Pad PET HPD

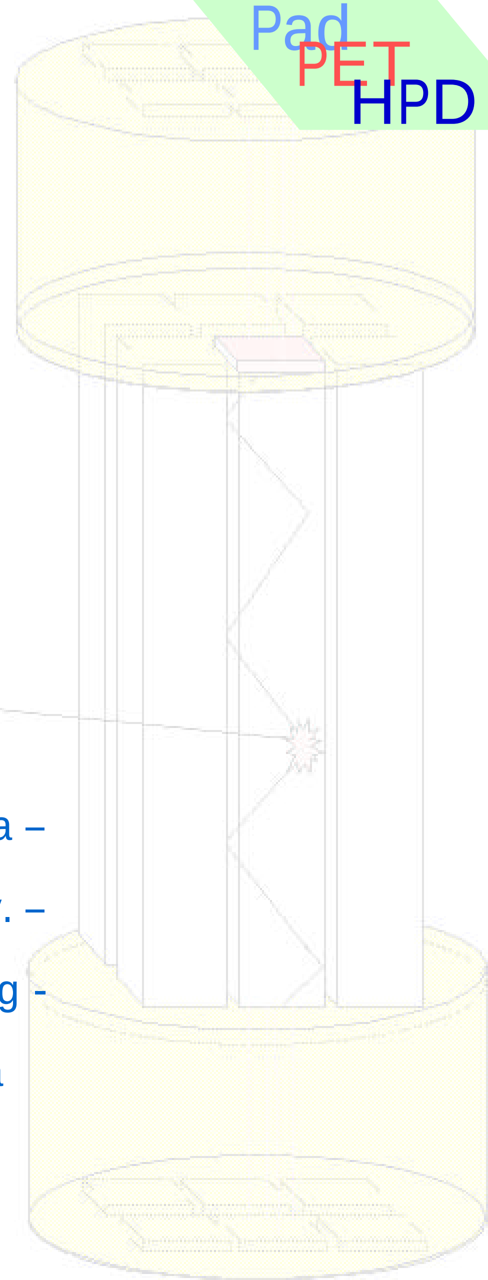
PET Detector
with
Parallax-free
Compton Enhanced
3D Gamma Reconstruction

C. Joram / CERN

representing

Bari – CERN - Cracow - Univ. Hospital Geneva –
Univ. Geneva – Lisbon ITN - Ohio State Univ. –
Oslo - ISS Rome – Ioffe Inst. St. Petersburg -
Ljubljana - Michigan State Univ. - Valencia

§§ Patent application filed under PCT/EP 02/07967 §§



Motivation

- Existing PET scanners are limited in resolution, sensitivity, rate. Limitations are partly due to

  - parallax error, no DOI information

  - modest energy resolution

  - coarse segmentation, low readout speed (no data spying during acquisition)

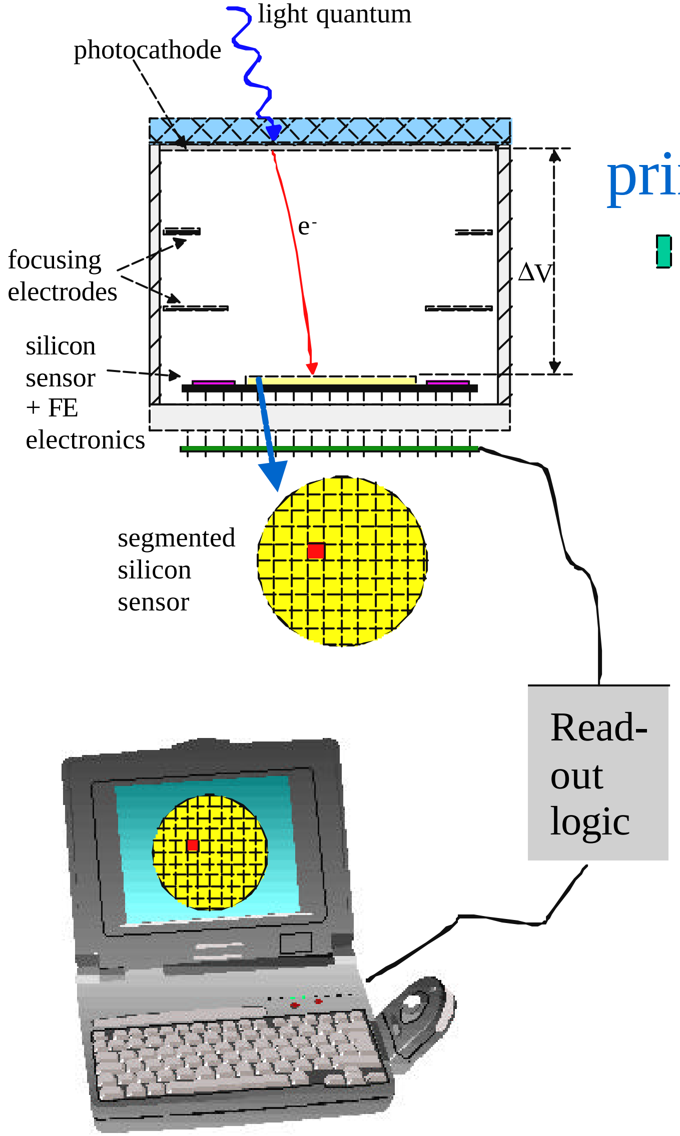
- Apply expertise and experience, gained in development of Si sensors and HPDs for particle physics (e.g. LHCb) to medical imaging

- Apply expertise and experience, gained in development of electronics / readout for particle physics, to the medical field in general

Outline

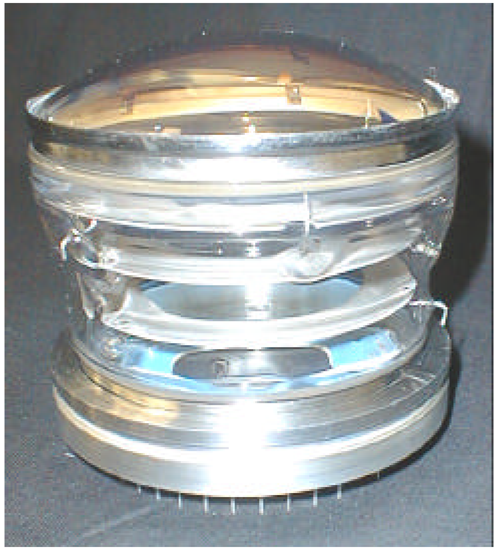
Pad PET HPD

Primer I: Hybrid Photodiode (HPD)



principle

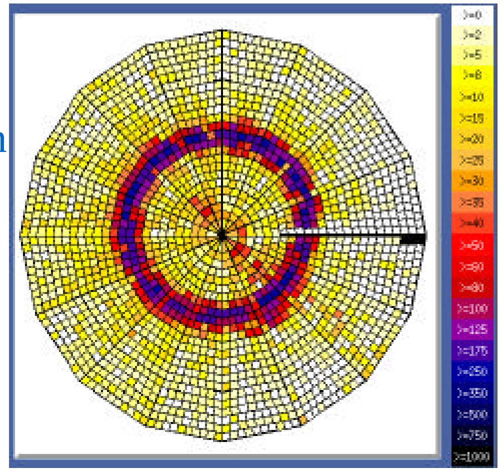
real device



Pad HPD 127mm Ø

Developed and built @ CERN

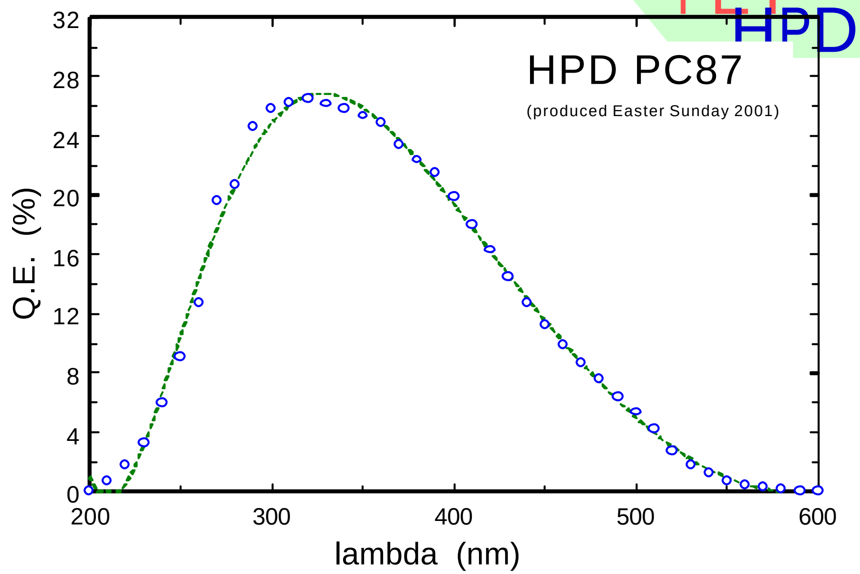
Single photon imaging with 2048 channels



Primer II: HPD performance

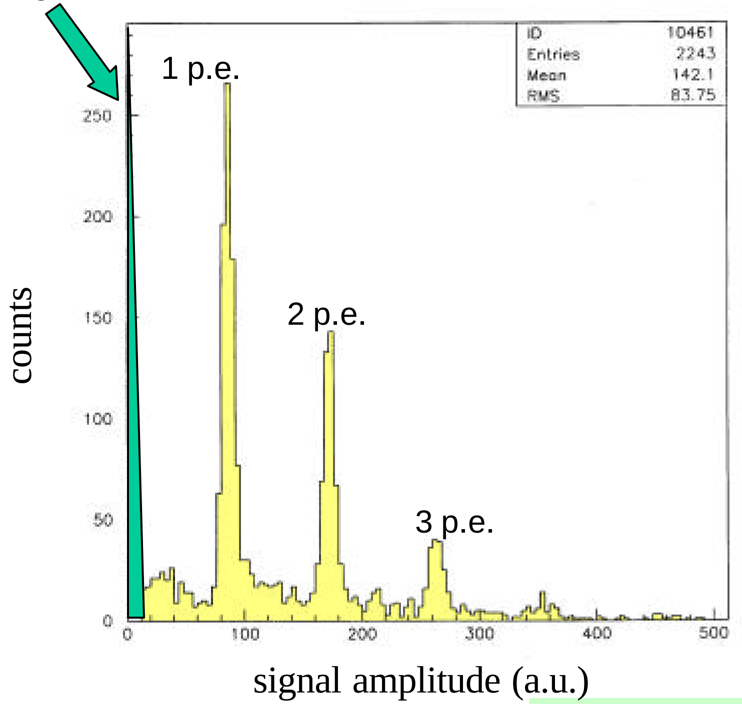
HPD combines single photon sensitivity of PMT with spatial and energy resolution of silicon sensor.

