Low-Dose Total-Body Time-of-Flight PET Using High-Resolution Gamma Ray Multiplier Tubes

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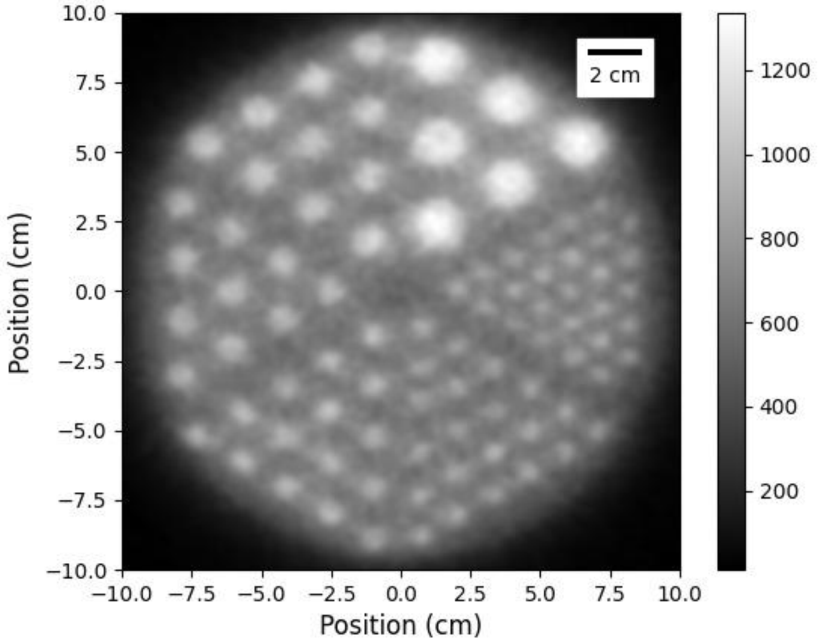
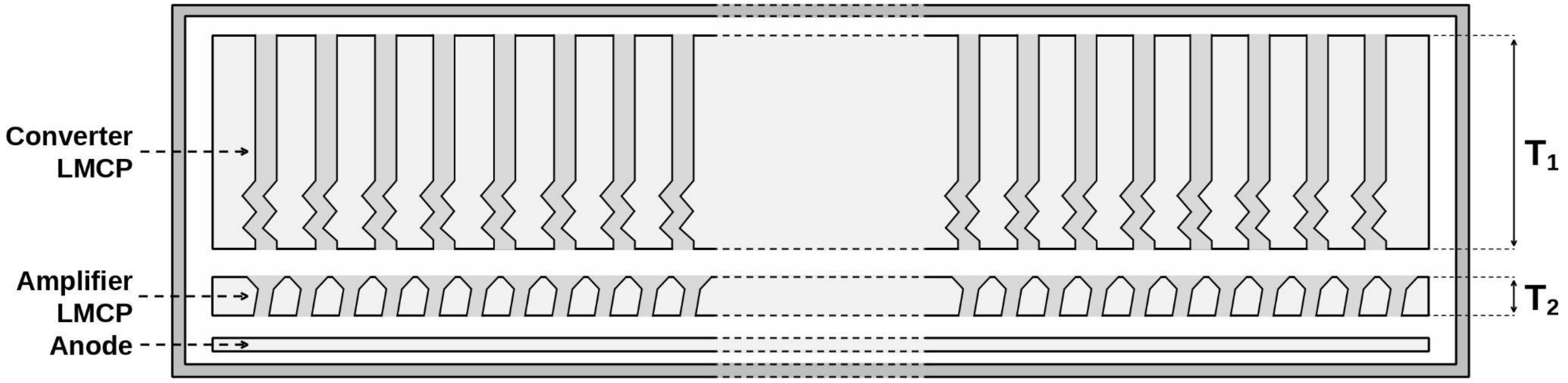
Overview

1. Hi-res gamma ray multiplier tube ($HGMT^{TM}$): low-dose TOF-PET with no scintillators or photocathodes
2. Surface direct conversion and the laminar microchannel plate ($LMCP^{TM}$)
3. TOPAS and Geant4 simulations of HGMT-based TOF-PET
4. Next steps in simulation and manufacturing



Derenzo brain phantom at 1/100th dose, using a TOPAS-simulated Pb-glass HGMT scanner

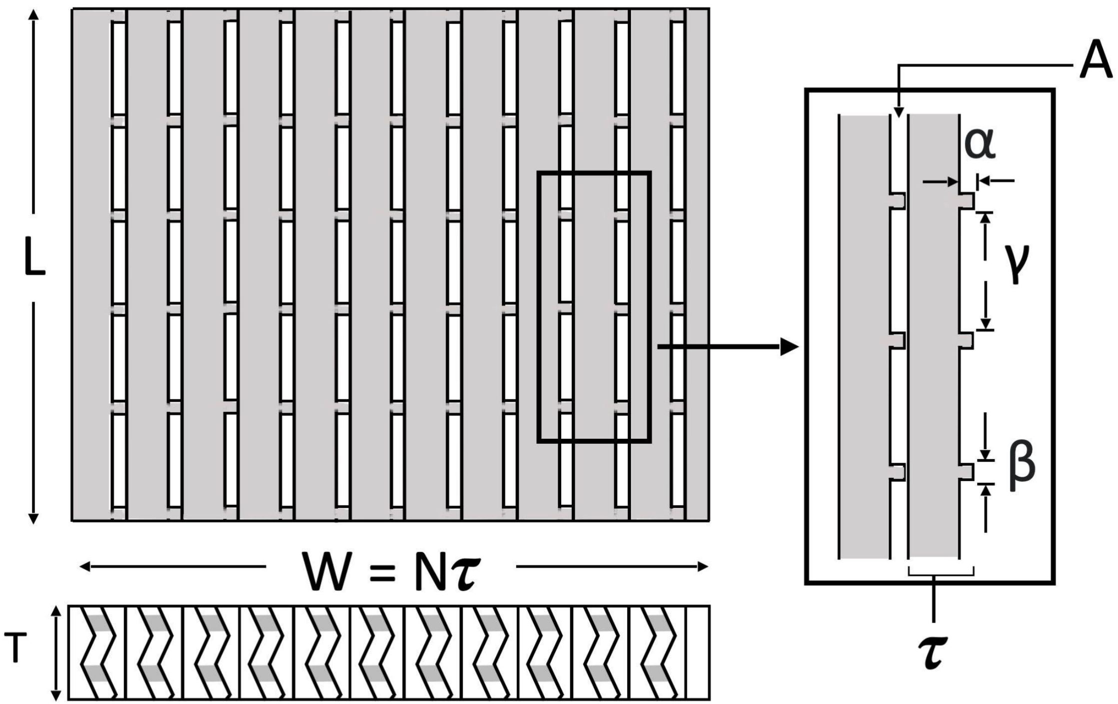
High-resolution Gamma Ray Multiplier Tubes (HGMTs)



