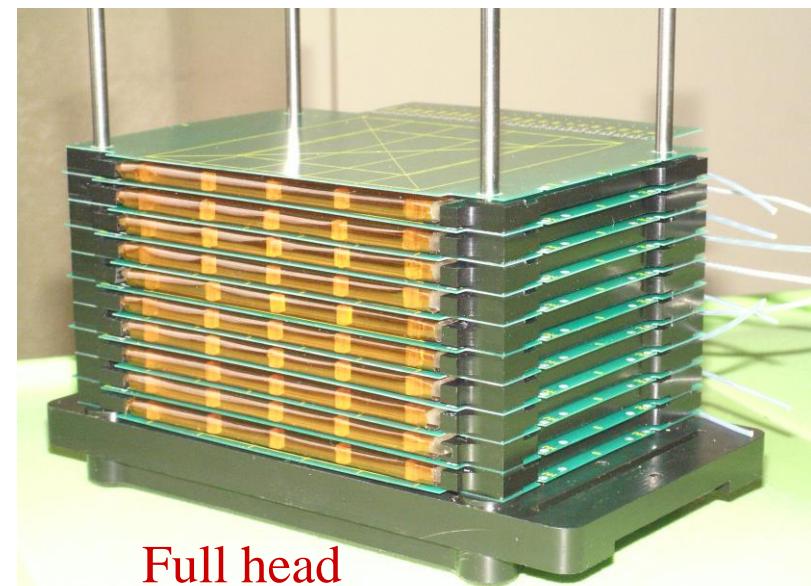


Detector & readout



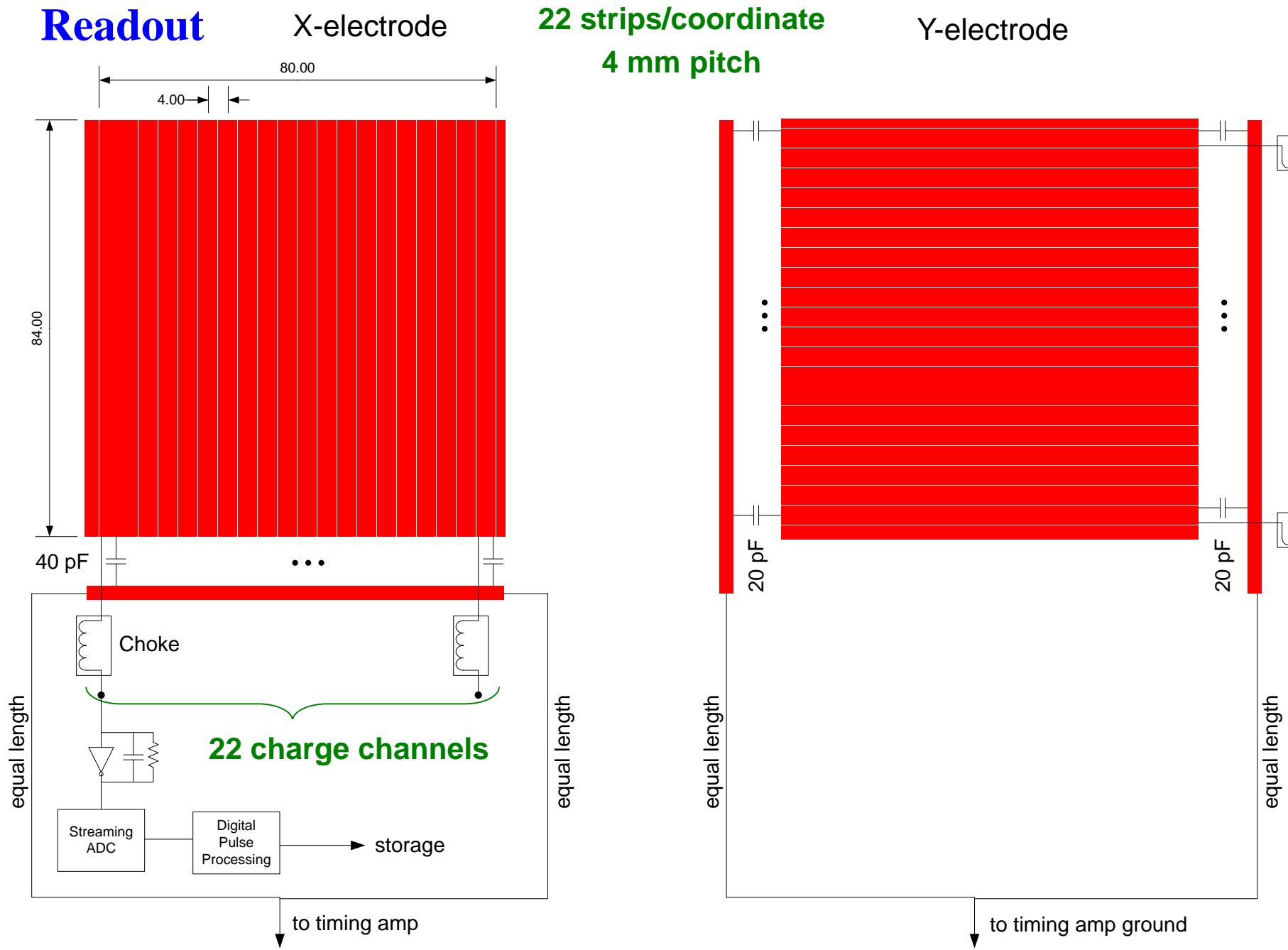
HV distribution layer
(signal-transparent)
kapton insulation