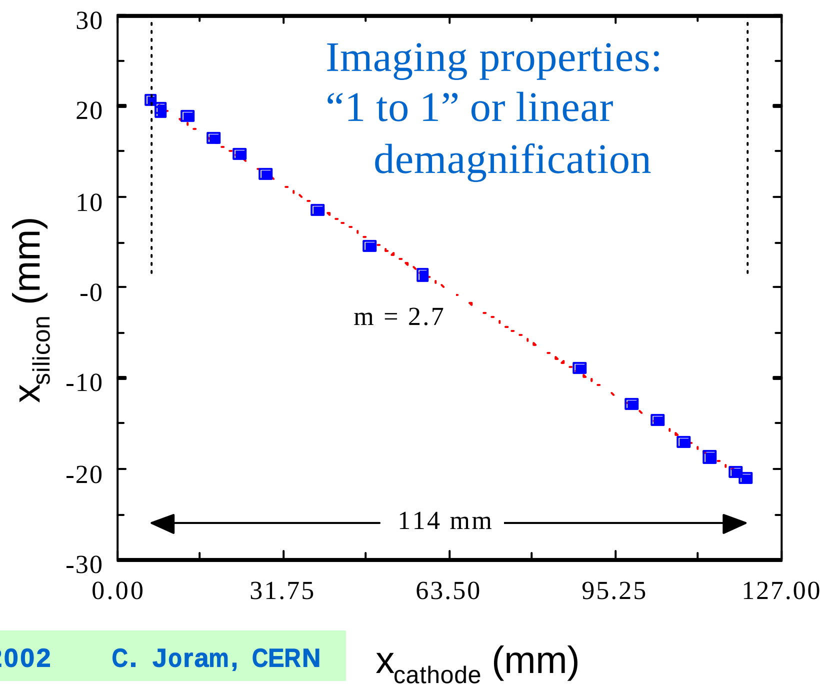
Sensitivity like classical PMT



Electronics noise well separated from signal

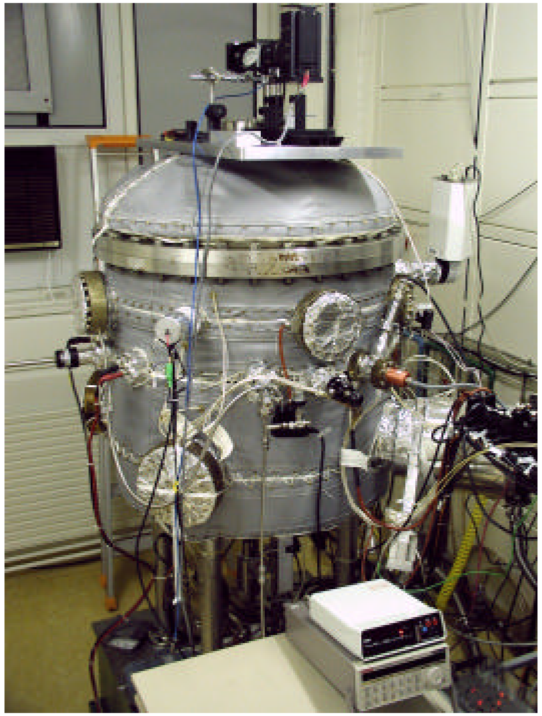
Signal definition and energy resolution

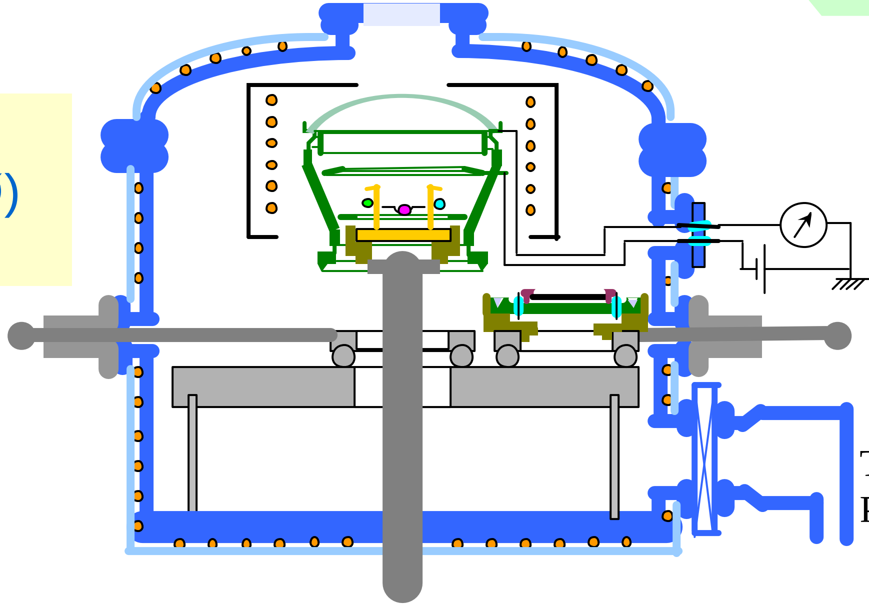




Primer III: HPD fabrication

Facilities and infrastructure for the fabrication of large HPDs (up to 10"Ø) have been developed at CERN.



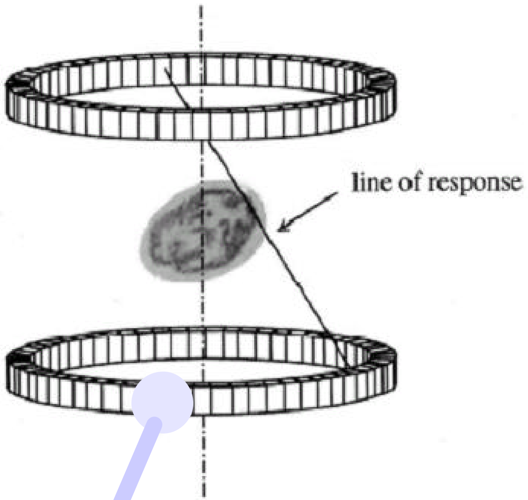


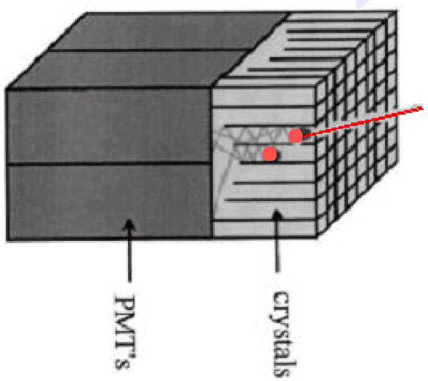
All ingredients for photodetector production are available:

- Design/simulation
- Photocathode processing ($bialkali$, Rb_2Te, CsI)
- Glass / ceramic tube manufacturing
- Indium sealing technique

I. The PET concept

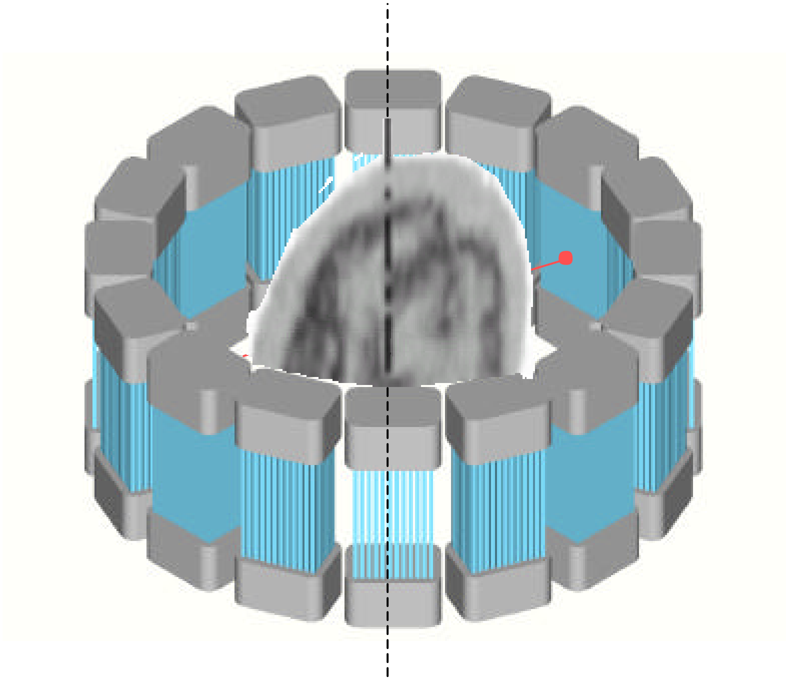
"Conventional" PET geometry





- Every PMT reads 4 crystals.
- Slotted blocks of scintillator crystals are read out by 4 PMT.
- Hit cell identified by charge ratio of PMTs.
- No DOI.

Our new PET geometry



- Axial arrangement of individual long scint. crystals
- Readout by HPDs on both sides.
- 1 crystal = 1 HPD channel

Main advantages of the concept

- Full 3D reconstruction of γ quanta without parallax error
  x,y from silicon pixel address,
  z from amplitude ratio of the 2 HPD's
  ➔ Precise Depth of Interaction DOI measurement

- Measurement of light yield on both sides of crystals
- Negligible statistical fluctuations in HPD
  ➔ Good γ energy resolution

- Reduced random coincidence rate due to fine granularity

- 3D reconstruction provides possibility of recuperating part of γ's which underwent Compton scattering in the detectors
  ➔ Compton enhanced sensitivity

Pad PET HPD

Critical issues of the concept

- How to obtain optimum z – resolution ?
- How to arrange modules for very long (full body) scanners ?

The PET-HPD (details later) may also be interesting for a conventional PET geometry and other imaging applications.

PadPET HPD

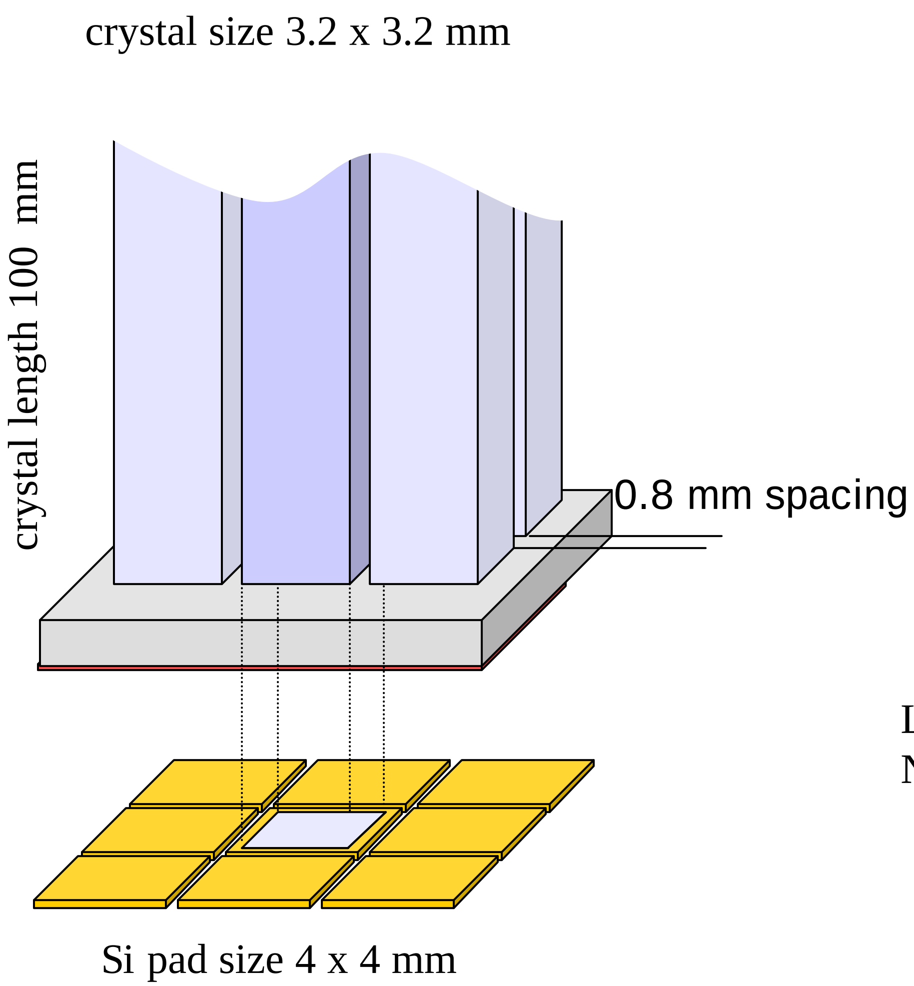
Scintillation crystals

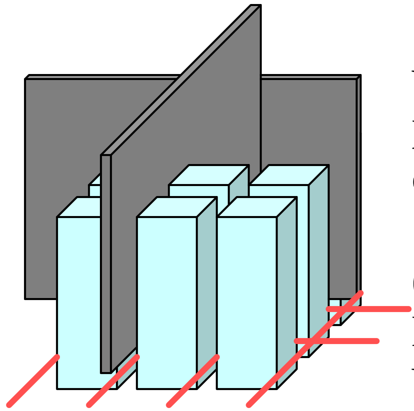
- Criteria to be taken into account: light yield, absorption length, photo fraction, self absorption, decay time, availability, machinability, price.
- All preliminary performance estimates are based on YAP:Ce (availability!)