- Package of a) converter laminar microchannel plate (LMCP), b) amplifier LMCP, and c) anode
- Electron cascade in the MCPs produced via surface direct conversion of an incident gamma ray
- No scintillators/photocathode

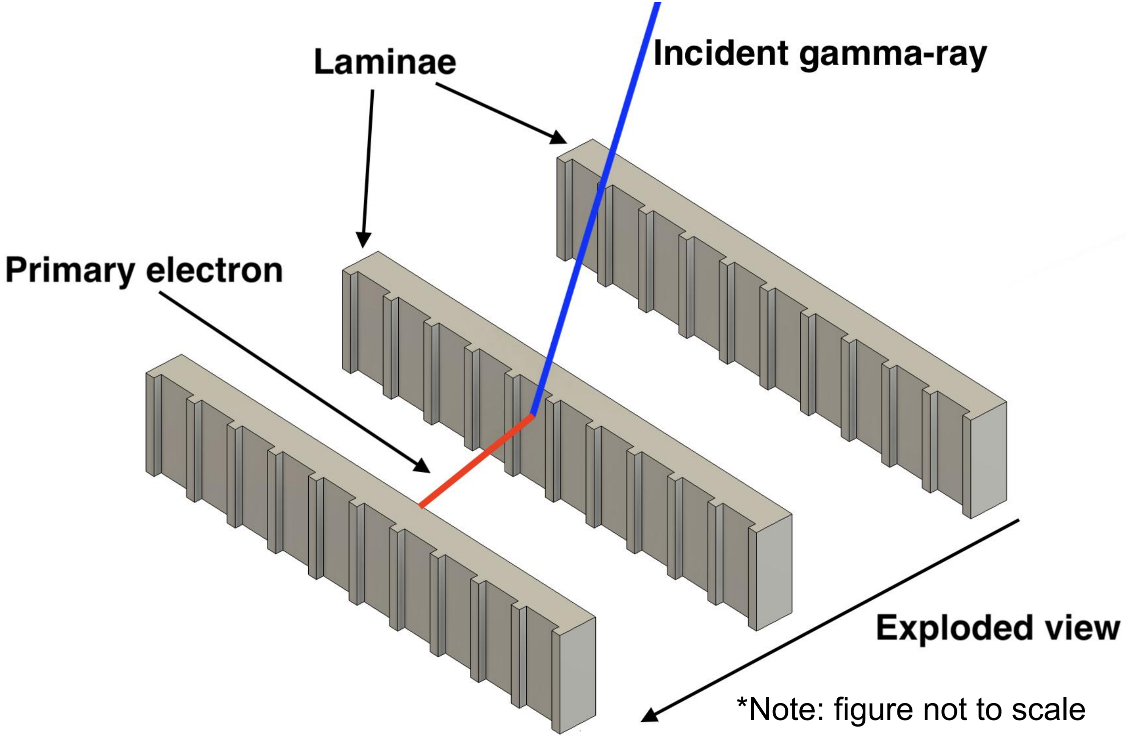
Laminar Microchannel Plates (LMCPs)

- LMCPs ≡ thin patterned laminae stacked to form microchannels
- Advantages of the laminar method (compared to drawn glass capillary MCPs):
  - Access to pore surfaces
  - New secondary coatings
  - Non-uniform voltage distributions
  - Complex channel geometries
- Different manufacturing approach, but laminar method still produces MCP-PMTs



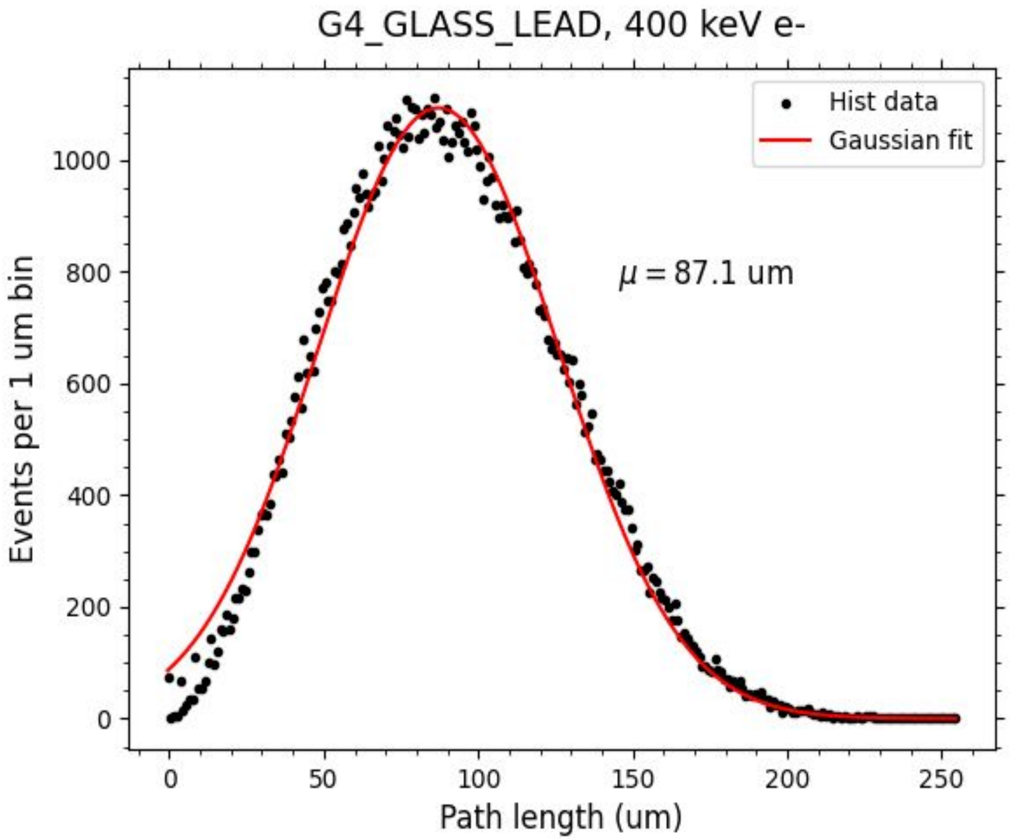
Surface Direct Conversion

- High energy photons interact via Compton or photoelectric effect -> producing an electron that escapes pore wall and creates cascade in pore
- Photon must be of a) of sufficient energy to produce an electron that can escape pore wall b) close enough to a pore wall for it to escape