5 gaps 0.35 mm
6 x 0.38mm glass
~5 mm thick



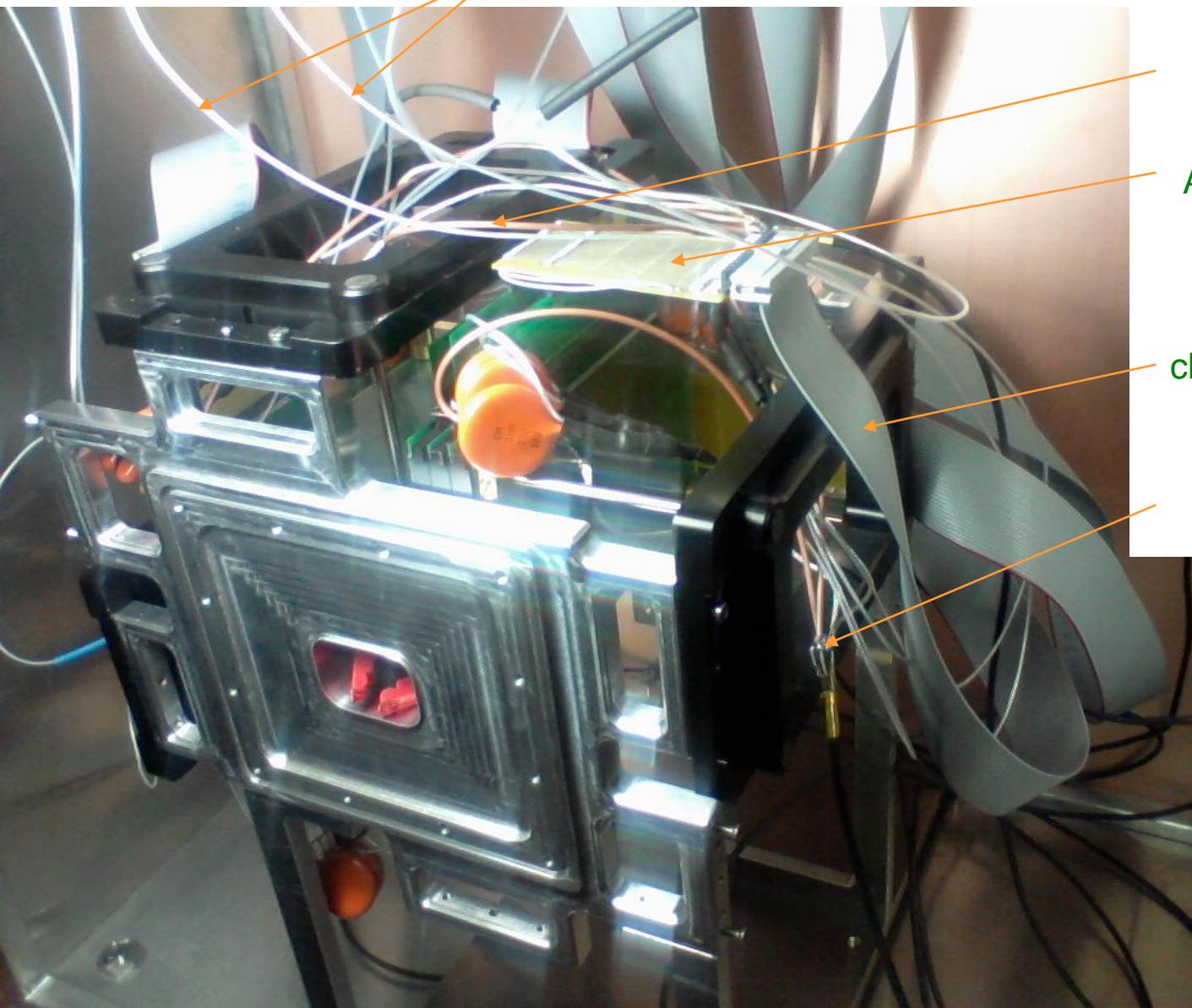


Readout





Readout



Auxiliary coarse Z
determination

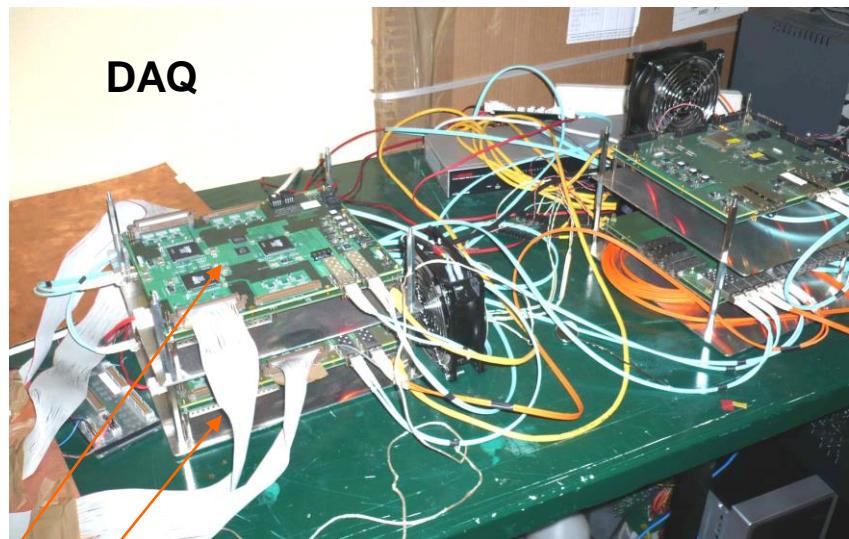
All electrodes readout in
parallel

24 charge
channels/coordinate/head

Time readout
(for trigger)



Readout (meant for accuracy)