	YAP:Ce	LSO:Ce	LuAP:Ce	$LaCl_3$:Ce	$LaBr_3$:Ce
Density *r* (g/cm^3)	5.55	7.4	8.34	7.86	5.3
Effective atomic charge *Z*	34	66	65	49.5	46.9
Scintillation light output (photons / MeV)	18000	25000	≈ 20000	≈ 46000	
Wavelength of max. emission (nm)	370	420	370	330, 352	
Refractive index *n* at 370 nm	1.94	1.82	1.95		
Bulk light absorption length l_a (cm)	14				
Principal decay time (ns)	27	18	38	26,210,1000	
γ attenuation length at 511 keV (mm)	22.4	11.5	10.5	29	22
Photofraction at 511 keV (%)	4.5 !	32.5	30.6	15	14

- YAP is OK for proof of principle, however suffers from low Z (high absorption length, low photo fraction)
- LSO and LuAP are the really interesting candidates.

The crystal matrix





wires define precise spacing of crystals.

(Black paper for light shielding between crystals ?)

Light propagates by total internal reflection.
No reflective coating.

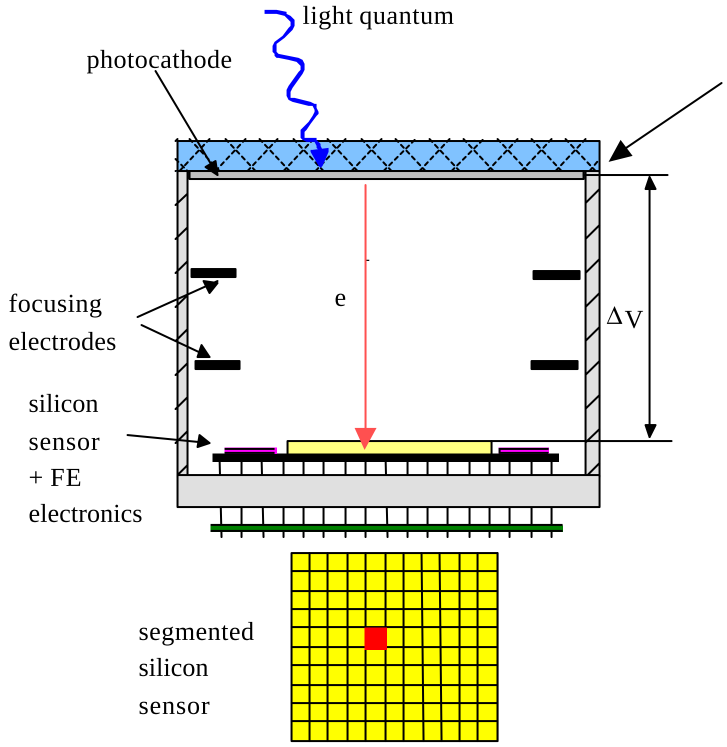
PadPETHPD

The photodetector – basic considerations

HPD needs about 200 channels.

Electronics encapsulated in vacuum envelope.

Electronics must be auto-triggering.



HPD window must be flat and as thin as possible

proximity focused electrostatics

Segmentation of Si sensor matches crystal matrix

Minimize dead space

Rectangular HPDs with rectangular Si sensor would give the best filling factor

II. Performance estimates

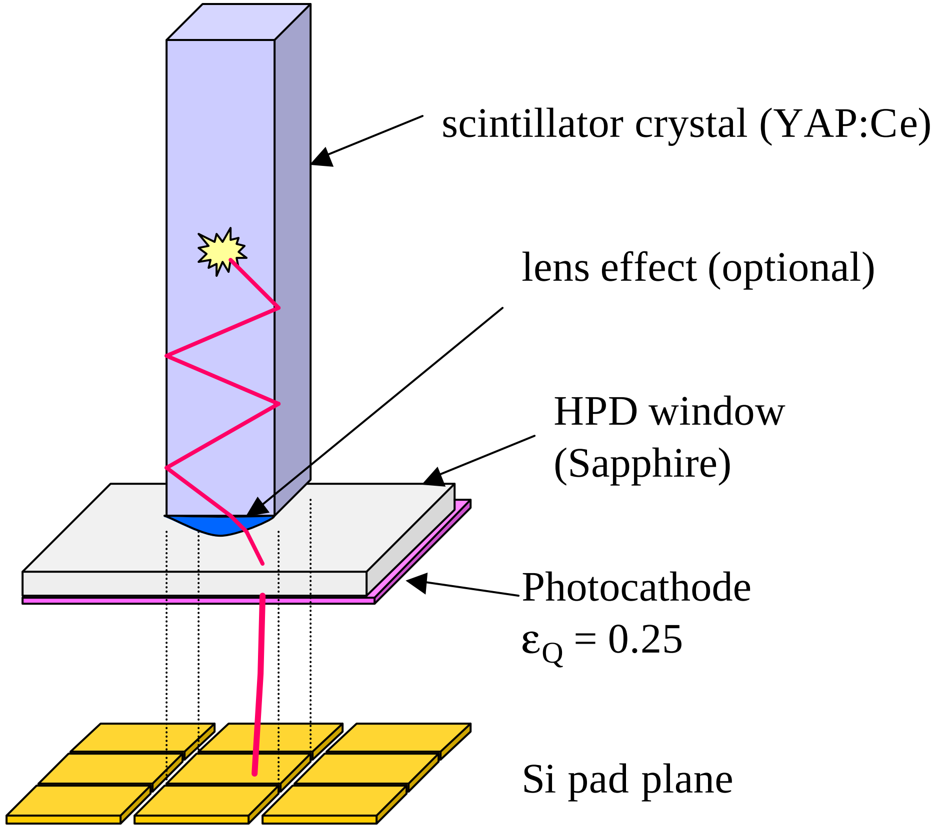
based on analytical calculations and M.C. simulations

scintillator: YAP:Ce

PadPETHPD

Ingredients of 'microscopic' simulation

- Isotropic generation of scintillation light
- Propagation by total internal reflection
- Refraction at refractive index change
- Loss due to refraction out of crystal
- Photon loss due to absorption
- Photon loss due to reflections (R < 1)
- HPD quantum efficiency
- HPD point spread function



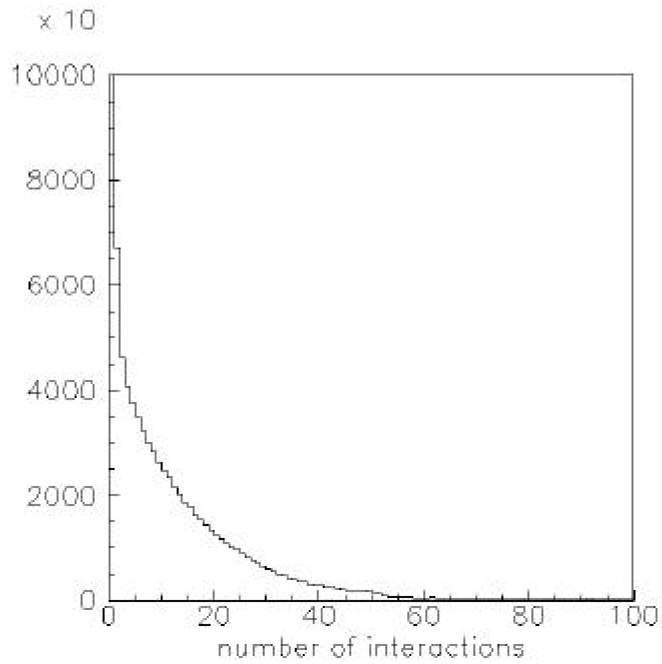
Light Yield

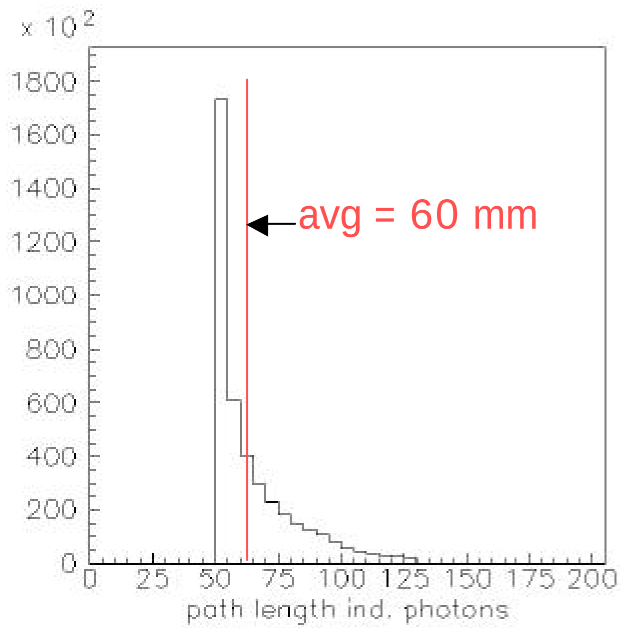
- Number of generated photons per 511 keV γ: N_{ph} = 18.000 x 0.511 = 9200
- Number of reconstructed photons (for both HPDs together)

$$N_{rec} = N_{ph} \cdot e_C \cdot e_Q \left(e^{-\frac{z_{eff}}{l_a}} + e^{-\frac{L-z_{eff}}{l_a}} \right)$$

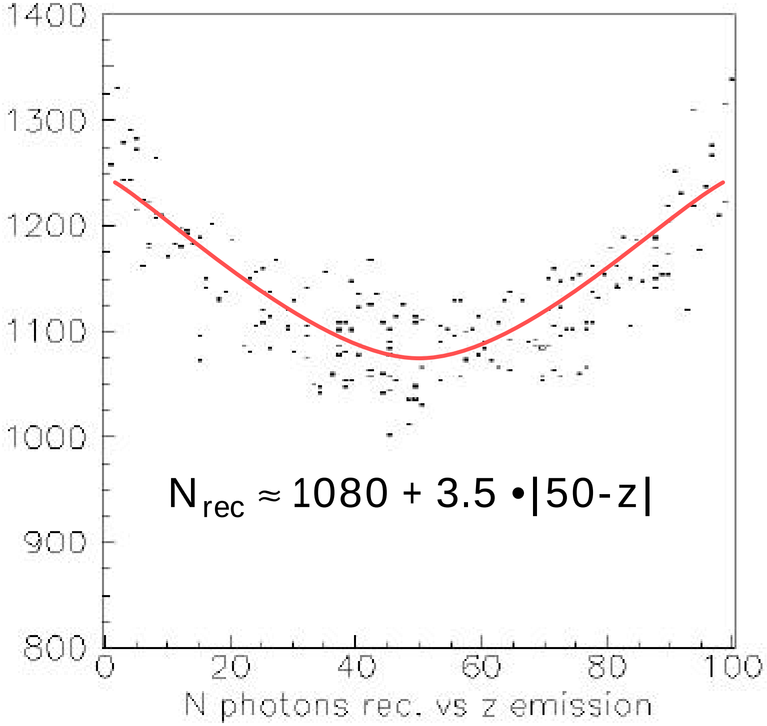
transport efficiency $\varepsilon_C \approx 0.4$ / side
(rectangular crystals, n=1.94, $\lambda_{abs} = \infty$).