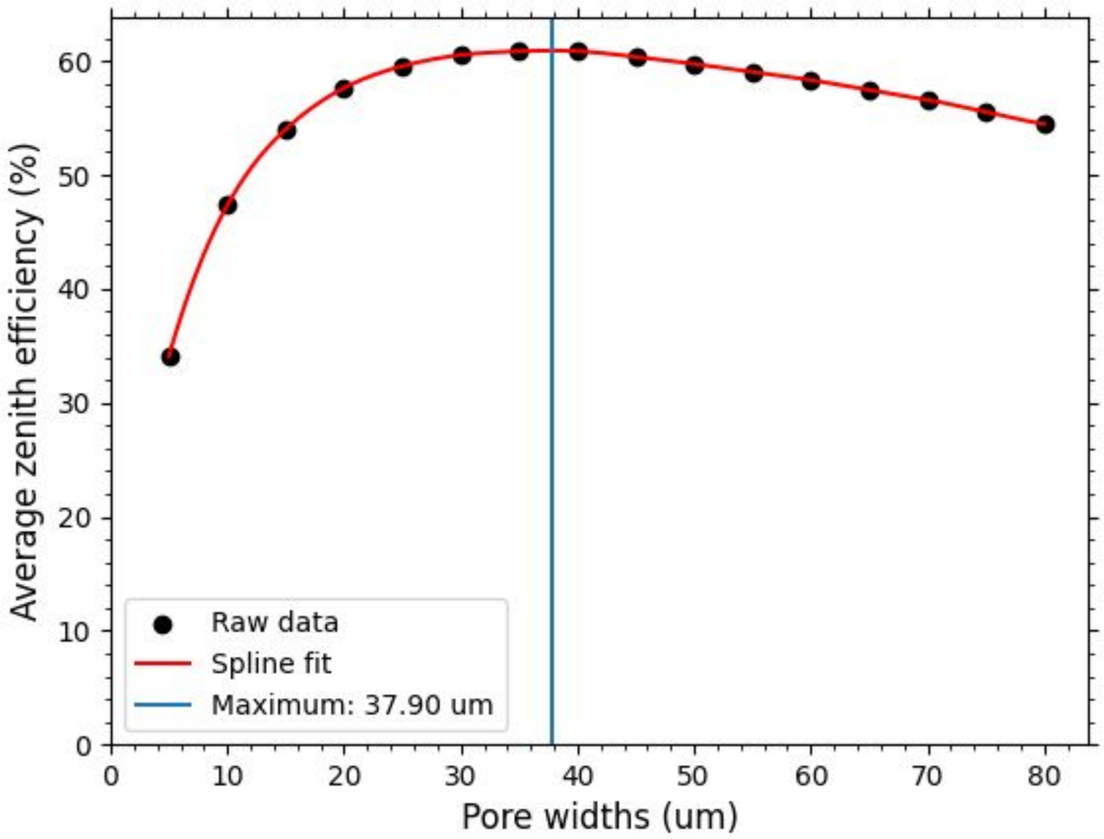
Maximum Feature Size for Surface Direct Conversion

- <u>"Surface" component is important</u>: 400 keV primary electrons travel ~90 um (in Geant4 simulation of NIST lead glass).
- Feature size for a given material must be on order of the mean path length traveled by ~400 keV electrons, lower preferred
- Chose 50 um for PET simulations



Optimizing Pore Width

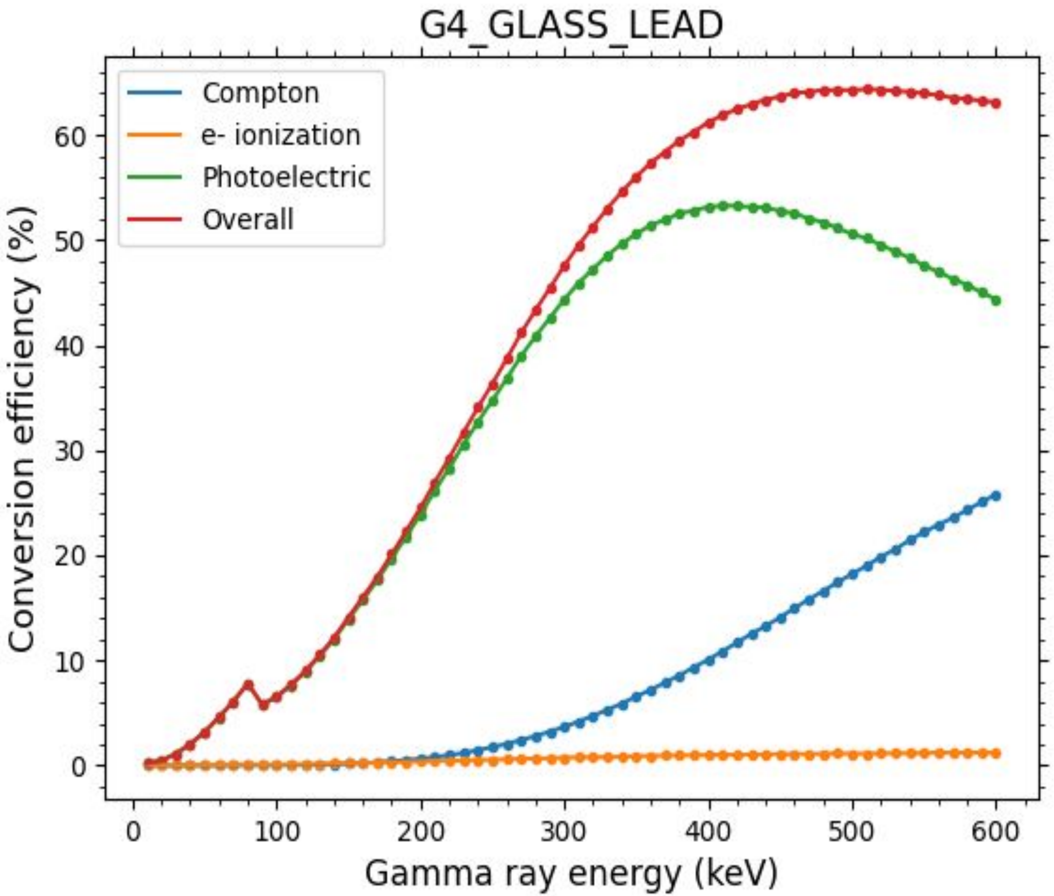
- Conversion efficiency ≡ fraction of gamma rays that produce primary electrons that traverse a pore wall
  - Still researching efficiency of primary e- to secondary e-
- Competing processes: substrate per unit volume vs. surface area to volume ratio
- Chose 50 um pore width for PET simulation
- Flatter maximum -> can afford to use slightly narrower or wider pores