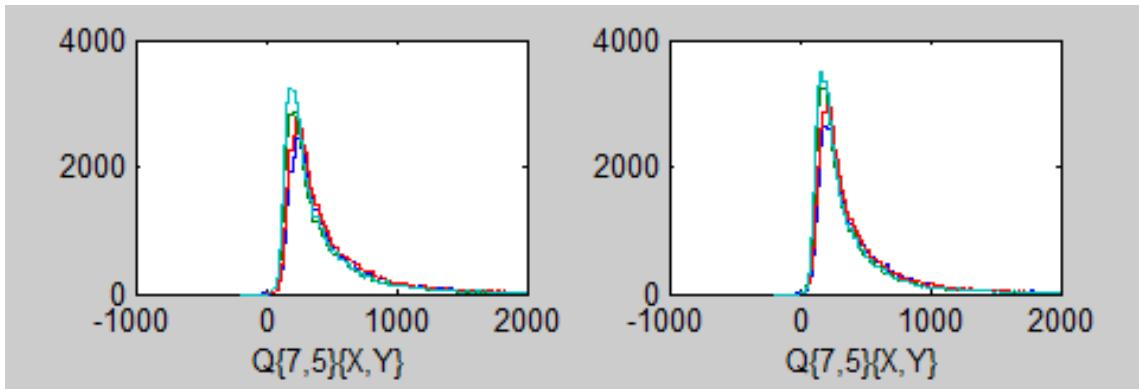
192 charge amplifiers optimized for large Cin
192 channels 12 bit streaming ADC
Digital Pulse Processing by software
Few channels of 100ps TDC also used

Provided by the HADES DAQ group
GSI, IKF (Germany) and JU (Poland).

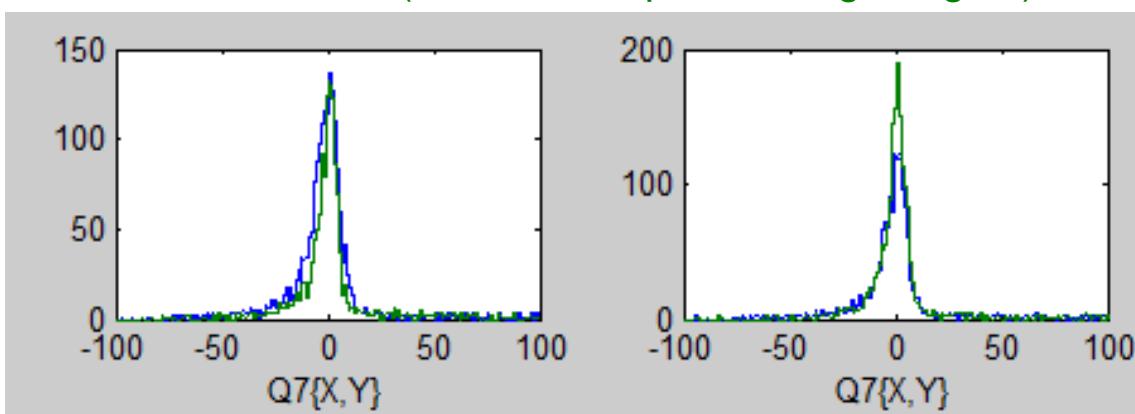
Not so much hardware \Rightarrow low cost

