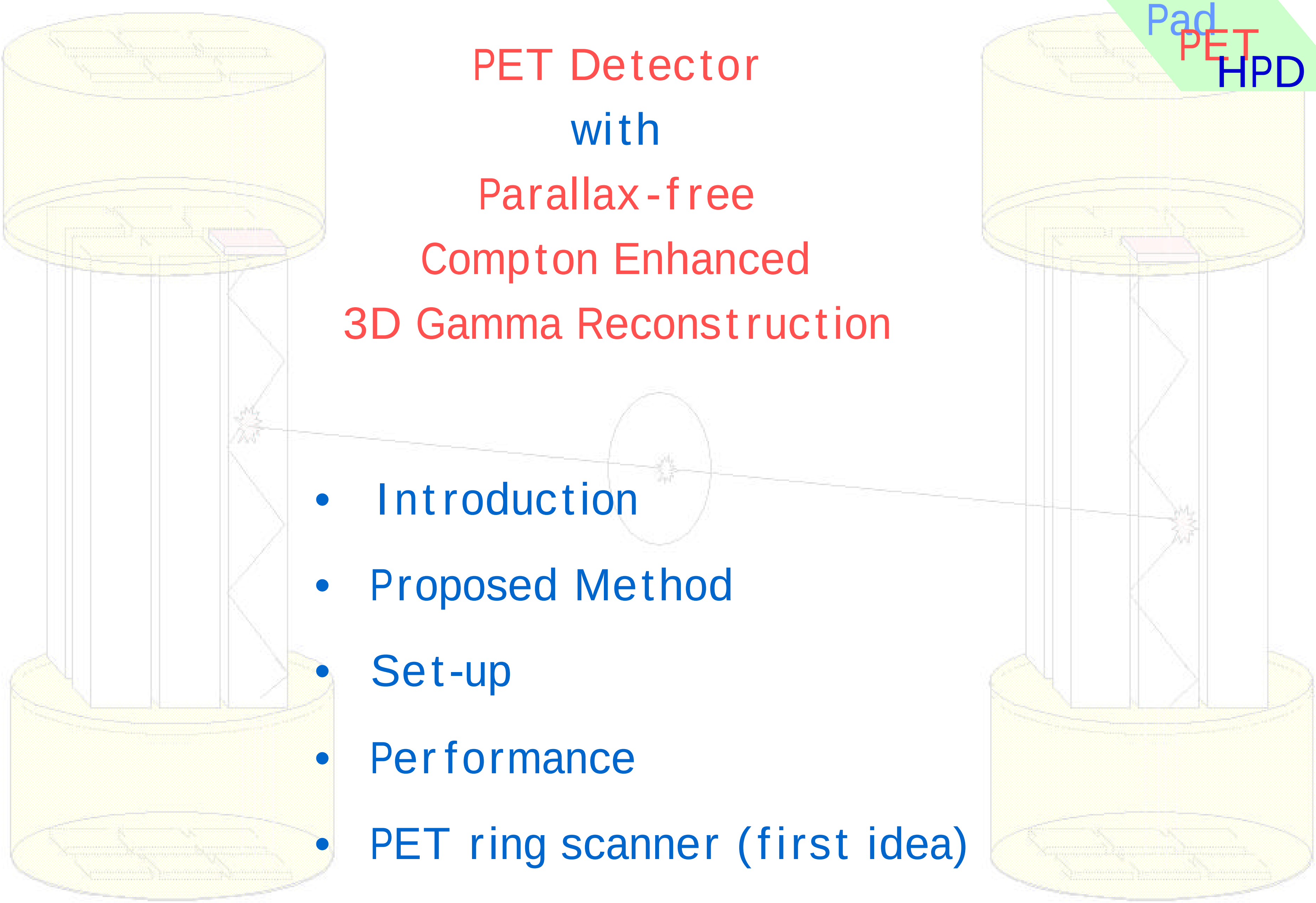
PET Detector
with
Parallax-free
Compton Enhanced
3D Gamma Reconstruction