Quantum efficiency $\varepsilon_Q \approx 0.25$
(bialkali PC at 370 nm)

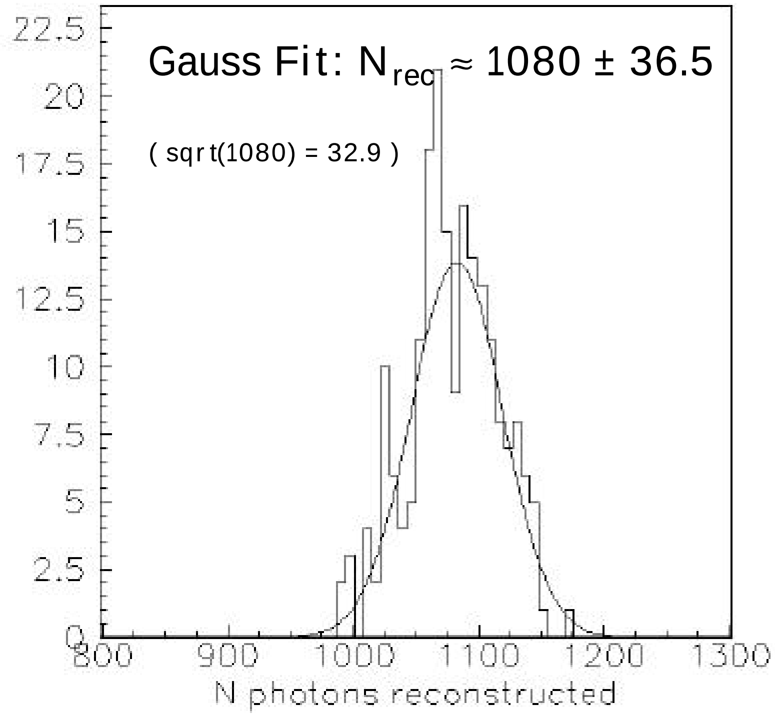




Photons generated at z = 50 mm and arriving at photodetector at z = 50 mm



$N_{rec} \approx 1080 + 3.5 \bullet |50 - z|$



Gauss Fit: $N_{rec} \approx 1080 \pm 36.5$

(sqrt(1080) = 32.9)

$\sigma(N)/N = 0.03$

Statistical contribution to energy resolution = 2.8 - 3% (sigma) or 6.5 - 7.1% (FWHM)

- Energy resolution

$$R = \frac{\Delta E}{E}(FWHM) = R_{Sci} \oplus R_{stat} \oplus R_{noise}$$

R_{stat} → 2.5 %

R_{noise} → negligible (discussed later)

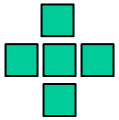
$$R_{stat} \approx (6.5 - 7.1)\% \cdot \sqrt{\frac{511}{E_g\,(\mathrm{keV})}}$$

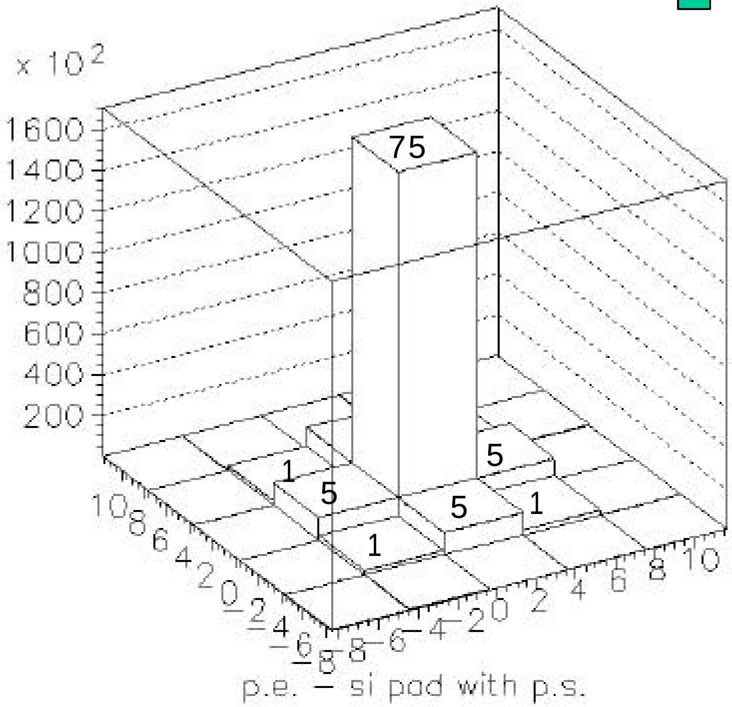
R ≈ 7 – 7.5% (FWHM) at E_γ = 511 keV

≈ 16% at 100 keV

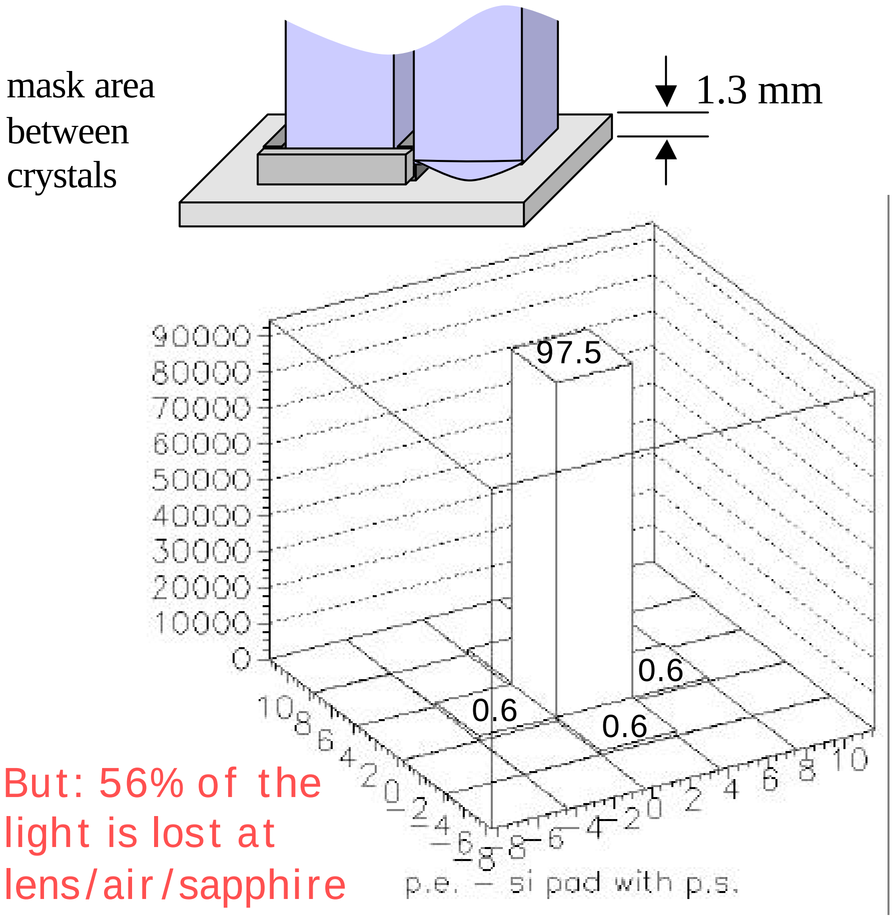
Photoelectron distribution on Si plane (1 crystal 'uniformly illuminated')

75% of p.e. hit the central pad
95% are concentrated on 5 pads





Polishing the crystal ends to a spherical lens plus small masks ➔ 97.5% of the light on central pad.



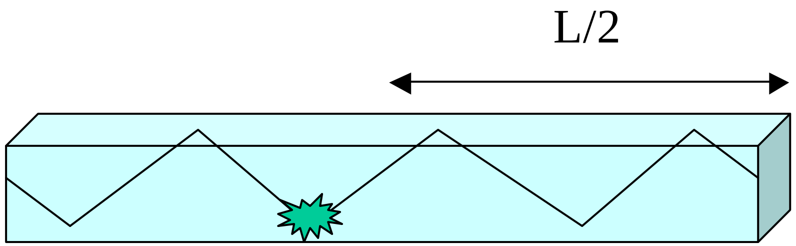
But: 56% of the light is lost at lens/air/sapphire interface.

Not pursued for the moment.

- Reconstruction of the interaction point

x-y: dimension of crystal determine precision

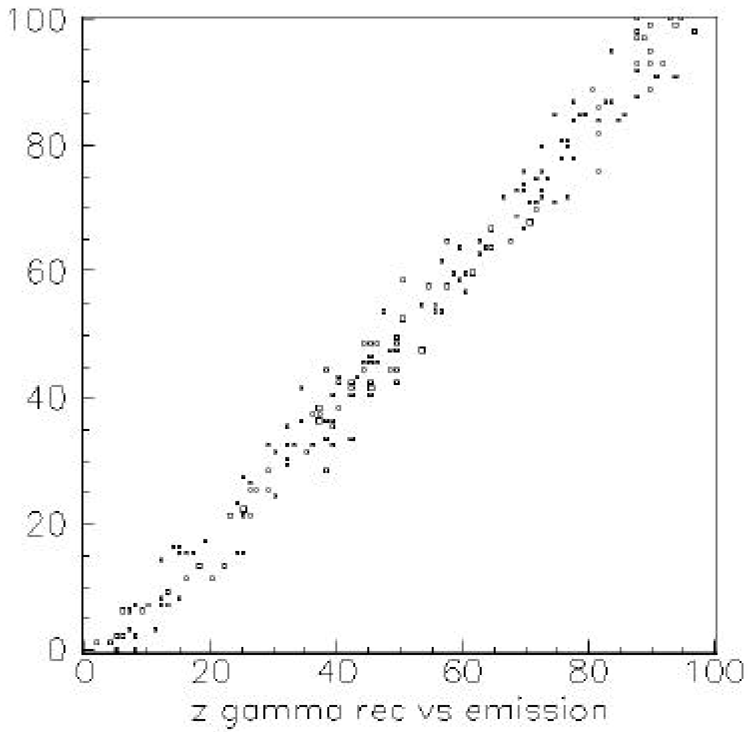
$$s_x = s_y = \frac{1}{\sqrt{12}} s \quad \approx 2.4\ \text{mm (FWHM)}$$



z: ratio of light detected by the 2 HPDs

$$z = \frac{1}{2}\left(L + k_g \cdot l_a \cdot \log\left(\frac{Q_R}{Q_L}\right)\right)$$

k_g is a geometrical factor $k_g = \left\langle \frac{z_{eff}}{z} \right\rangle \approx 0.8$



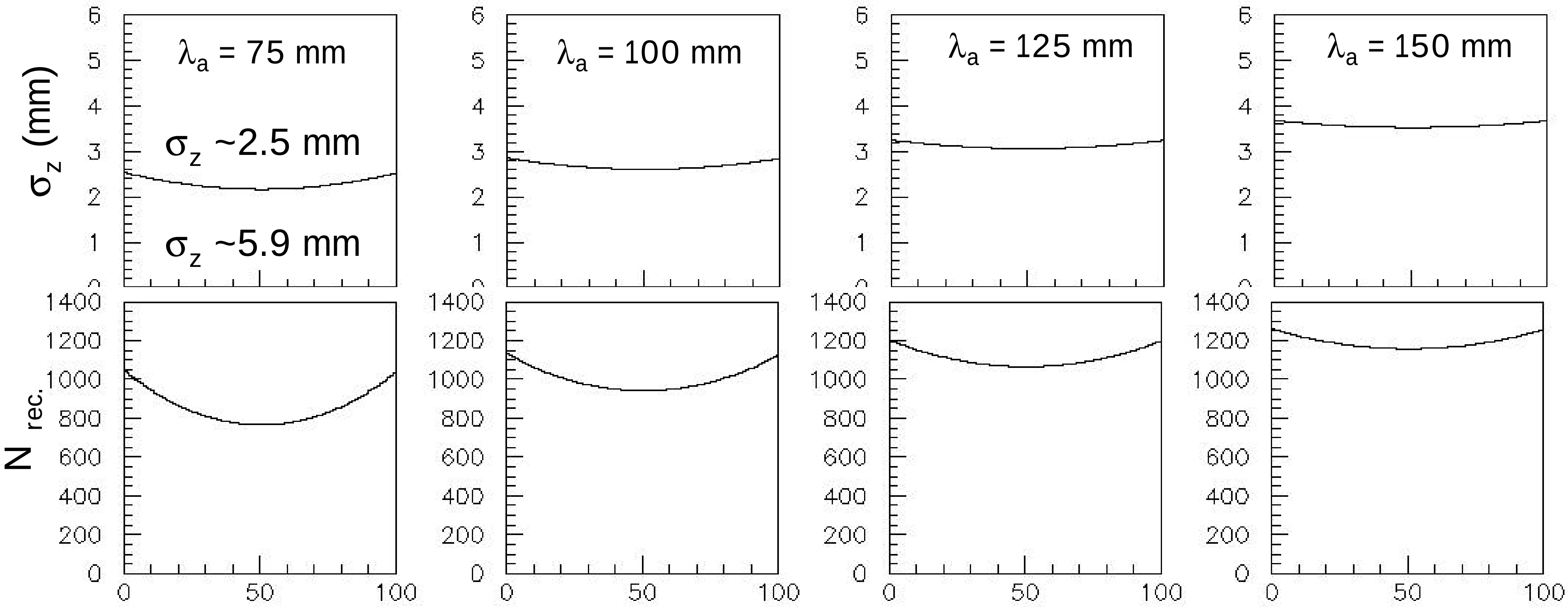
perfectly linear !