Readout (meant for accuracy)

Typical charge spectra with gammas

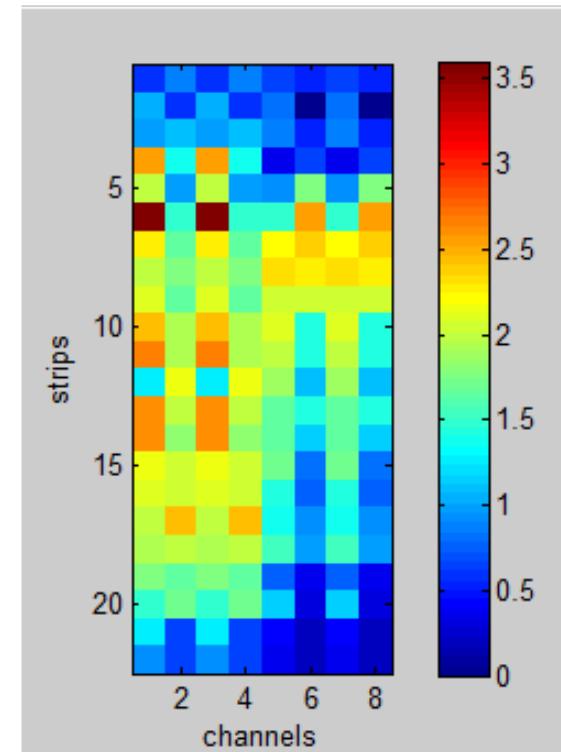


Pedestals (sum of 7 strips with larger signal)



Mean $Q \sim 320$ ADC units
 RMS pedestal ~ 7 ADC units } SNR ~ 45
 RMS pedestal/strip ~ 2 ADC units

RMS pedestal/strip

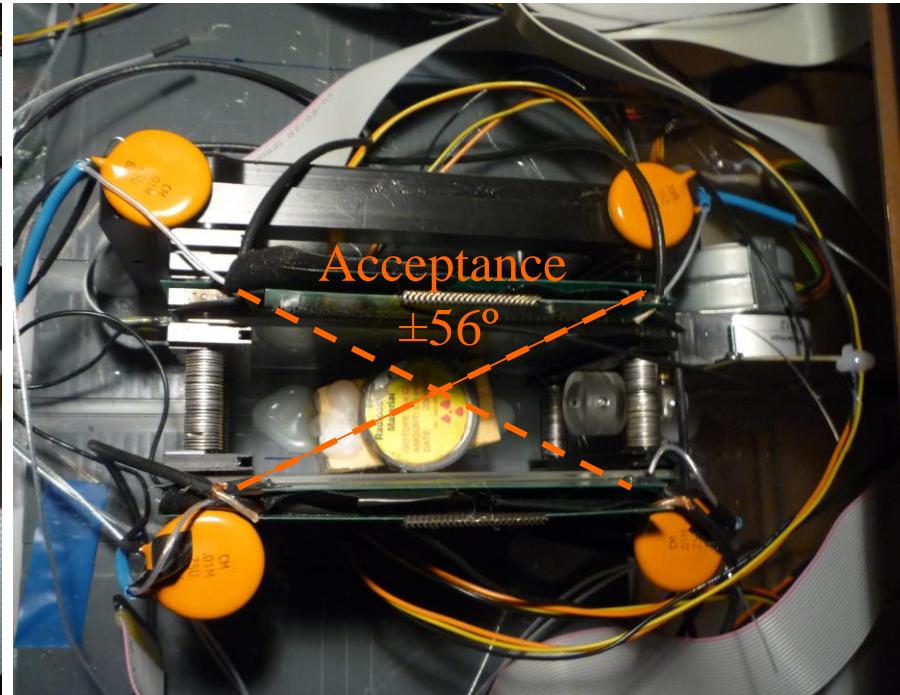
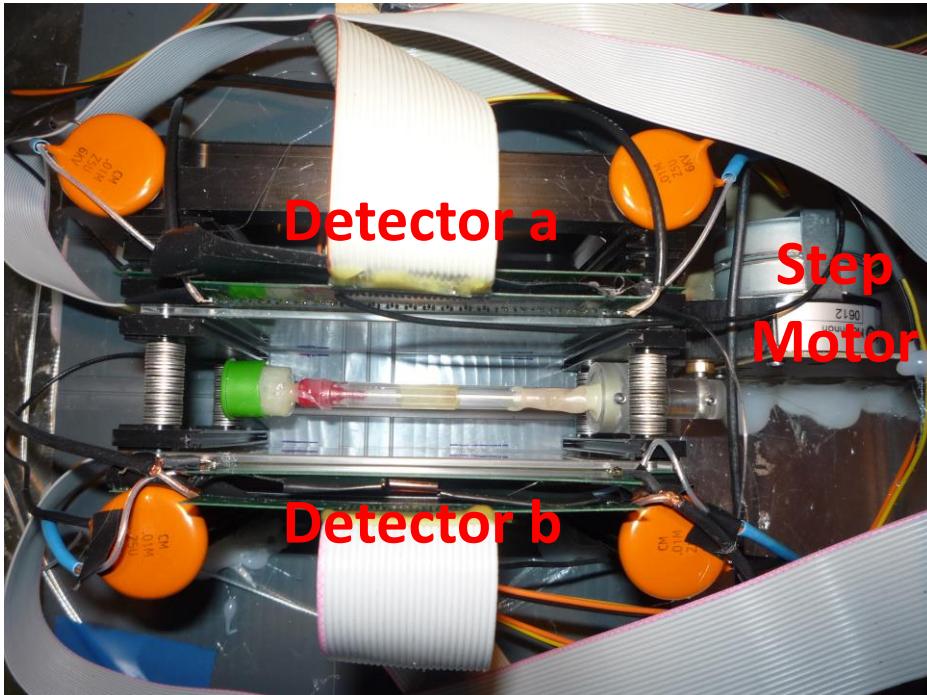