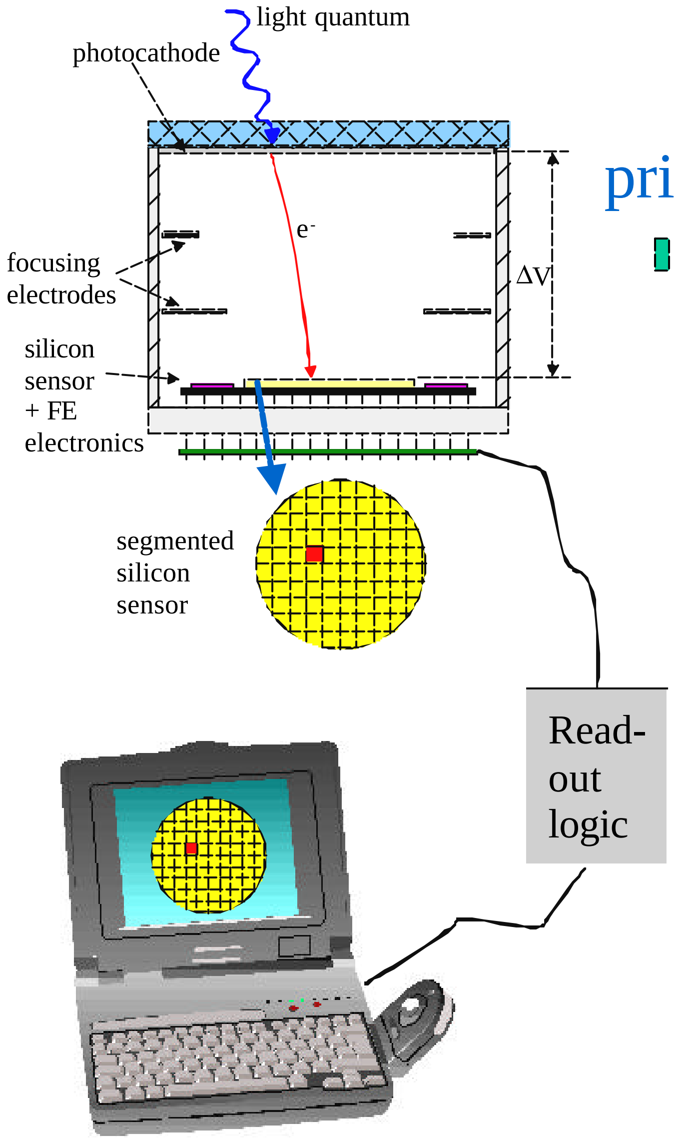


- Introduction
- Proposed Method
- Set-up
- Performance
- PET ring scanner (first idea)

Motivation

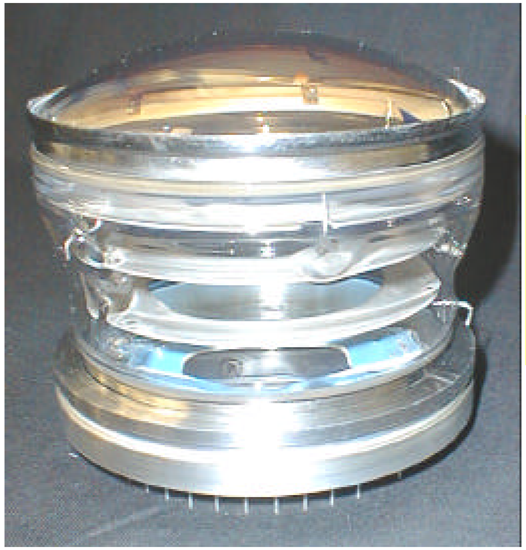
- Existing PET scanners are limited in resolution, sensitivity, rate. Limitations are partly due to
  - parallax error, no DOI information
  - coarse segmentation
- Apply expertise and experience, gained in development of HPDs for particle physics (e.g. LHCb) to medical imaging
- Apply expertise and experience, gained in development of electronics for particle physics, to the medical field in general

Primer I: Hybrid Photodiode (HPD)



