Low-dose TOF-PET based on Surface Electron Production in Dielectric Laminar MCPs

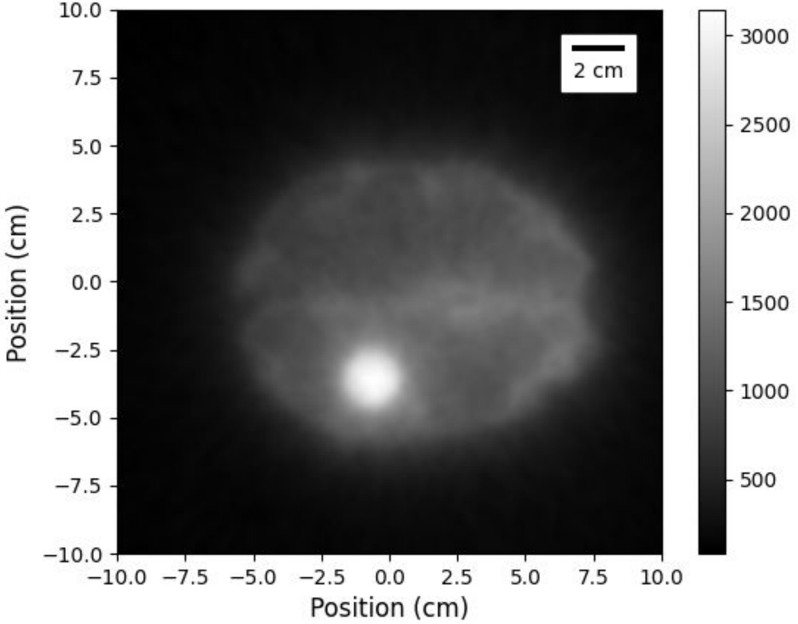
Kepler Domurat-Sousa[1], Cameron Poe[†1], Henry Frisch[1], Bernhard Adams[2], Neal Sullivan[3], Camden Ertley[4]

IEEE Ultra-low-dose PET Workshop, 2023

[†]Presenter
[1]Enrico Fermi Institute, University of Chicago; [2]Quantum Optics Applied Research; [3]Angstrom Research Inc; [4]Southwest Research Institute

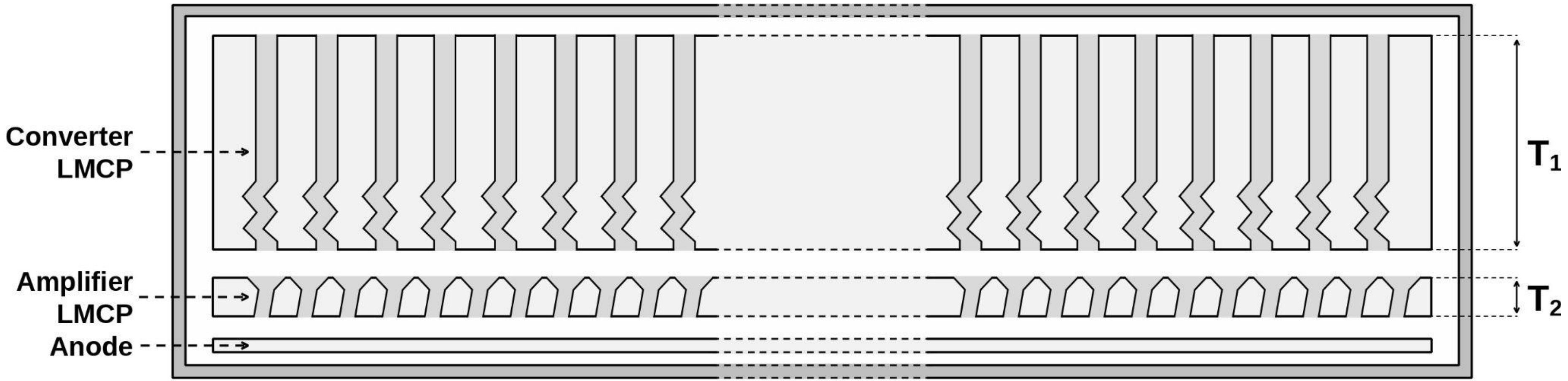
Overview

1. Hi-res gamma ray multiplier tube (HGMT™): low-dose TOF-PET with no scintillator crystals or photocathodes
2. Surface direct conversion and the laminar microchannel plate (LMCP™)
3. TOPAS simulations of HGMT-based TOF-PET
4. Next steps towards manufacturing
5. Questions