z - resolution

$$s_z = \frac{k_g \cdot l_a}{2}\left[\frac{Q_L + Q_R}{Q_L \cdot Q_R}\right]^{1/2} \qquad Q_L = Qe^{-z/l_a} \qquad Q_R = Qe^{-(L-z)/l_a}$$

$$s_z = \frac{k_g \cdot l_a}{\sqrt{2Q}}\left[e^{z/l_a} + e^{(L-z)/l_a}\right]^{1/2}$$

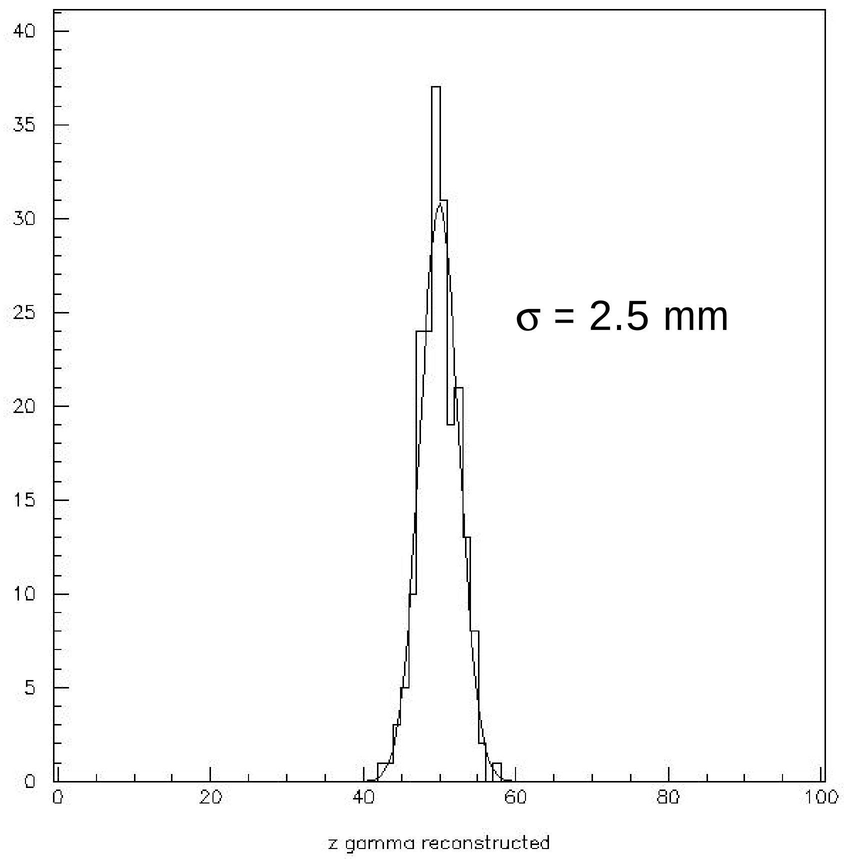
(E_γ = 511 keV, L = 100 mm)



Verification of z – resolution in full simulation

PadPETHPD

emission at z = 50 mm, λ_a = 75 mm, E_γ = 511 keV



Electronics (encapsulated in HPD vacuum envelope)

Pad PET HPD

IDEAS VaTagp3, 128 channels

Features: charge sensitive amplifier, shaper, sample+hold, multiplexed analogue readout, self-triggering logic (2 parallel shapers), sparse readout

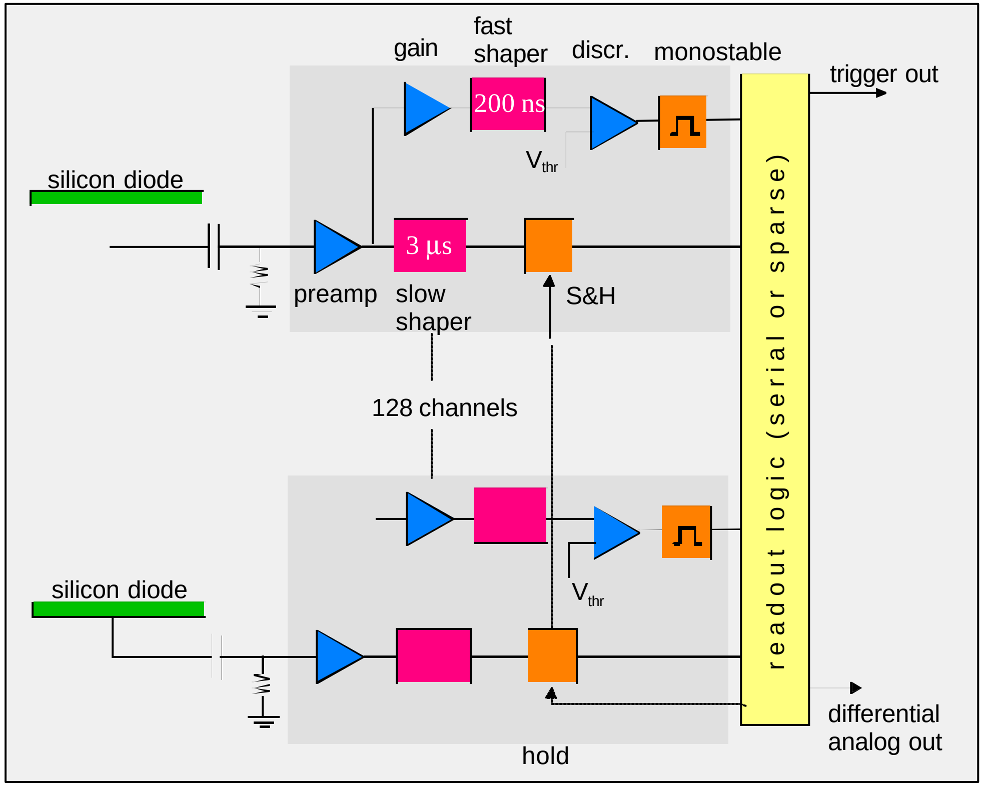
Existing chip:

t_{peak}^{slow} = 3 µs, t_{peak}^{fast} = 150 ns

Future chip, optimised for PET:

t_{peak}^{slow} = 1 µs, t_{peak}^{fast} = 35 ns

Peter Weilhammer will give more details.



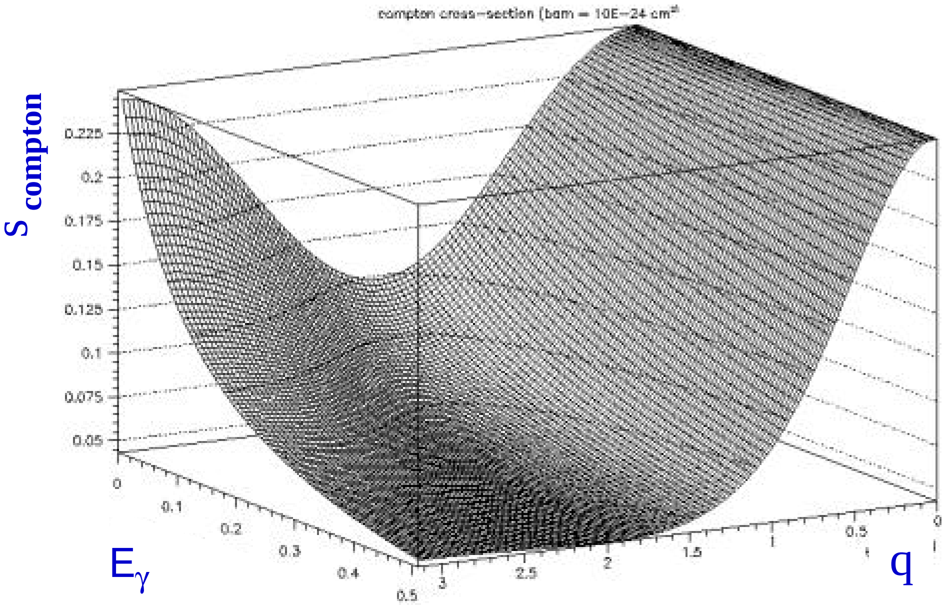
Compton enhanced reconstruction

Pad PET HPD

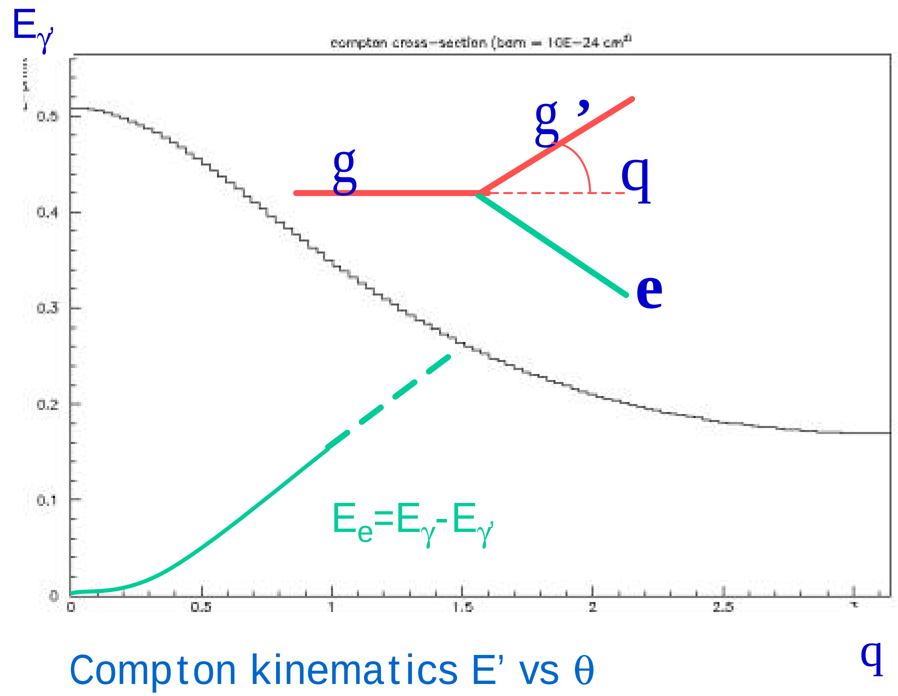
Problem: Photofraction in YAP:Ce (Z=32) is relatively low $\varepsilon_{\gamma}^{photo} = 4\%$

$$\varepsilon_{\gamma\gamma}^{photo}(coinc.) = 0.16\%$$

- Compton scattering dominates, also in other materials.
- Can one use Compton scattered events ?
- Yes, but only if point of 1st interaction can be reconstructed.



Compton cross-section according to Klein-Nishina



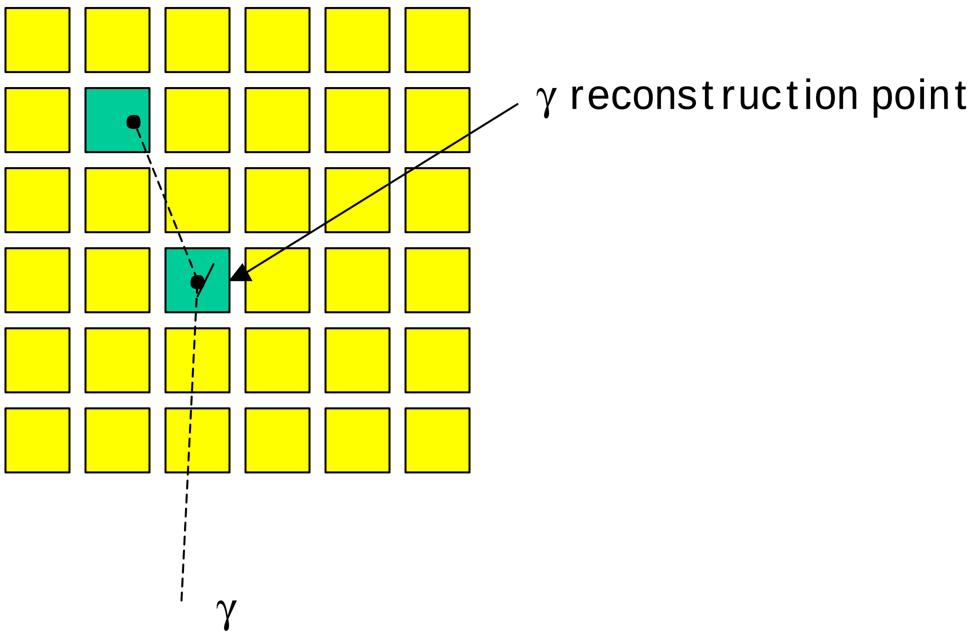
Compton kinematics E' vs θ

Scattering angle is known if energy deposit of Compton electron can be measured.