principle

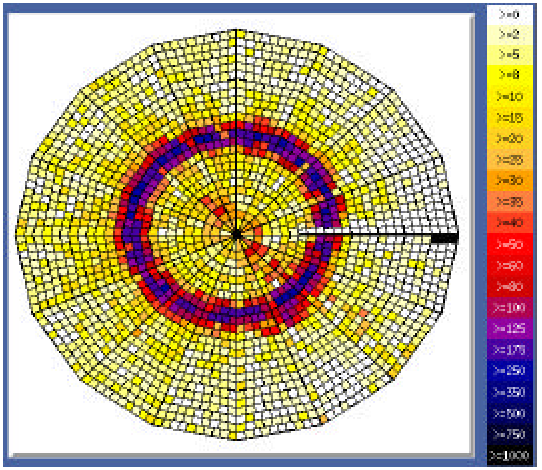
real device



Pad HPD 127mm Ø

Developed and built @ CERN

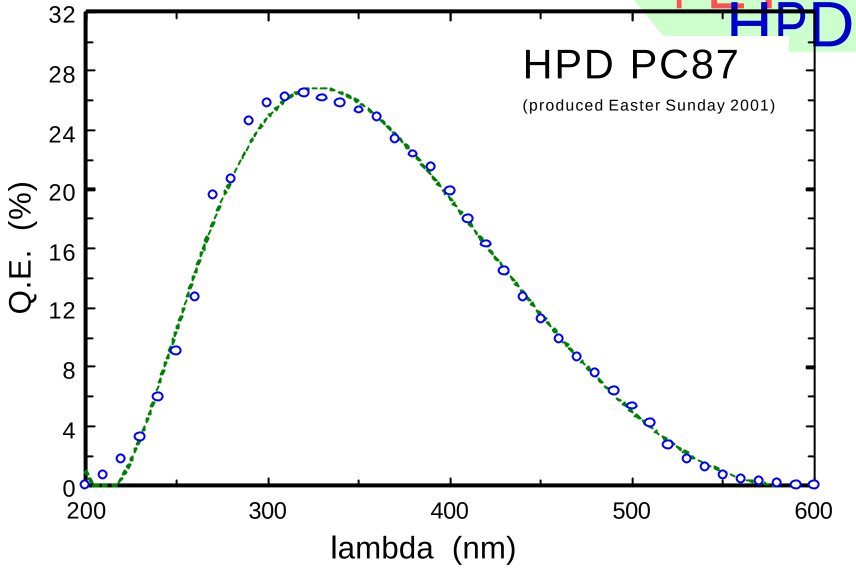
Single photon imaging with 2048 channels



Primer II: HPD performance

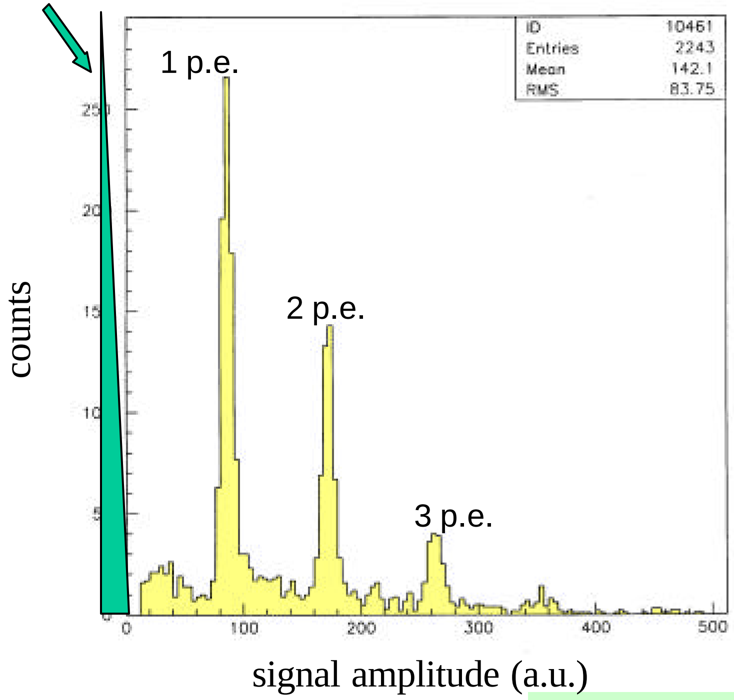
HPD combines single photon sensitivity of PMT with spatial and energy resolution of silicon sensor.