“TOFtracker” (RPC2012)

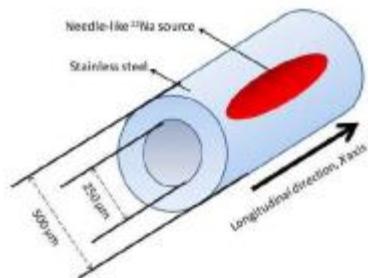
36 μm resolution
 tracking cosmic rays

Resolution tests in simplified geometry

Two detectors with XY localization

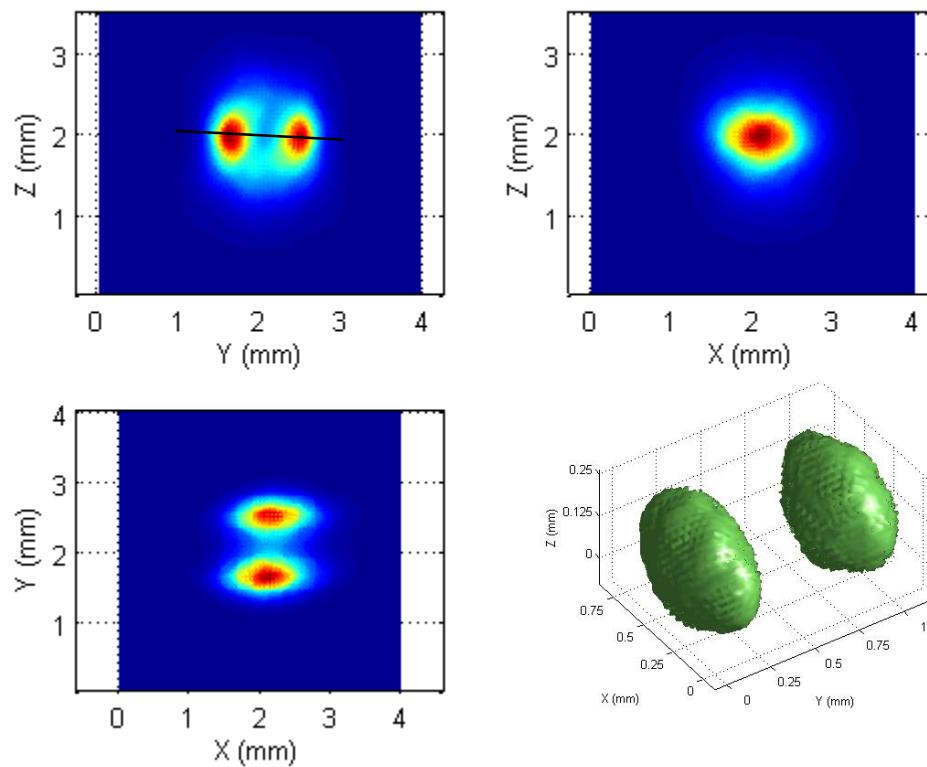


Needle source, 0.2 mm Ø int.