Geant4 simulation of 1-in thick NIST lead glass LMCP with square pores and 50 um wall thickness

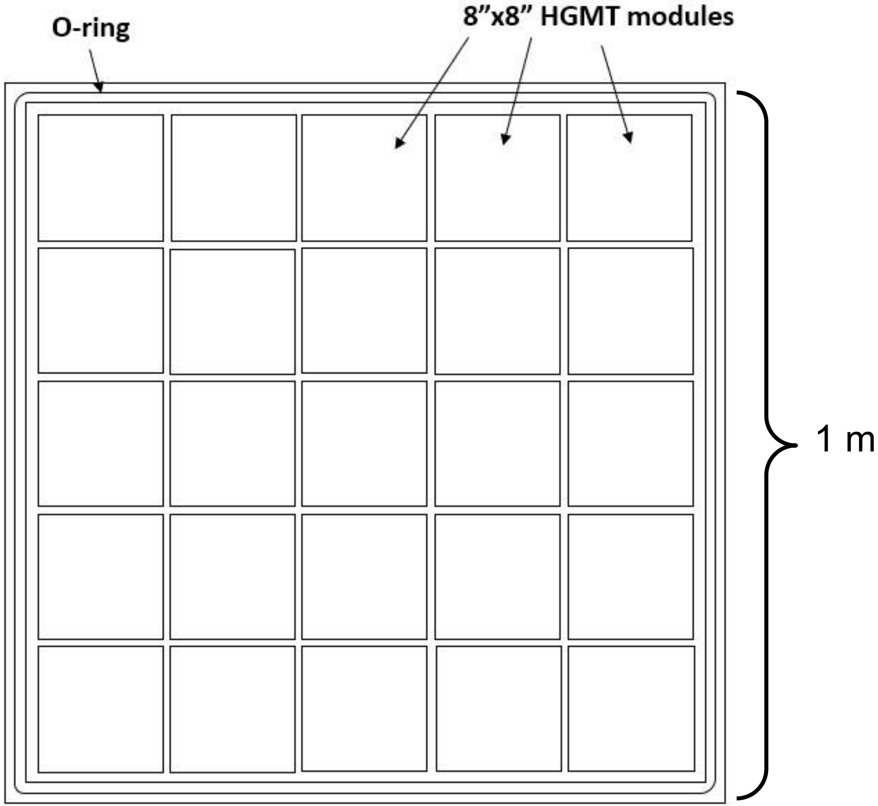
Gamma Detection Efficiency and Relative Interactions

- Geant4 simulation, 50 um square pores, 100 um laminae, NIST Pb-glass
- Conversion efficiency includes effects from interaction cross sections and geometry
- LMCP material can select for certain interactions in the substrate (Compton vs. photoelectric)