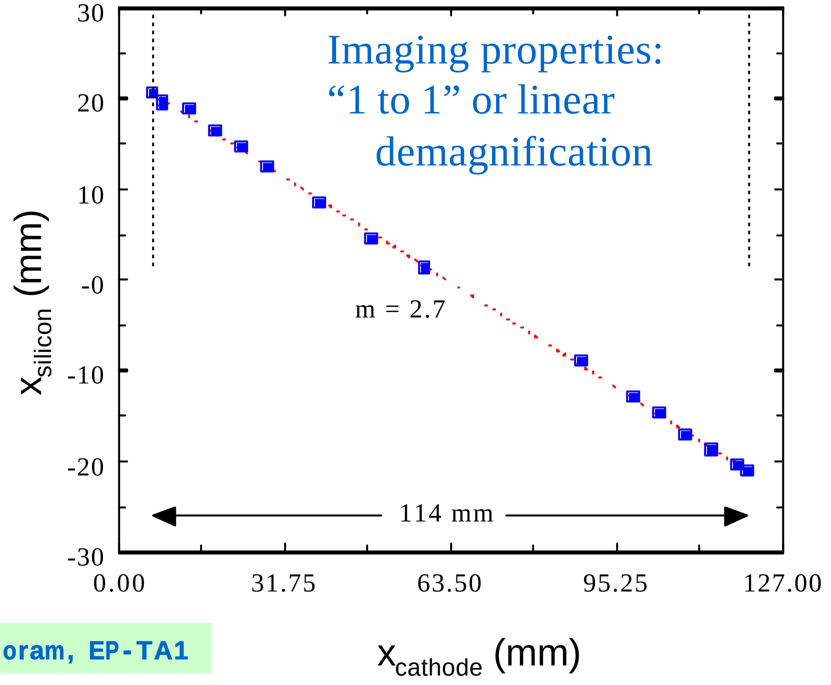
Sensitivity like classical PMT



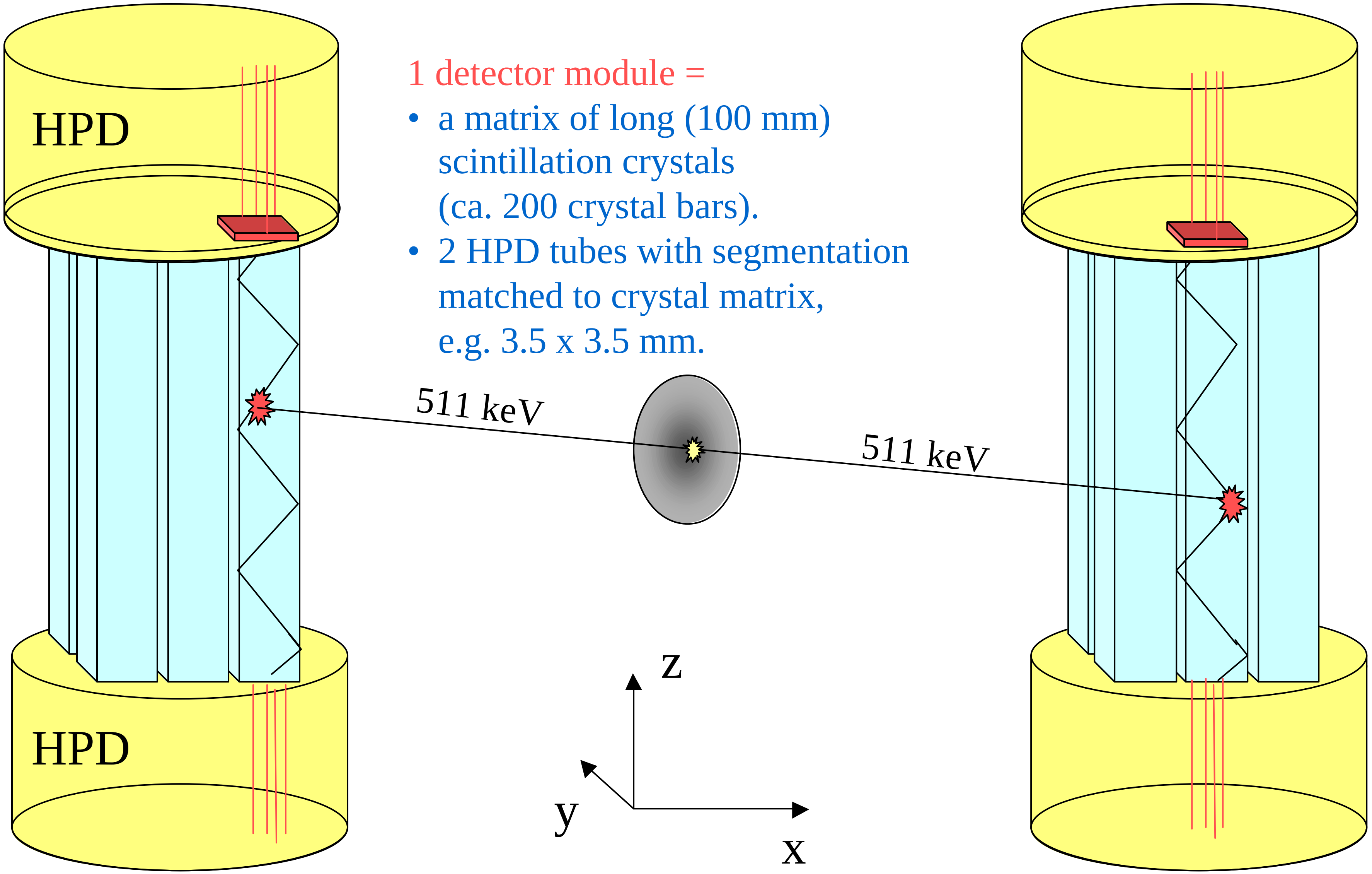
Signal definition and energy resolution

Electronics noise well separated from signal




Imaging properties: “1 to 1” or linear demagnification

A novel concept for a 3D parallax free PET camera module



1 detector module =

- a matrix of long (100 mm) scintillation crystals (ca. 200 crystal bars).
- 2 HPD tubes with segmentation matched to crystal matrix, e.g. 3.5 x 3.5 mm.