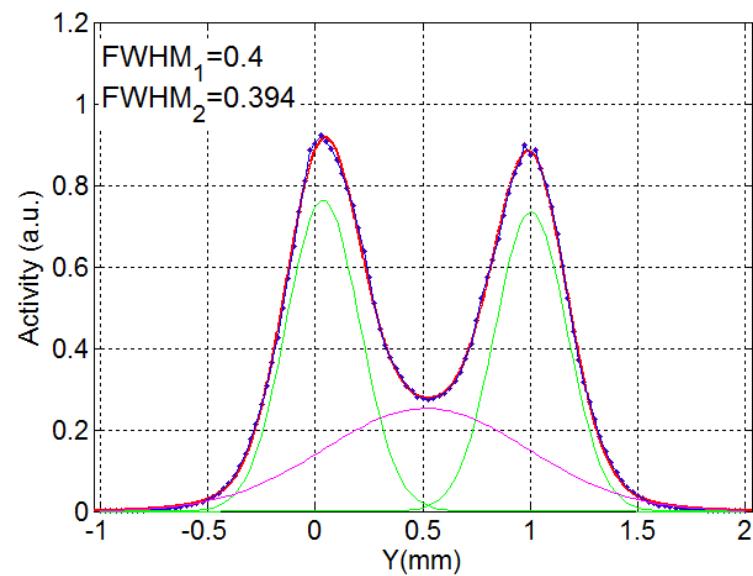
Planar (disk) source

Resolution tests (needle source)



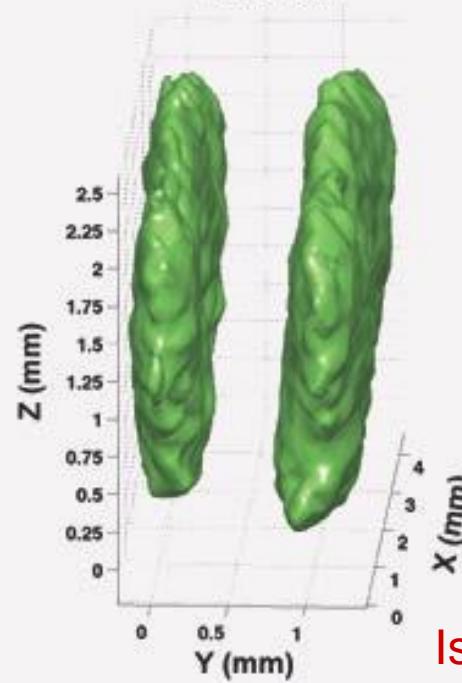
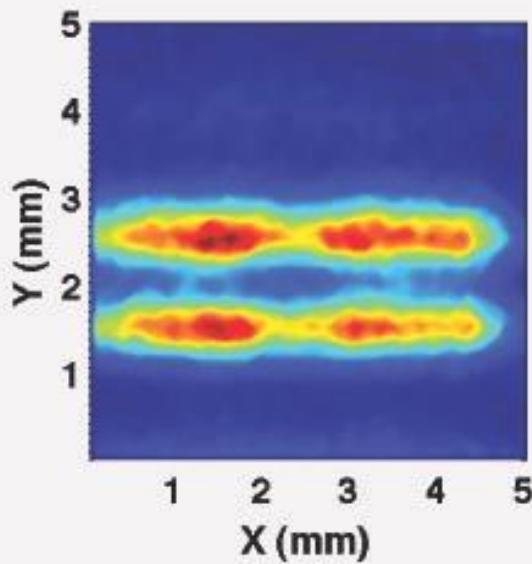
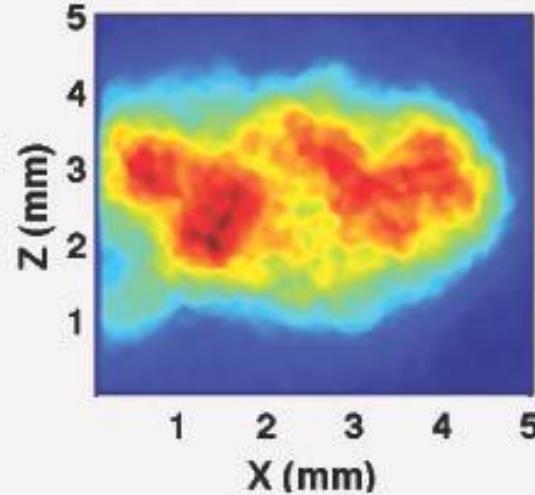
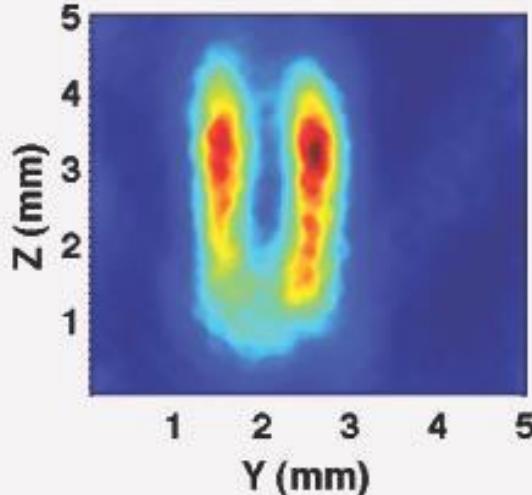
Joint reconstruction of the source in 2 positions separated by 1mm.
~130k LORs in 3.5M $25\mu\text{m}$ voxels.
Color maps: planar profiles including peak density point.
Isosurfaces: 50% rel. activity