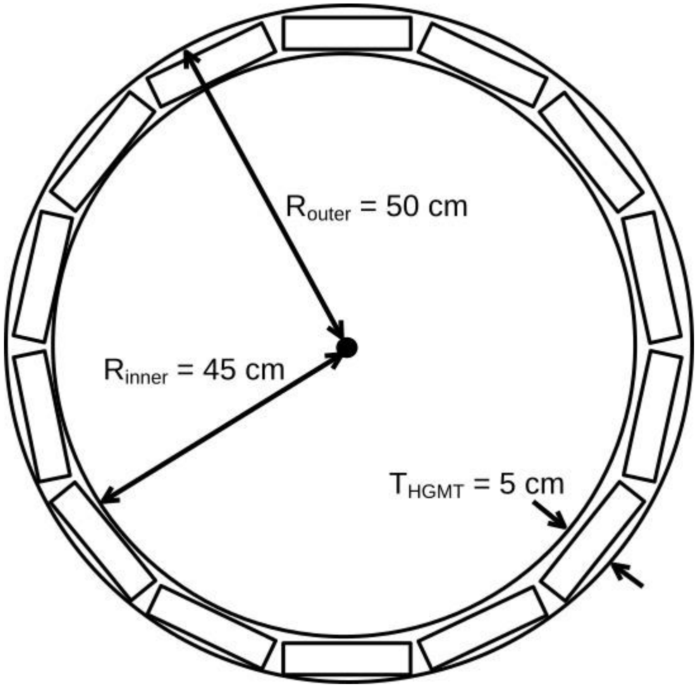


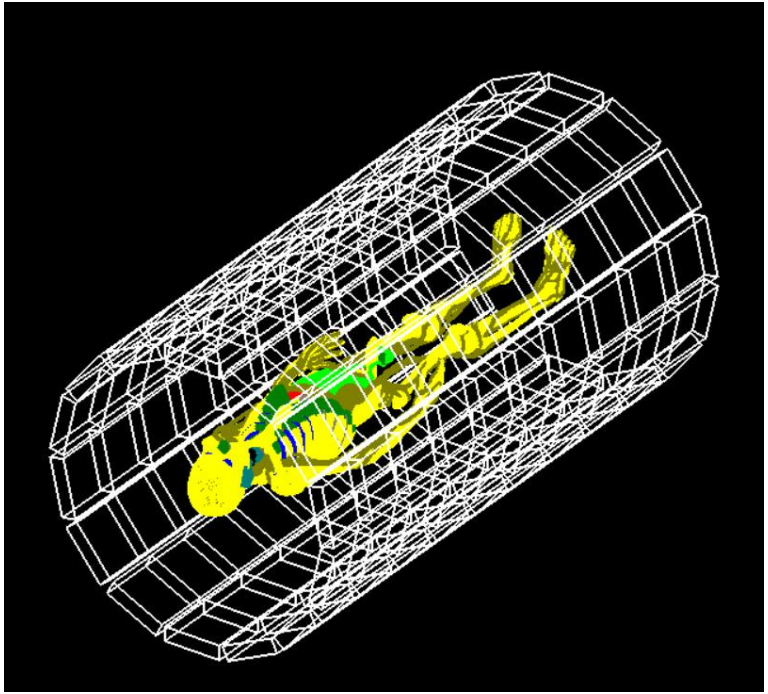
HGMT Mechanical Configuration

- Surface direct conversion means no photocathode
- No photocathode eliminates need for ultra-high vacuum and permanent seal (can assemble in air)
- $20 \times 20 \times 5$ cm^3 (wide dimensions same as LAPPDs)
- Can package multiple HGMTs in a single enclosure, like 5-by-5 array to the right



TOPAS Simulations of HGMT-based PET

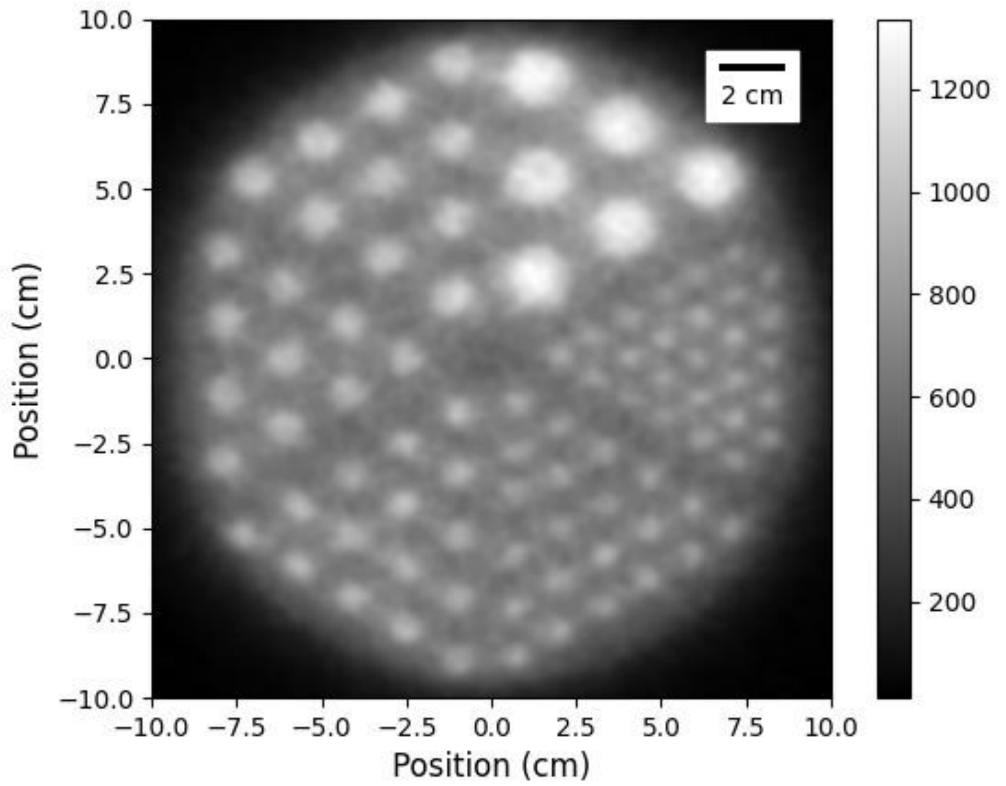




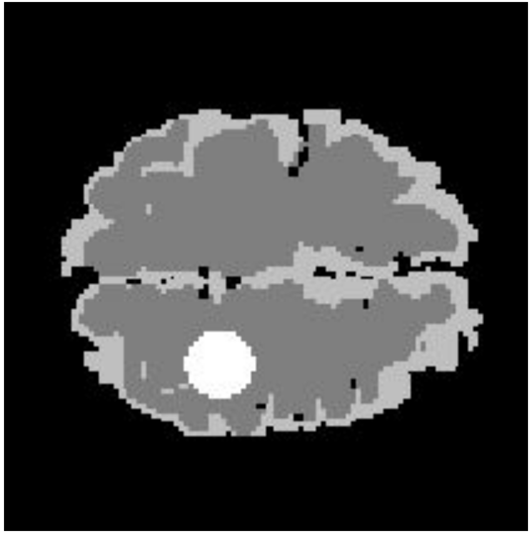
- XCAT phantom in the detector from TOPAS: 2 m long, 45 cm bore radius, 5 cm thick
- HGMTs shown are rectangular, but can curved, non-planar, or with varying thickness
- Directionality of pores can vary with position

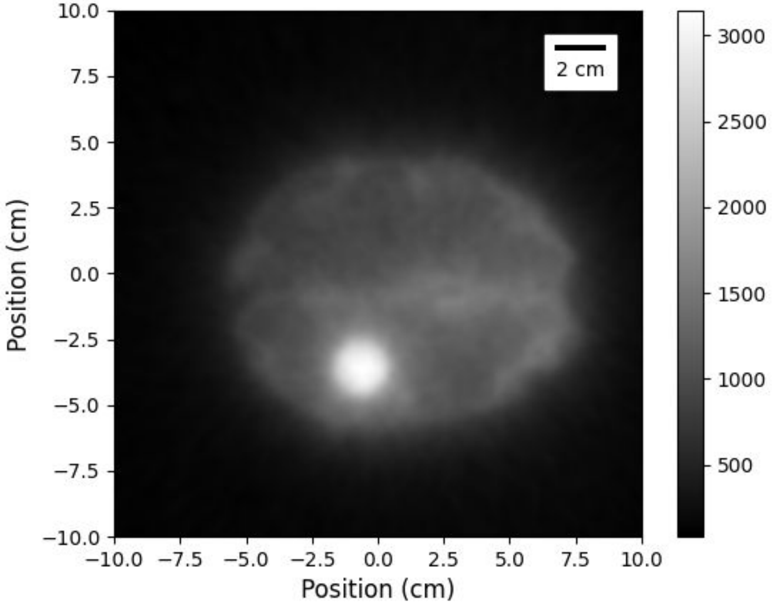
TOPAS Simulations of HGMT-based PET: Derenzo