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

- Good energy, spatial and temporal resolution

- Reduced random coincidence rate due to fine granularity

- Large FOV (in particular in the axial coordinate). Full body scanner

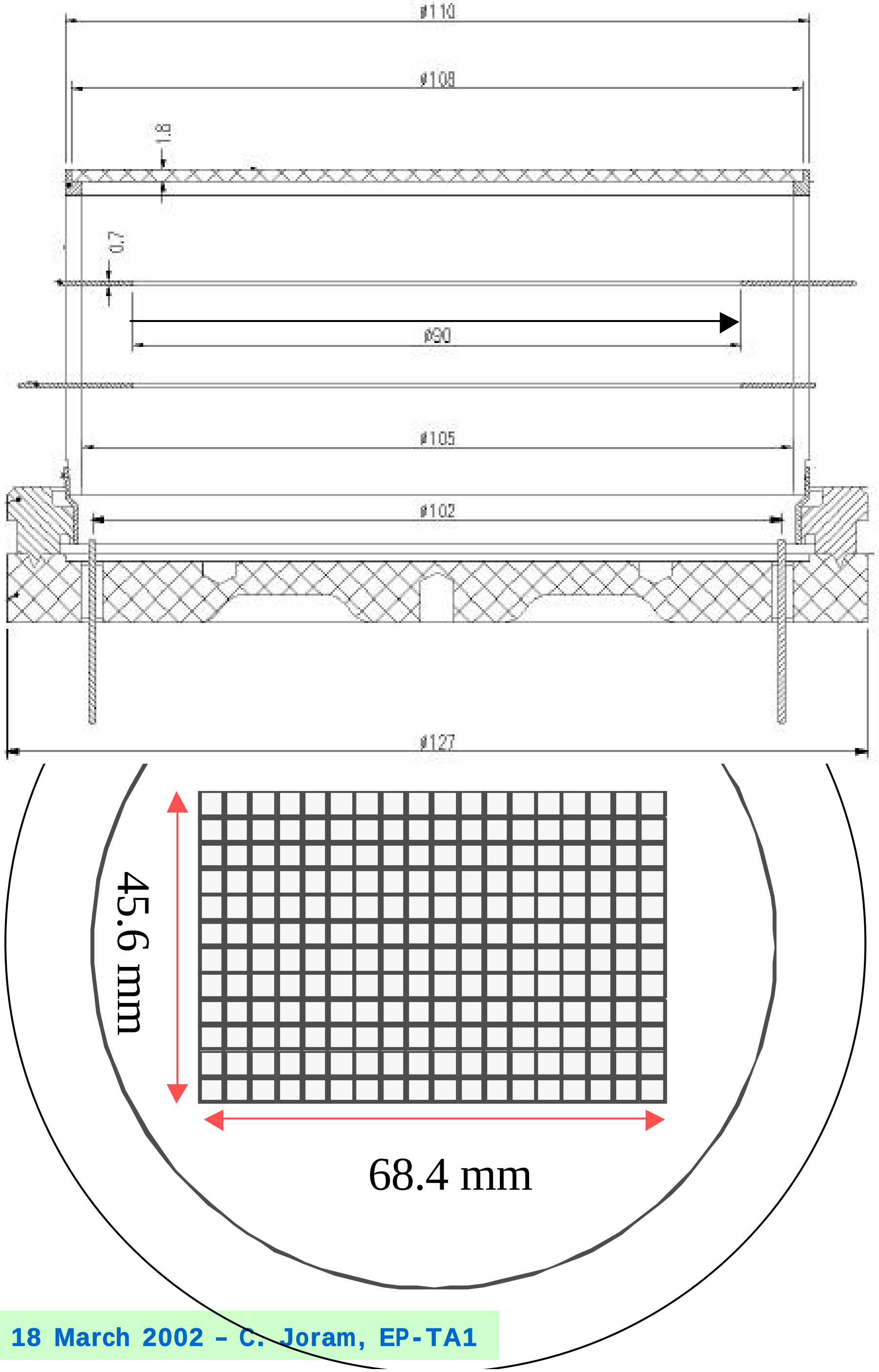
- Possibility of using γ's which underwent Compton scattering in the detectors
  ➔ Compton enhanced sensitivity

The (Pad) PET HPD

possible prototype design

- 127 mm Ø
- Proximity focused
- Bialkali photocathode
- Ceramic body
- Sapphire window
- QE(370 nm) ≈ 25%
- $U_C \approx 12$ kV
- Gain ≈ 3000

- Sil. Sensor 12 x 18 pads
- 3.8 x 3.8 mm^2
- 2 VaTagp3 chips
- Self triggering
- Chips encapsulated in vacuum envelope



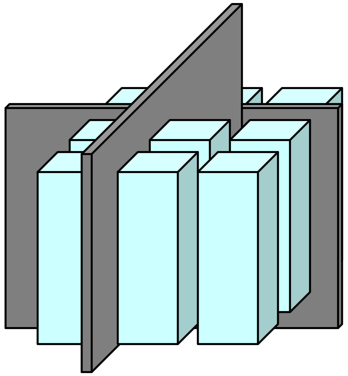
Scintillation crystals

- 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. However LSO and LuAP are also very interesting candidates.