Full area, all angles (up to 56°),
all gaps (DOI)
MLEM reconstruction

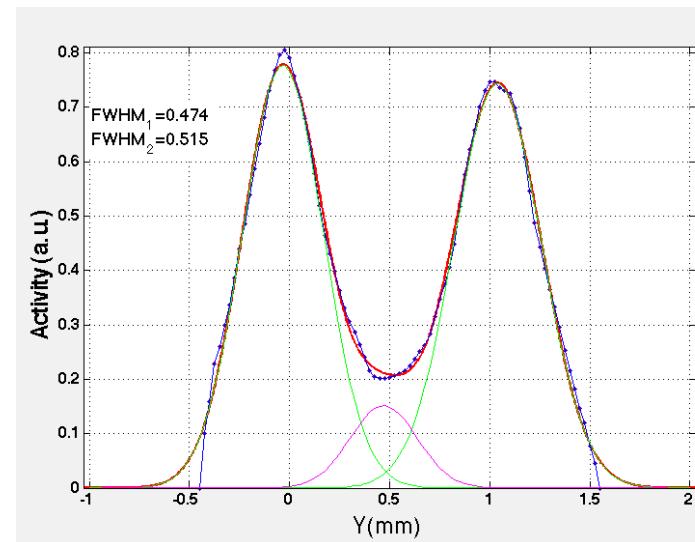


Reconstructed activity profile across the black line shown in the upper left panel.
Resolution **~0.4mm FWHM +background**
(Note: source is 0.2mm diam.)

Resolution tests (planar source)