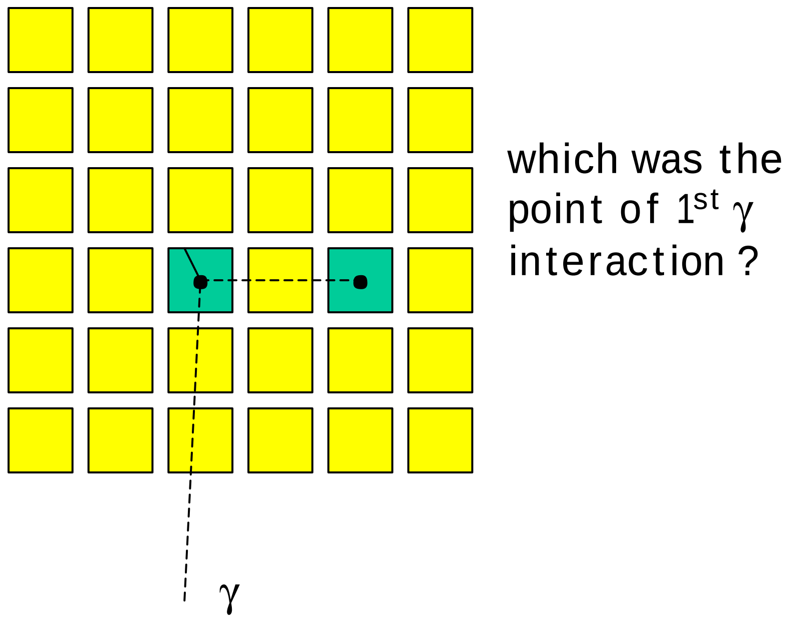
Pad PET HPD

Fine 3D segmentation and large volume make it possible...

"unambiguous"



"ambiguous"

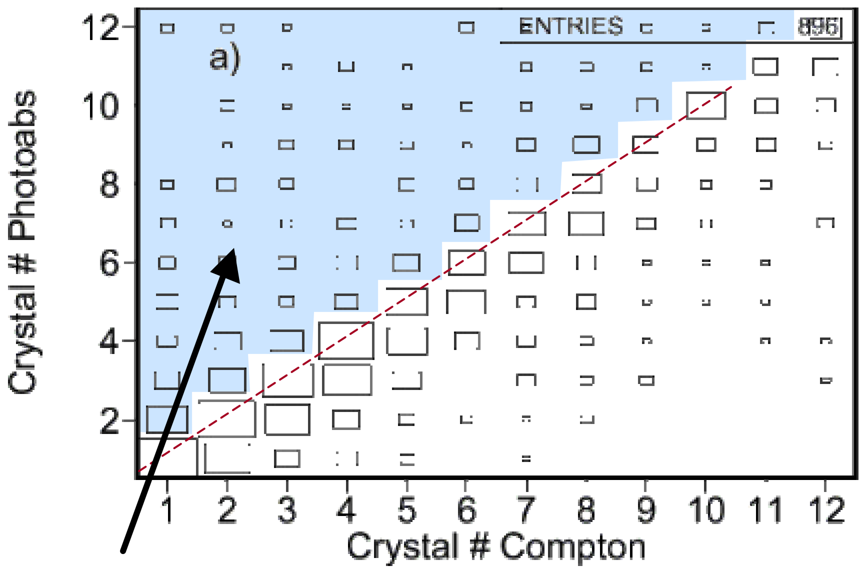


- ➔ Select only events in which Compton scattering happens in forward hemisphere
- ➔ Restrict to Compton angle $10° \leq \theta \leq 60°$
- ➔ Ask for energy deposit in first interaction $E \leq 170$ keV

Geant4 LowEnergy

- Full microscopic simulation of low energy interaction in YAP and LSO
  - Photo effect (PE)
  - Compton effect (CE) (even Rayleigh scattering)

Unambiguous events



Unambiguous events: the photo-absorption takes place in a crystal 'after' the Compton interaction

	YAP	LSO
PE	4.2%	34%
CE + PE in same crystal	0.4%	2.4%
detection probability	0.21%	13.2%
1 CE + PE unambig.	2.1%	9.6%
total det. probability	0.43%	20.6%
gain	~2.1	~1.6

III. The PET HPD

Pad PET HPD

Round prototype "PCR5"

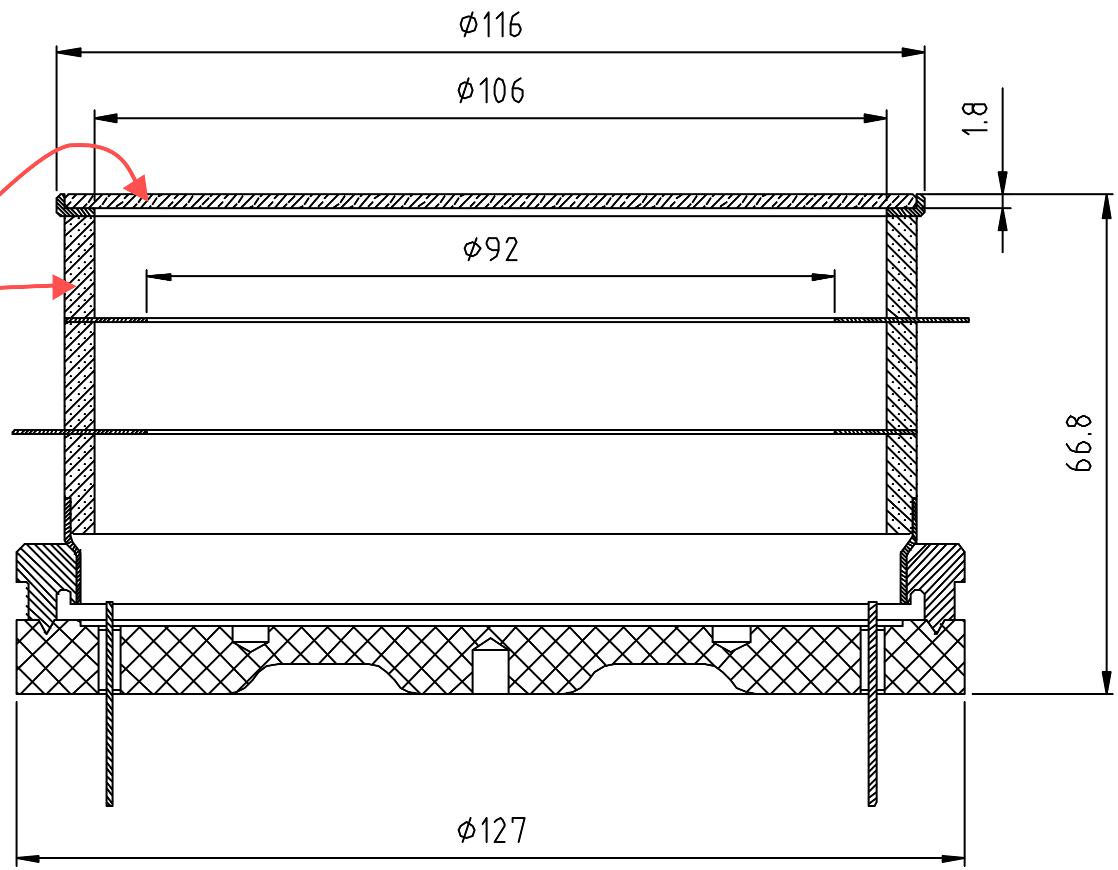
- 127 mm Ø overall
- Proximity focused

- Sapphire window (d=1.8 mm)
- Ceramic body

- Nb skirt
- Nb electrodes

- Bialkali photocathode
- QE(370 nm) ≈ 25%

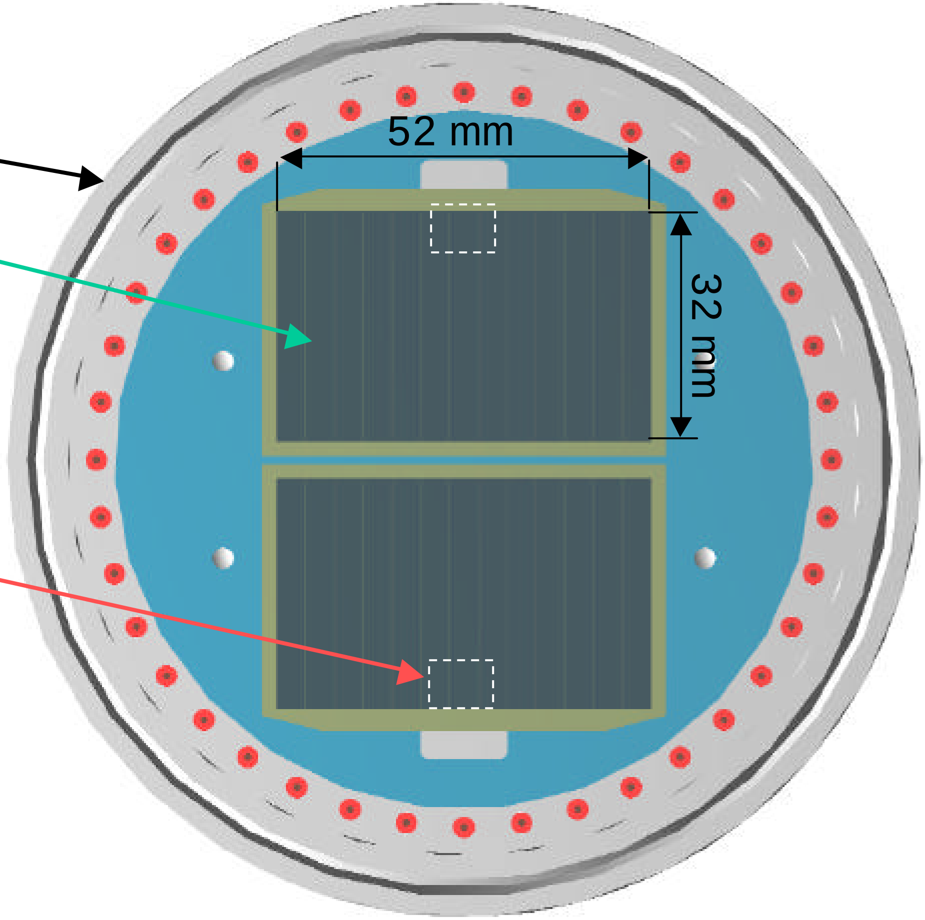
- $U_C \approx 12$ kV
- Gain ≈ 3000



Body construction by ceramic / metal brazing technique (under vacuum). Technology available at CERN.