Properties of YAP:Ce

Density r (g/cm^3)	5.55
Effective atomic charge Z	32
Scintillation light output (photons / MeV)	18000
Wavelength of max. emission (nm)	370
Refractive index n at 370 nm	1.94
Bulk light absorption length L_a (cm) at 370 nm	14
Principal decay time (ns)	27
γ attenuation length at 511 keV (mm)	22.4
γ absorption length at 511 keV (mm)	60.5

Principle of crystal matrix



Stainless steel wires define precise spacing of crystals.
Black paper for light shielding.

Light propagates by total internal reflection.
24 % transport efficiency/side.

- YAP may be a good candidate for demonstration of principle, however suffers from low Z (high absorption length, low photo fraction)
- LuAP may be the final choice once it is available in quantities and appropriate dimensions.

Performance

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

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

$$N_{rec} = 553 \cdot \left(e^{-\frac{z}{L_a}} + e^{-\frac{L-z}{L_a}} \right)$$

$$N_{rec} = 823 - 9.8 \cdot z \quad 0 \leq z(cm) \leq 5$$

N_{rec} = 823 at z=0, 774 at z =5 cm

- Energy resolution

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

R_{Sci} → 2.5 % R_{noise} → negligible

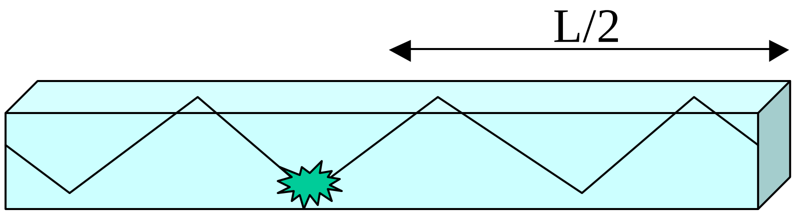
$$R \approx R_{stat} = \frac{2.35}{\sqrt{N_{rec}}} \approx 8.5\% \cdot \sqrt{\frac{511}{E_g\,(\mathrm{keV})}}$$

R ≈ 8.6 - 8.8% (FWHM) at E_γ = 511 keV

≈ 19% at 100 keV

- Reconstruction of the interaction point

x-y: $s_x = s_y = \frac{1}{\sqrt{12}} s$ ≈ 2.4 mm (FWHM)



z: $z = \frac{L}{2} A_Q \qquad A_Q = \frac{Q_R - Q_L}{Q_R + Q_L}$

$$s_z = \frac{L}{Q^2}\left(Q_L s_{Q_R} \oplus Q_R s_{Q_L}\right) \qquad Q = Q_R + Q_L$$

$$s_{Q_{R,L}} = \sqrt{N_{rec_{R,L}}}$$

s_z/L = 1.8 % in the middle of the crystal (z = 5 cm)
s_z/L = 1.7 % at the ends

L = 10 cm, E = 511 keV s_z = 1.75 mm → 4.1 mm (FWHM)
E = 100 keV → ≈ 9 mm (FWHM)

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: $t_{peak}^{slow} = 3\ \mu s$, $t_{peak}^{fast} = 150$ ns

Future chip, optimised for PET: $t_{peak}^{slow} = 1\ \mu s$, $t_{peak}^{fast} = 35$ ns

- pedestal noise spread $\sigma = 300\ e^-$ (ENC)
- Threshold of fast trigger: 15,000 e^- (= 5 photons = 6.4 keV)
- Maximum signal: 1,200,000 e^- (= 400 photons = 511 keV)
- Dynamic range: 80

Timewalk: < 3.5 ns for signals between 50 and 500 keV

Coincidence time: 10 ns (monostable)