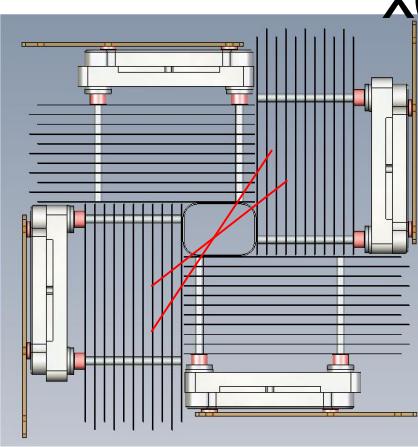
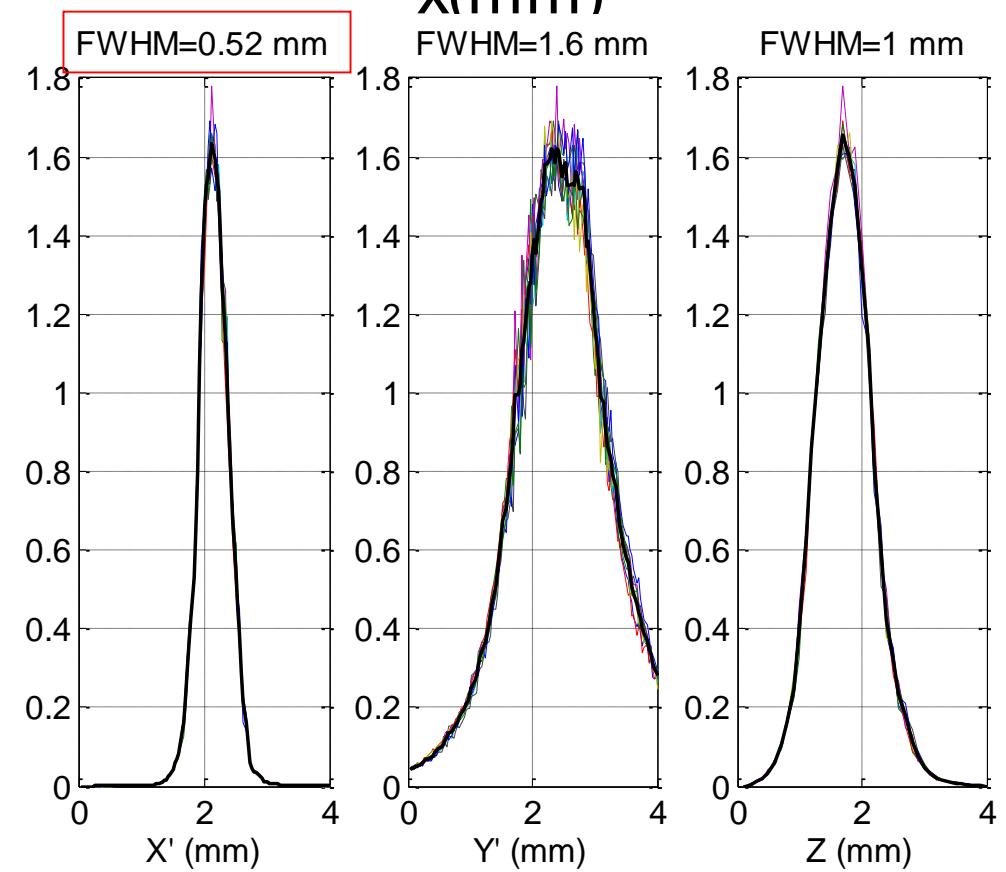
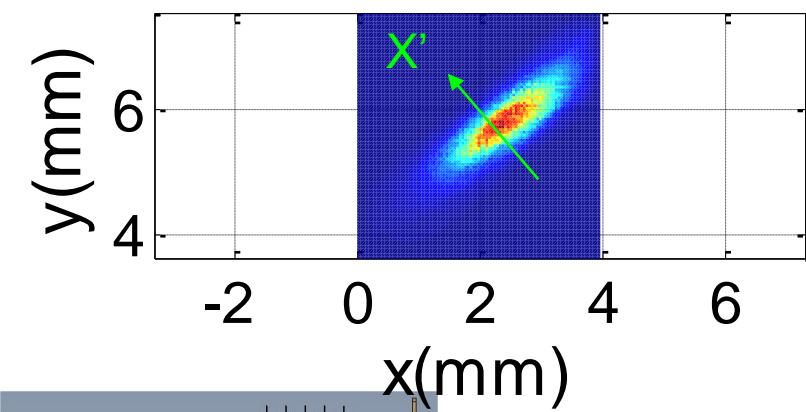
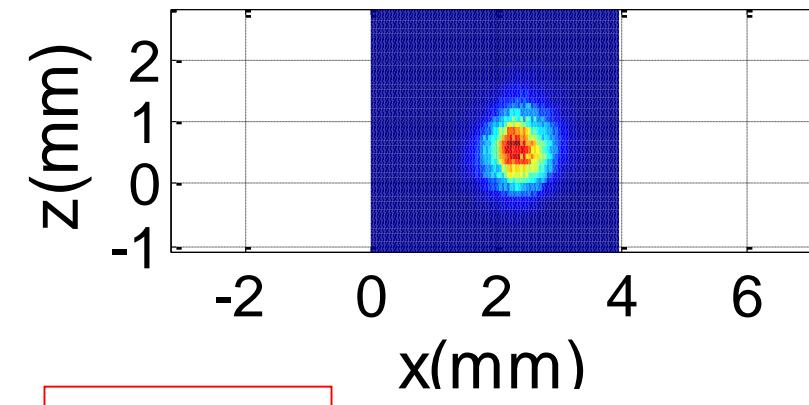
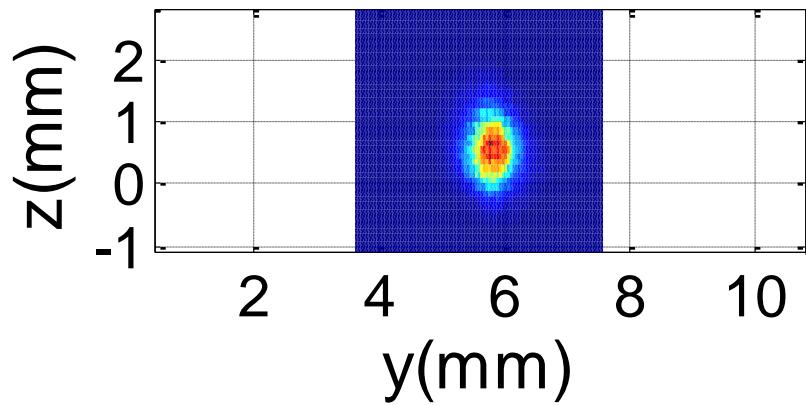
^{22}Na planar source edge-on
all angles, all gaps
1mm “mathematical” separation
MLEM reconstruction



Profiles across image
(0.5 mm FWHM)

Isosurfaces: 50% rel. activity

Resolution in final geometry (2 heads only, needle source)



PRELIMINARY
Calibration not
done in full.



Absolute efficiency in final geometry (2 heads only, needle source)

EVEN MORE PRELIMINARY

1.8%/gap to be compared to 2%/gap from GEANT



Conclusion

- An excellent space resolution of 0.4 mm FWHM was demonstrated in very realistic conditions without software enhancements (commercial tomographs > 1mm)
- A full scanner for mice is in an advanced completion stage, yielding a preliminary resolution of 0.52 mm FWHM
- It seems that the absolute efficiency may approach the simulated one.
- A competitive sensitivity (peakNEC) of 318Kcps has been suggested by simulations

- A very competitive PET scanner for small animals based on RPCs may be at hand, featuring excellent resolution (very much in demand today), reasonable efficiency and low cost.