- Image reconstruction: direct summation of LORs. No filtered back-projection, denoising, other methods.
- 1/100th dose, full dose is 10 min, 5 kBq/mL (background), 15 kBq/mL (rods)
- 100 ps FWHM timing resolution, 1 mm sigma spatial resolution, 50 um pores and wall thickness
- Smallest rods of r=3.2 mm clearly visible



TOPAS Simulations of HGMT-based PET: XCAT Brain

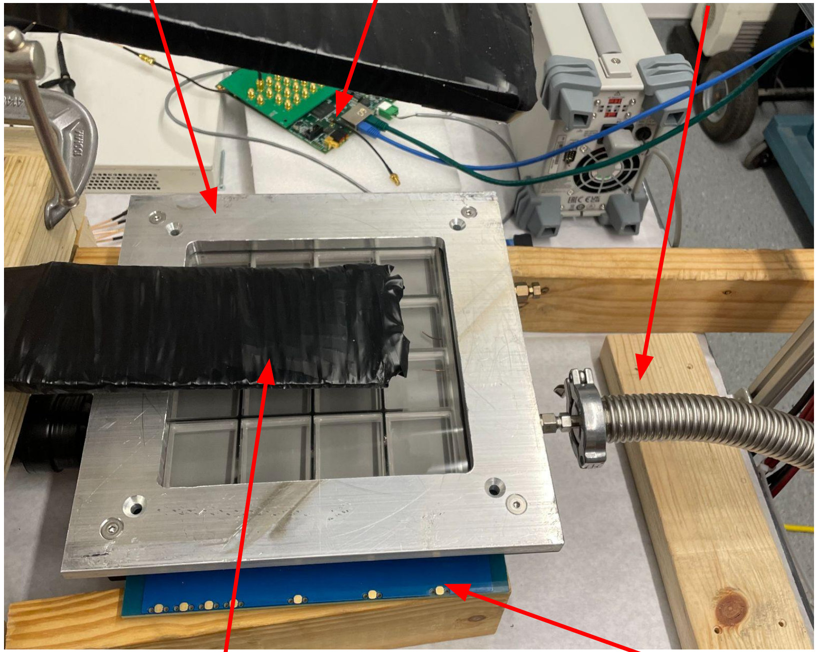




- Left: cross section of the XCAT brain
- Right: cross section of the XCAT brain imaged by the HGMT scanner in TOPAS
    - 1/100th dose, compared to benchmark 10 min, 8.25 kBq/mL (white matter), 33 kBq/mL (gray matter), 99 kBq/mL (lesion) - Hoffman brain activities
    - 100 ps FWHM timing resolution, 1 mm sigma spatial resolution, 50 um pores and wall thickness
    - 2-cm diameter lesion is unmistakable at 1/100th dose -> enables cancer screening and early detection in under-served populations at low-dose

Status of LMCP Manufacturing, Simulation

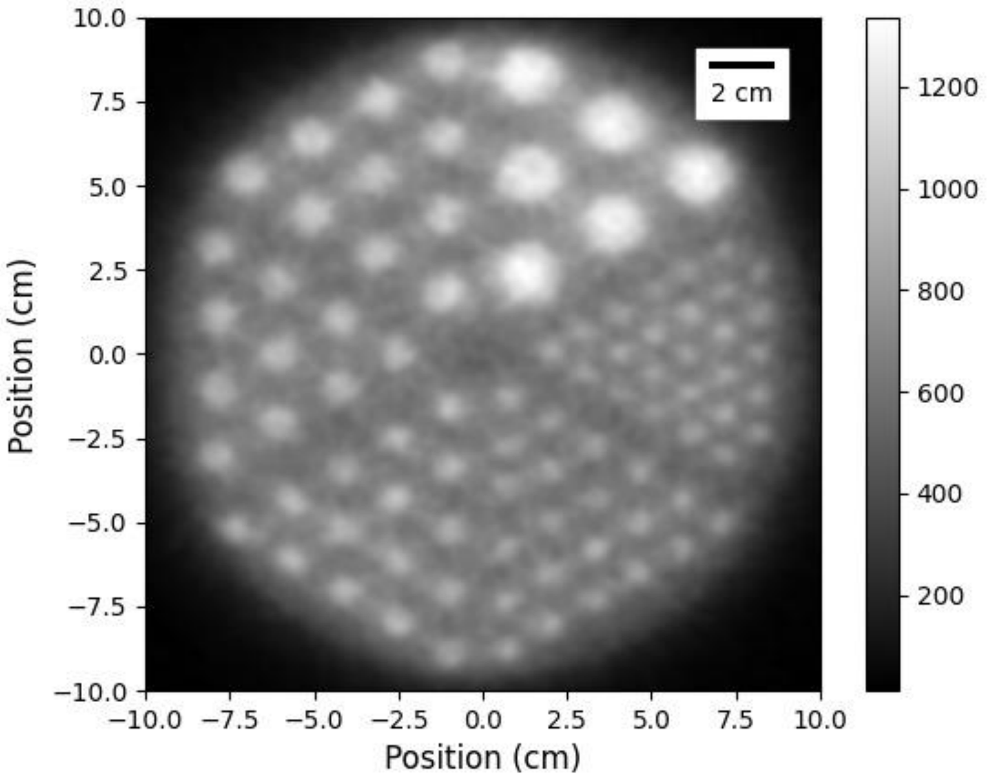
- Working with glass vendors, 3D printing
- Preliminary test setup (courtesy P. Scheidt)
- Pumped vacuum enclosure using Pfeiffer multi-purpose leak detector
- Stripline pick-up board, PSEC4 electronics (σ_t = 3.22 ps)
- Customizable enclosure window
    - Beta button sources
    - Gamma ray button sources + thin high-Z plates for direct conversion
- Simulation: characterizing low- vs. high-Z LMCPs, more detector rings



For more about PSEC4 electronics, see [E. Oberla, PhotoDet 2012, vol. 158, 15 Jun 2012.]