XCAT brain phantom at 1/100th dose, using a TOPAS-simulated HMGT scanner

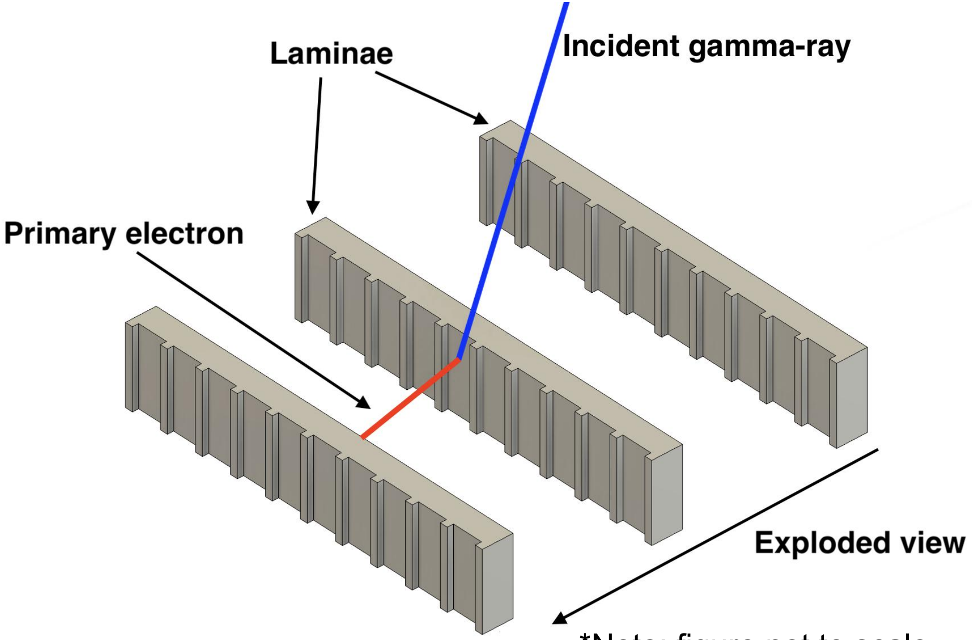
High-resolution Gamma Ray Multiplier Tubes (HGMTs)



- 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 scintillating crystal/photocathode

Surface Direct Conversion

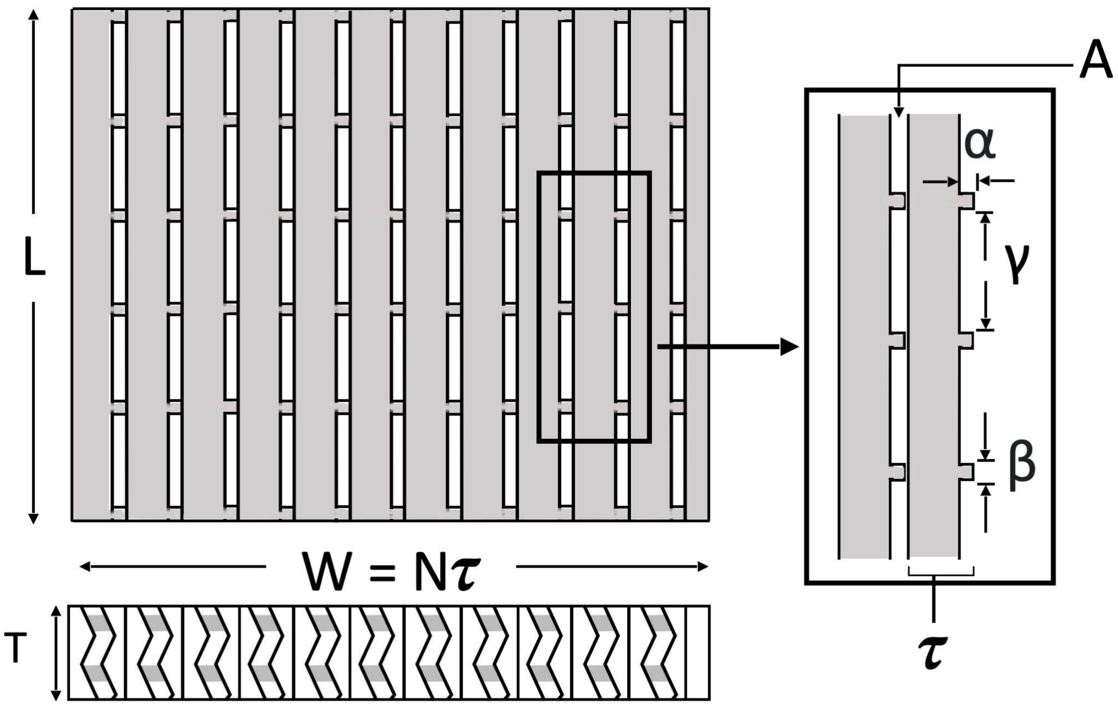
- Surface direct conversion:
  - Surface: gamma ray interacts near substrate surface
  - Direct: removes crystal scintillator step of converting gamma ray to scintillation light
  - Conversion: produces an electron (and signal)
- <u>“Surface” component is important</u>: 400 keV primary electrons travel ~80 um (in Geant4 simulation of NIST lead glass).
- Only primary electrons near a surface can exit