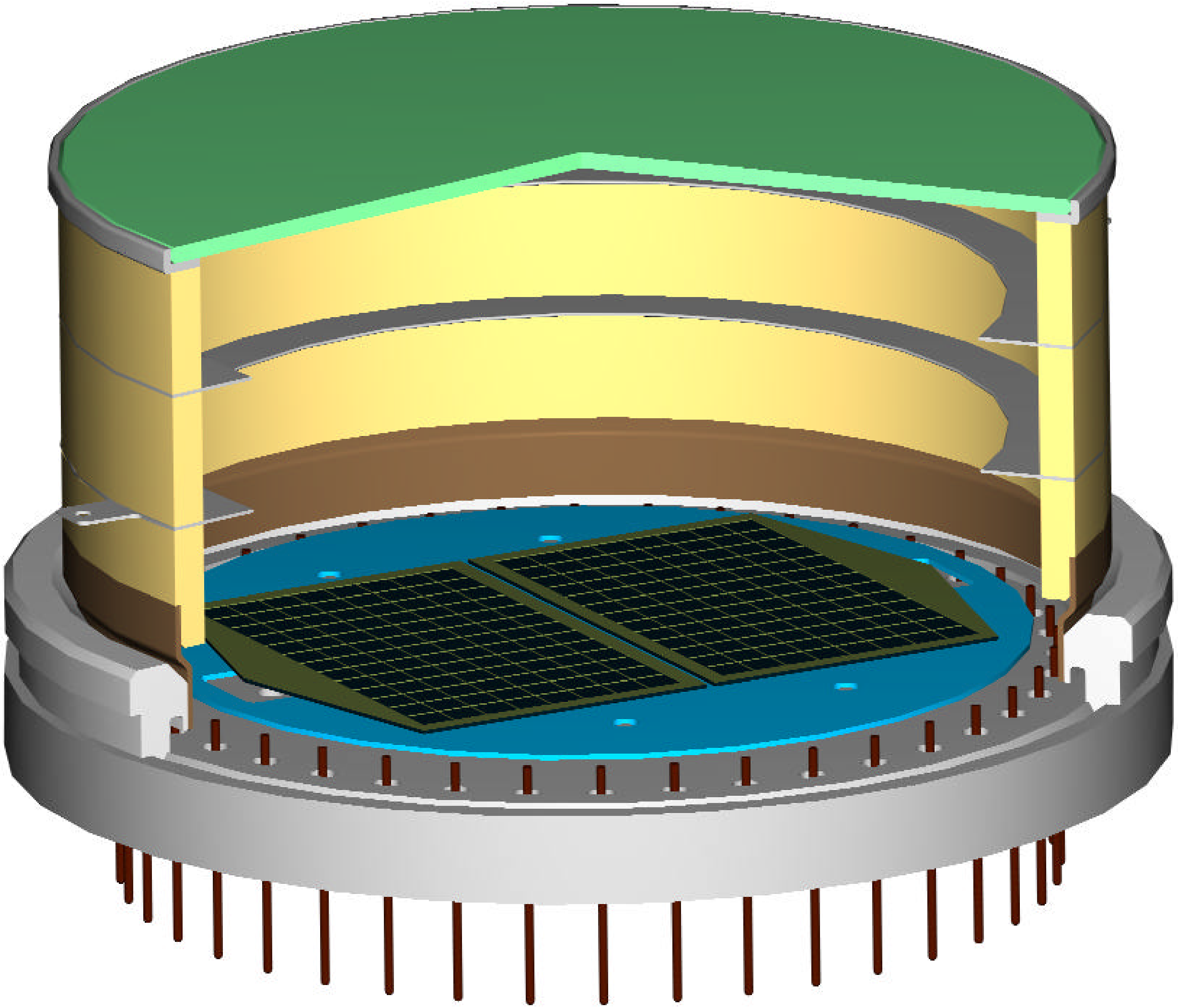
The HPD anode
(round prototype)

- Base plate 5" (existing)
- Si sensor (2 independent halves)
  8 x 13 pads each (208 total)
  pad size 4 x 4 mm^2
- Ceramic PCB
- 2 VaTagp3 chips underneath
  Chips encapsulated in
  vacuum envelope

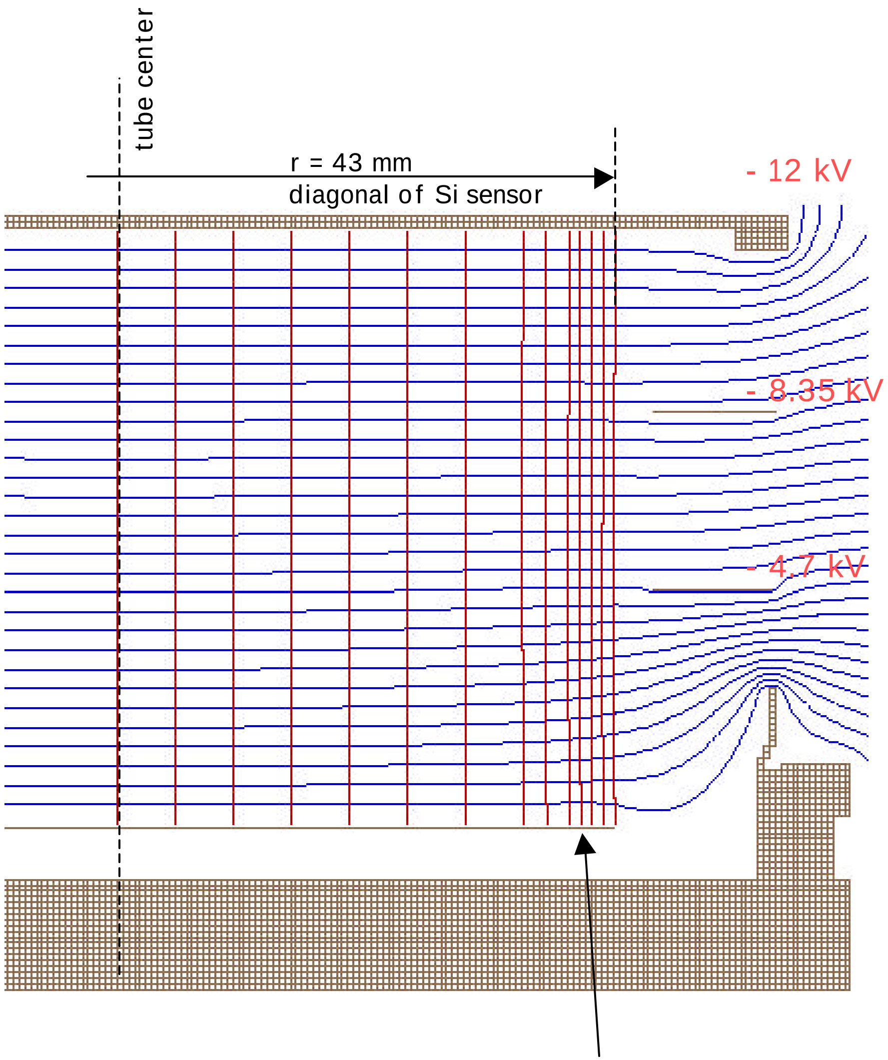


PET HPD

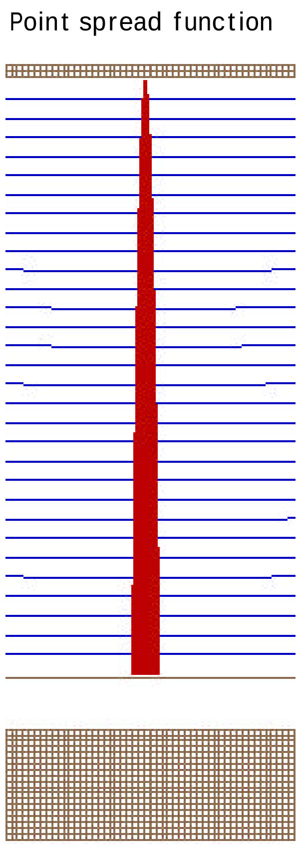
round prototype "PCR5"



Electrostatic simulations of PCR5 with SIMION 7



deviations < 0.2 mm

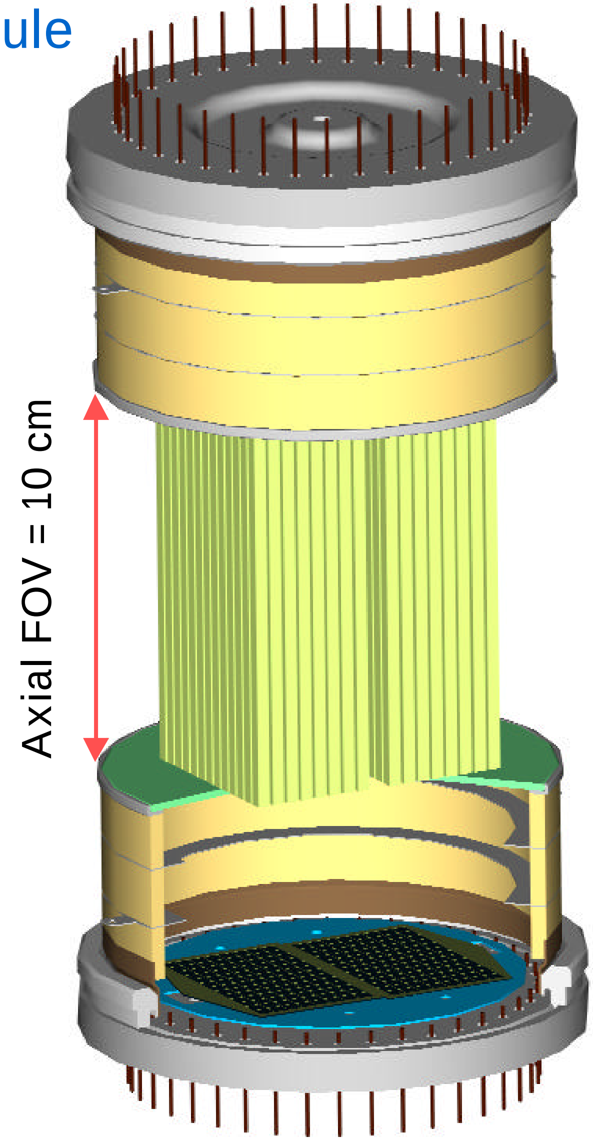


PSF ~0.3 mm

➔ expect almost perfect 1:1 correspondence of crystals to Si pads

PET camera prototype module

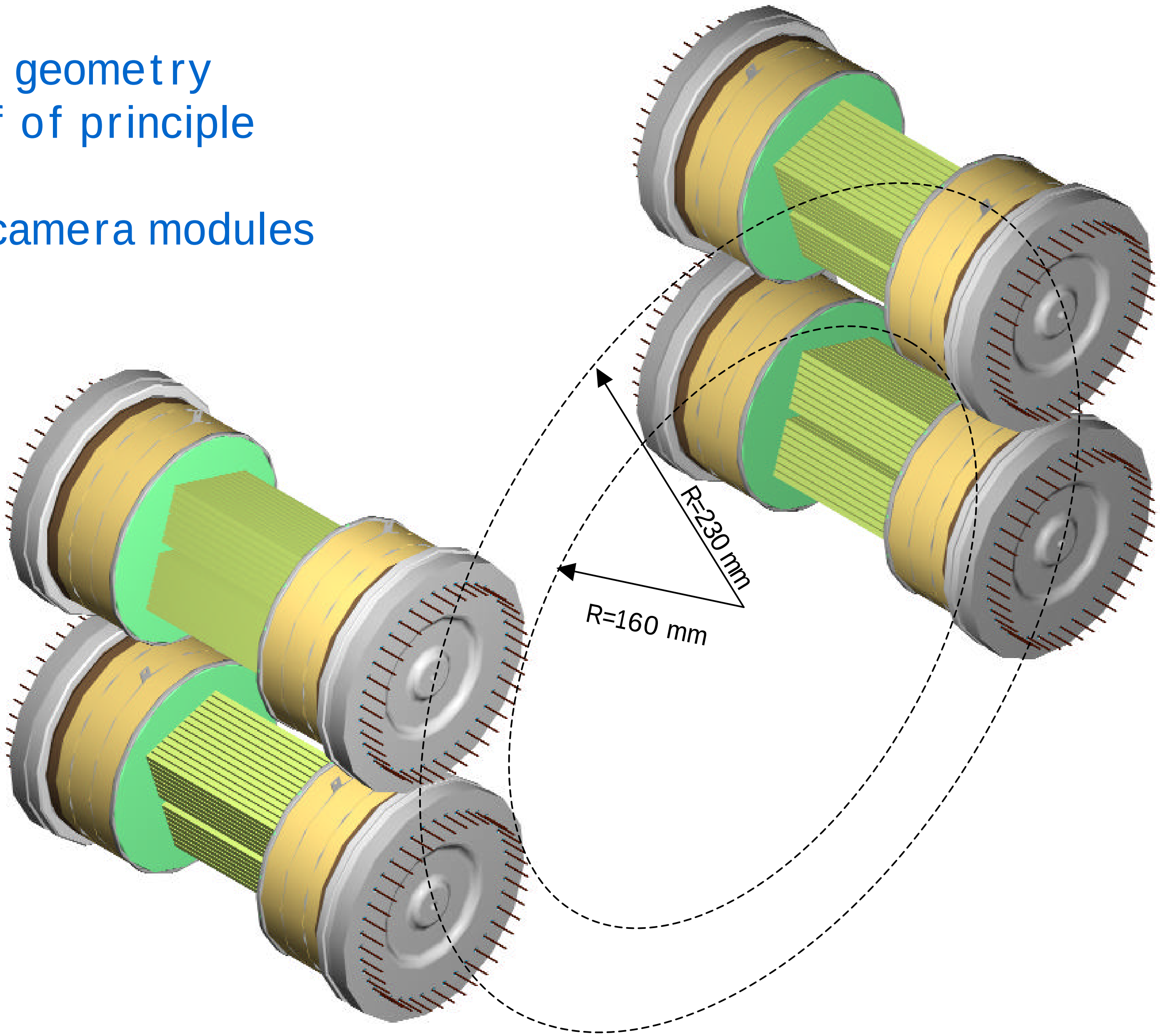
- 2 HPD PCR5
- Scintillator array (208 crystals)



Pad PET HPD

Proposed geometry for proof of principle

- 2 or 4 camera modules



Status of tube development (PCR5)

- All components designed
- Material ordered: Ceramic, sapphire, niobium
- material partly received, machining started
- First brazing tests of Ø 50mm body: ceramic/kovar, ceramic/Nb, Nb/sapphire
  No major problems.
- A first 5" body is expected to be produced in 1-2 months.
- First sealed tube with round Pad HPD Si sensor could be available by the end of the year.
- Si sensor design submitted for processing (SINTEF), ~12 weeks.