Summary

- HGMTs are a type of gamma ray detector that uses surface direct conversion instead of scintillators and photocathodes
- TOPAS simulation results of HGMT-based TOF-PET indicate 100x reduction in dose
- Have begun to find LMCP manufacturers and create a test stand



Thank you

References

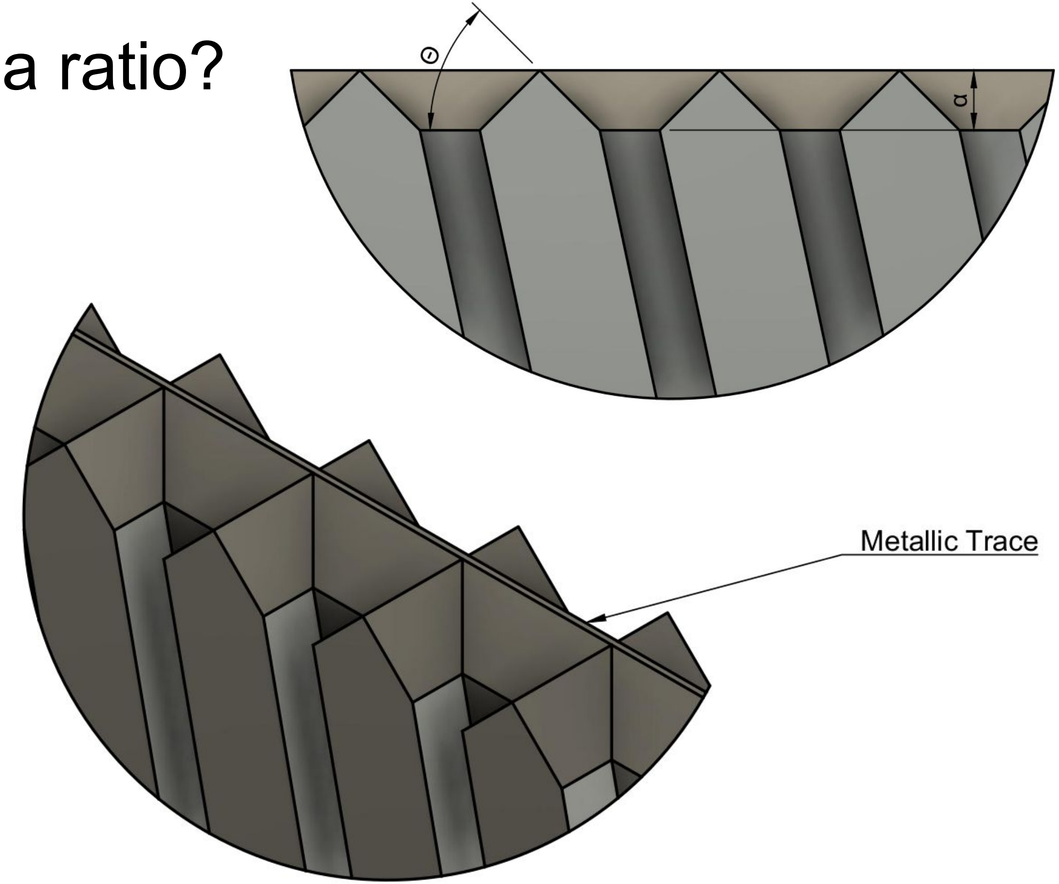
K. Domurat-Sousa, C. Poe, H. J. Frisch, B. W. Adams, C. Ertley, and N. Sullivan. Surface direct conversion of 511 kev gamma rays in large-area laminated multichannel-plate electron multipliers. *Nucl. Instrum. Methods*, 1951055:168538, 2023, https://doi.org/10.1016/j.nima.2023.168538.

K. Domurat-Sousa, C. Poe, H. J. Frisch, B. W. Adams, C. Ertley, and N. Sullivan. Low-dose TOF-PET based on surface electron production in dielectric laminar MCPs. *Nucl. Instrum. Methods*, 1057:168676, 2023, https://doi.org/10.1016/j.nima.2023.168676.

Extra Slides

What about the open-area ratio?

- LMCP assembly easier with thicker walls than conventional glass capillary MCPs
- OAR can increase with funnels
- Figure: square funnels during patterning for a single lamina, 3D printing
- Alternative: machining circular funnels after stacking laminae



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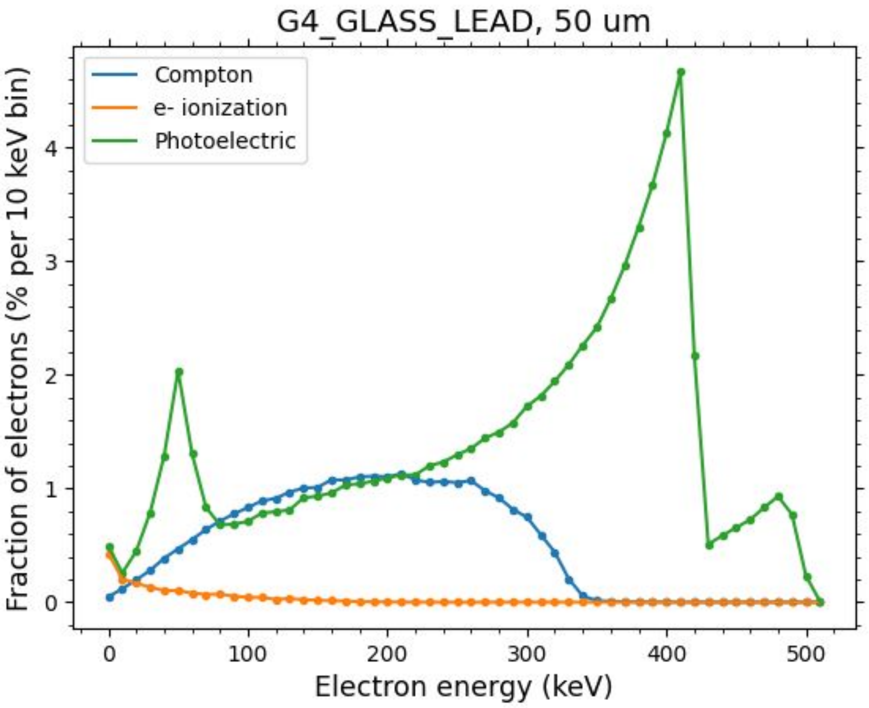
What are the energies of primary electrons?