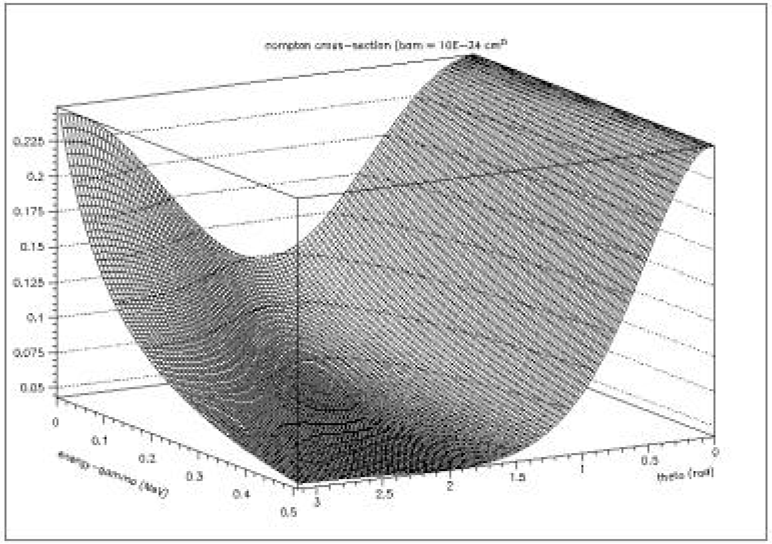
Compton enhanced reconstruction

Pad PET HPD

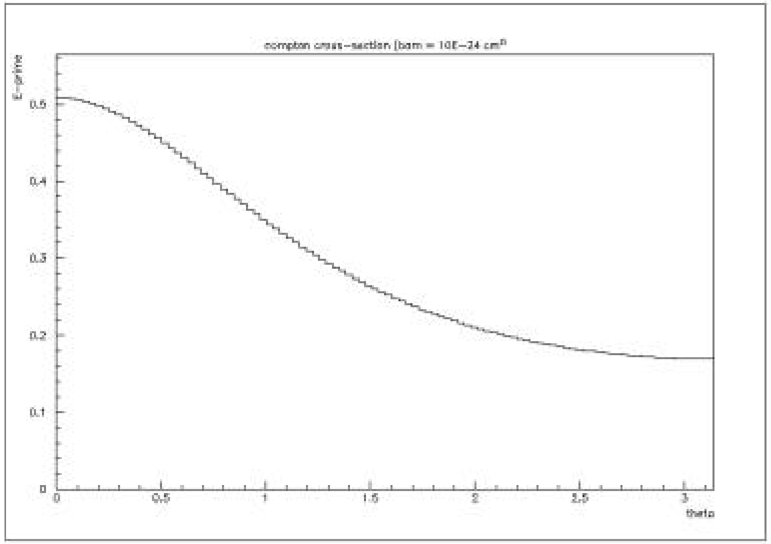
Problem: Photofraction in YAP:Ce (Z=32) is relatively low $\varepsilon_{\gamma}^{photo} = 4\%$