IV. towards an optimized PET HPD design ...

rectangular prototype (very preliminary)

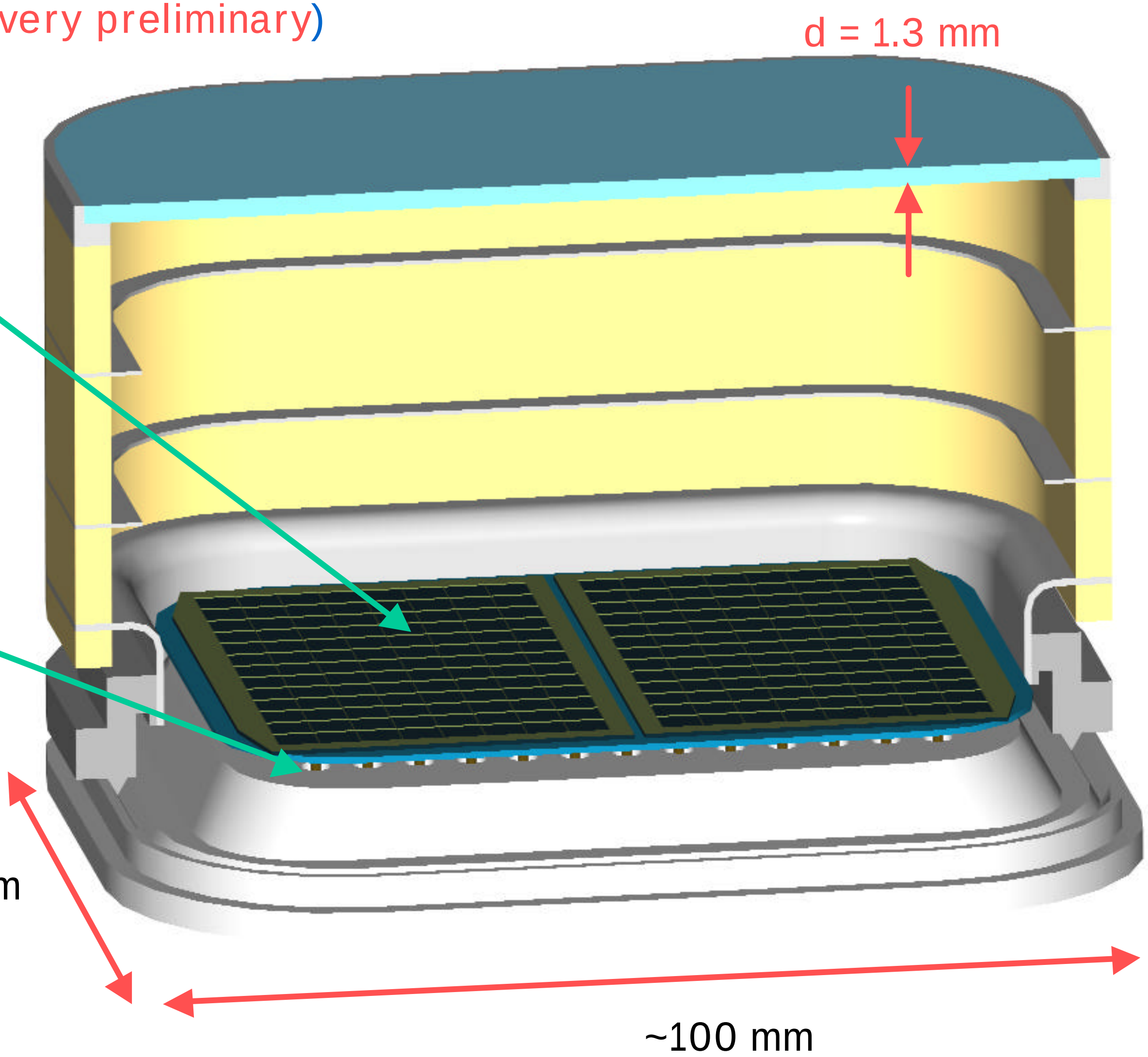
Use of same Si sensor as PCR5

Ceramic PCB needs to be re-designed.

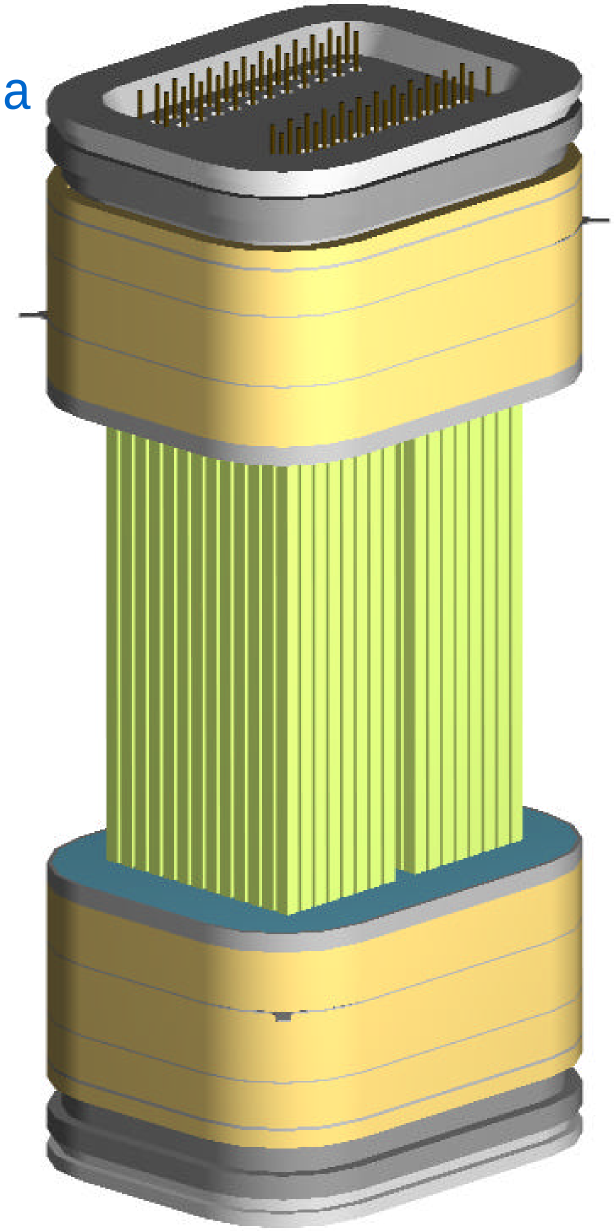
2 VATAGP underneath.

Vacuum feedthroughs hidden under PCB

Tricky but feasible connectivity (wire bonding)



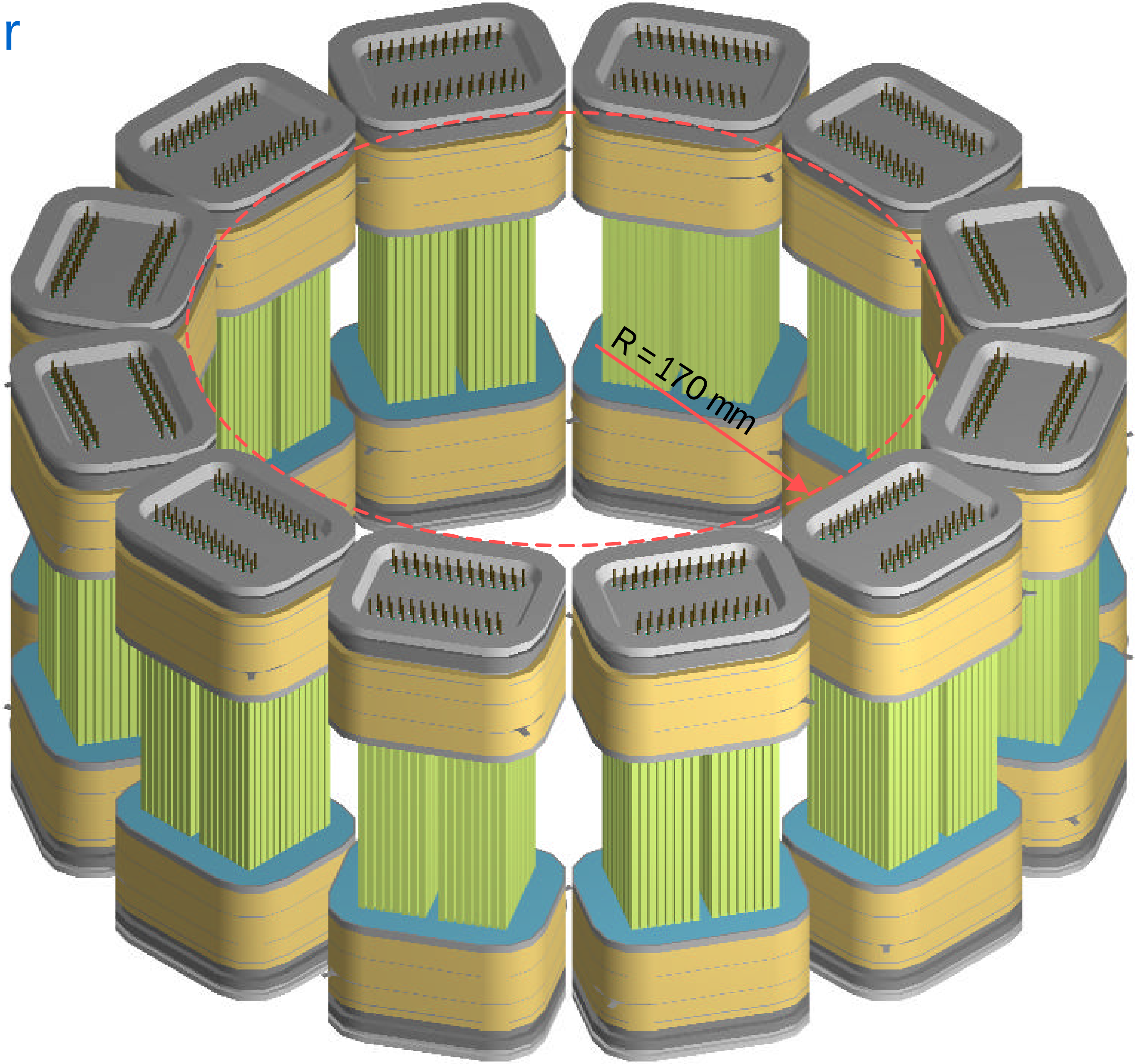
Rectangular PET camera prototype module



Pad PET HPD

Full ring scanner

Possible configuration
for a Brain PET



- 34 cm inner diameter
- 10 cm axial length
- 2496 crystals
- 24 HPDs
- total detection volume

  2556 cm^3
- Φ coverage 66%
- Ω coverage 18%

PadPETHPD

Summary of performance estimates (for YAP:Ce crystals)

• Detected photoelectrons for a γ of 511 keV:	540 - 625 per HPD
• Energy resolution:	7 – 7.5 % (FWHM)
• Spatial resolution in x – y:	2.4 mm (FWHM)
• Spatial resolution in z:	5.9 mm (FWHM)
• Coincidence interval:	~ 10 ns
• Compton gain:	~ 2

Next steps

- Built first ceramic HPD prototypes
- Continue VATAGP performance tests
- Perform sophisticated simulation studies (EIDALON, H. Zaidi et al.)
- Get feedback from experts (also from industry)
- Hope for funding through FP6 (European union)