- Depends on the substrate material
- Low-Z -> predominantly Comptons at 511 keV gamma rays
  - Electron energies < 300 keV
- High-Z -> mix of Compton and photoelectric
  - Electron energies peak at ~450 keV due to K-shell energy loss
- Figure: Geant4 simulation of 1 in^3 NIST lead glass LMCP with 50 um wall/pore width, gamma rays incident at 45 deg from normal



Why remove optical conversion?

- Optical conversion ≡ step between gamma ray and electro cascade where gamma ray is converted into optical photons fo detection at photocathode
- Removing optical conversion improves timing resolution
- For PET, expanding to under-served populations (rural, young, elderly) requires good sensitivity at low dose

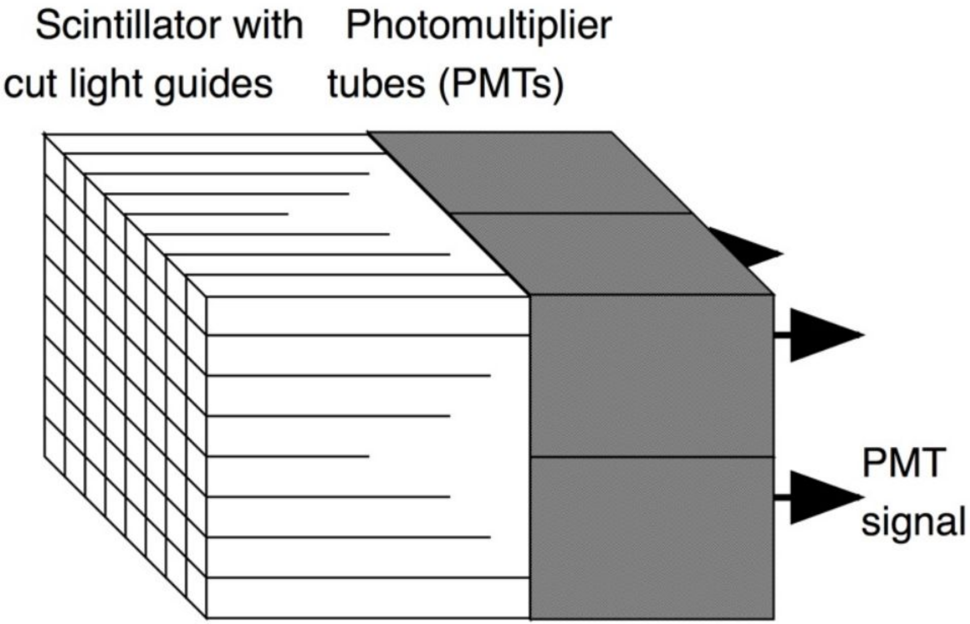
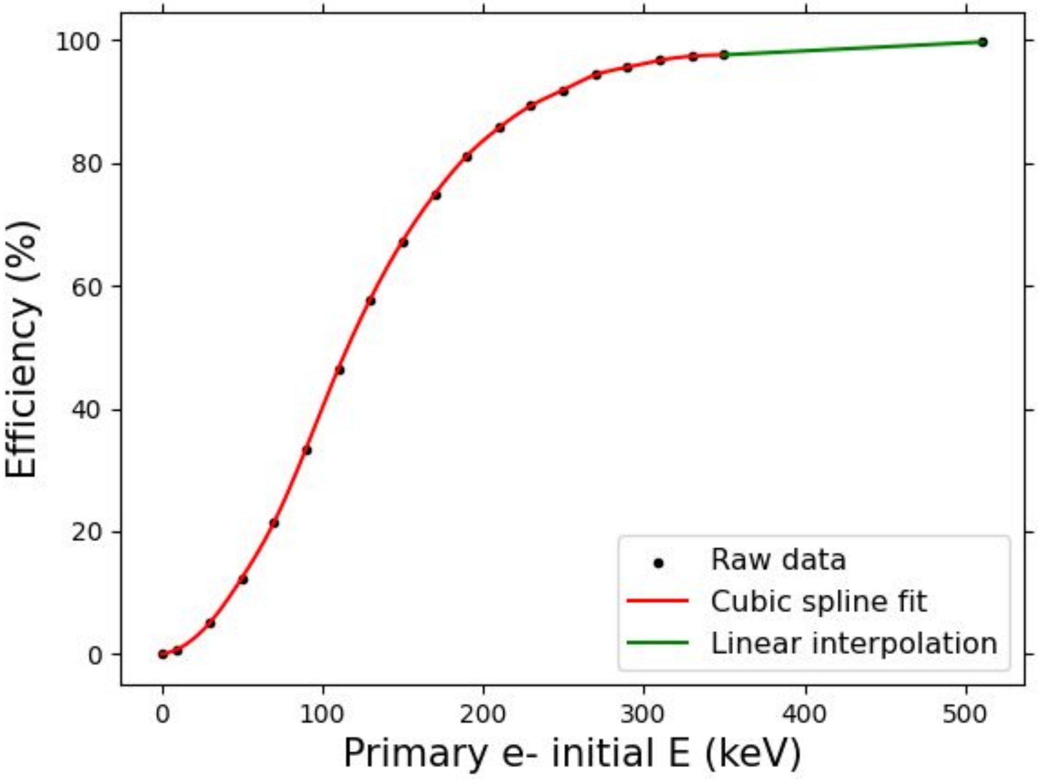


Figure from: R. Schmitz, A. Alessio, P. Kinahan, *The Physics of PET/CT Scanners*, 2013

What is the HGMT energy resolution?

- Still active area of research, simulations have no energy res.
- HGMT geometry preferentially selects 511 keV gamma rays.
- Possibility of IPS rejection via Compton constraints in low-Z HGMTs
- Right: “pore entry” efficiency curve. How likely an electron of a given energy is detected when created by a 511 keV gamma compton scatter



Segmented HGMTs