*Note: figure not to scale

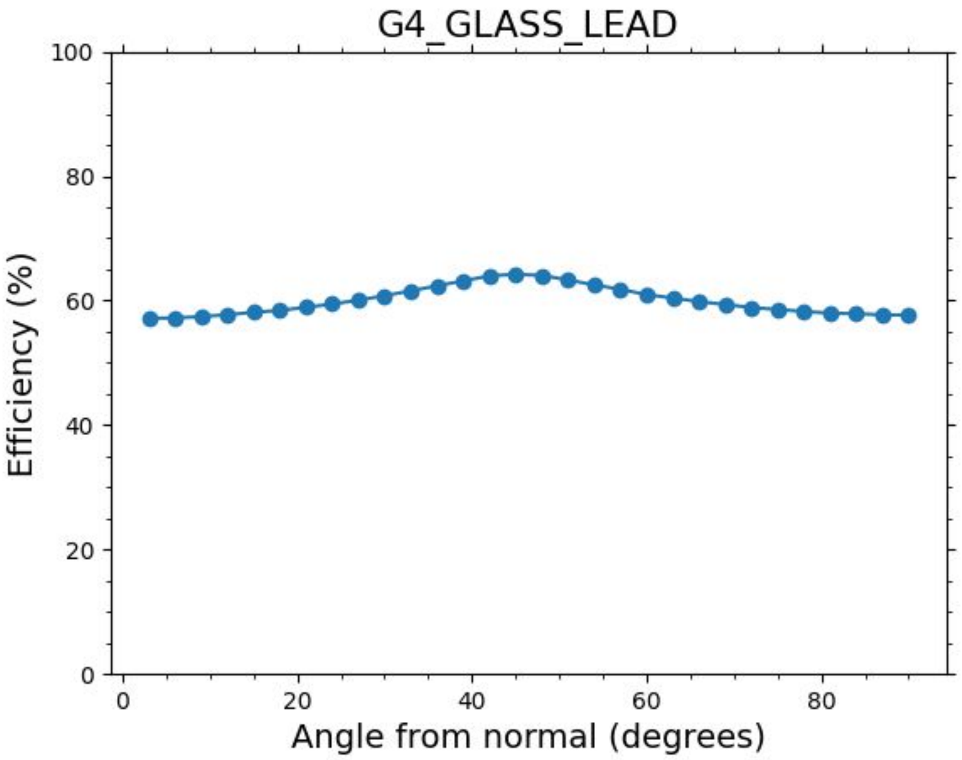
Laminar Microchannel Plates (LMCPs)

- LMCPs ≡ thin patterned laminae stacked to form microchannels
- LMCPs: one possible geometry for surface direct conversion
- 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