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

- 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



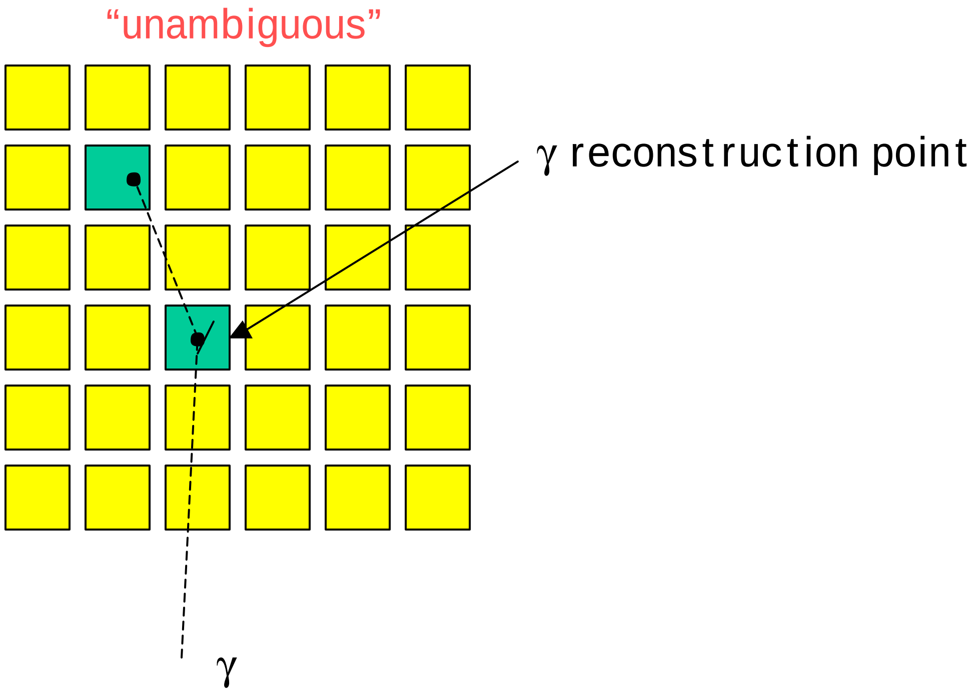
Compton kinematics E' vs θ

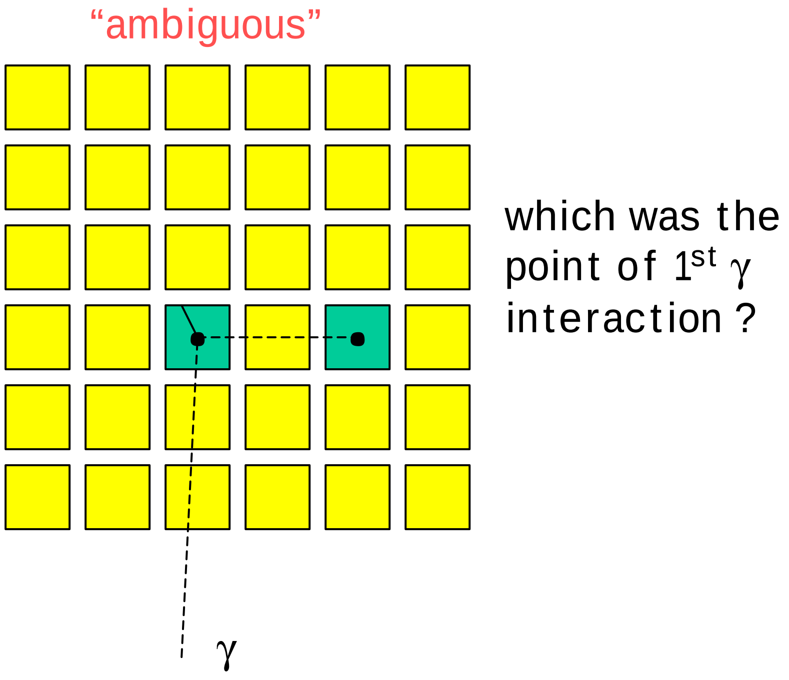
Scattering angle is known if energy deposit of Compton electron can be measured.

Classical low energy limit: $\sigma_{Thomson}$

$$\sigma = \tfrac{8}{3}\pi r_e^2 = 0.665\,\mathrm{barn/electron}$$

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





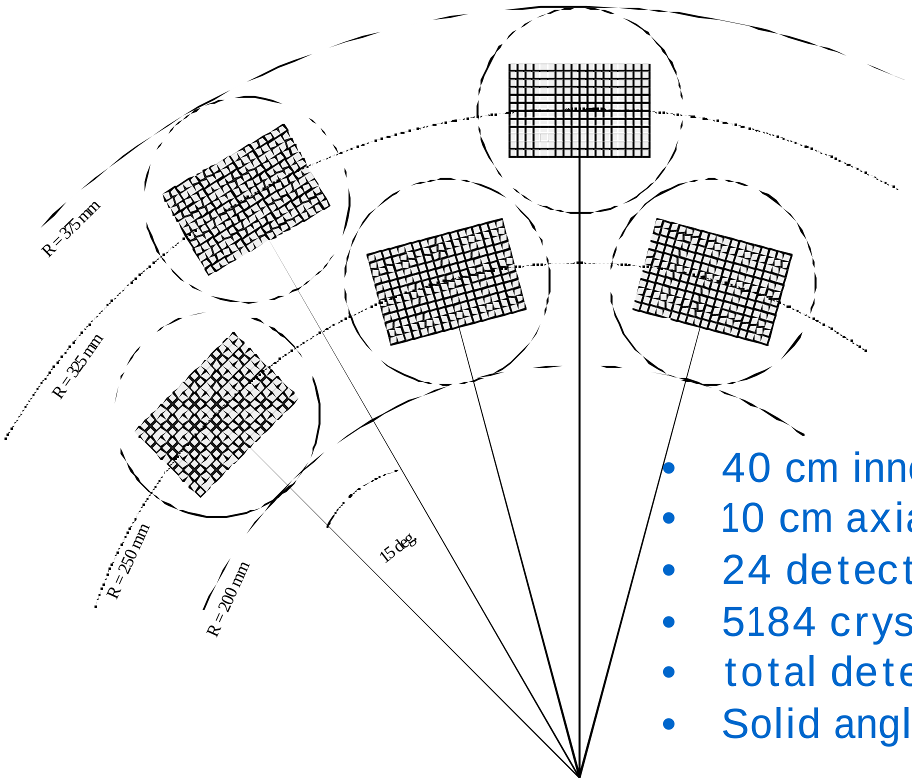
which was the point of 1st γ interaction ?

- ➔ 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

These conditions are fulfilled for at least ≈ 60% of all events (to be verified by M.C. studies). Events with double Compton scattering have to be rejected.

Coincidence detection probability increases from 0.16% to 0.4% (gain = 2.5)

A PET ring scanner (full body PET)



- 40 cm inner diameter
- 10 cm axial length
- 24 detector modules, read out by 48 HPD detectors
- 5184 crystals
- total detection volume: 6350 cm^3
- Solid angle per module: 0.87% of 4π

- Maximum source activity, assuming 1% random coincidences between 2 blocks: 57 MBq = 1.55 mCi

Summary of performance estimates (for YAP:Ce crystals)

• Detected photoelectrons for a γ of 511 keV:	390 – 410 per HPD
• Energy resolution:	8.6 – 8.8 % (FWHM)
• Spatial resolution in x – y:	2.4 mm (FWHM)
• Spatial resolution in z:	4 mm (FWHM)
• Coincidence interval:	ca. 10 ns
• Compton enhancement of detection efficiency:	ca. 2.5

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Very interested potential collaborators
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