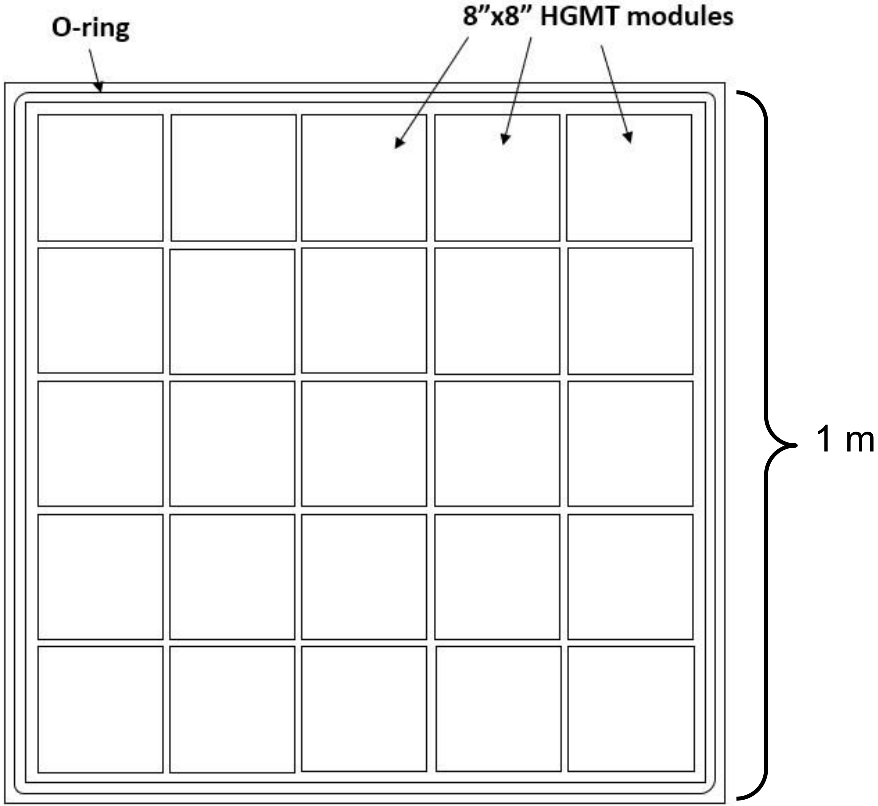
≳60% Efficiency of LMCP Surface Direct Conversion

- Efficiency ≡ fraction of gamma rays that produce primary electrons that traverse a pore wall
- Efficiency for 511 keV gamma ray conversion depends on:
  - Angle of incidence
  - Pore width
  - Wall thickness
  - Primary electron energy (substrate material)
- Still researching efficiency of primary e- to secondary e-
- Geant4 simulation indicates ≳60% efficiency for NIST lead glass 1-in thick LMCP (G4_GLASS_LEAD)

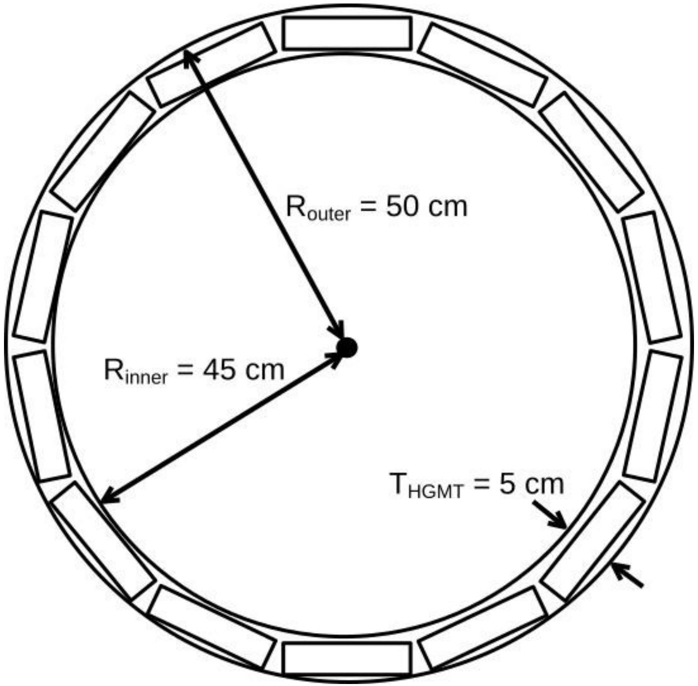


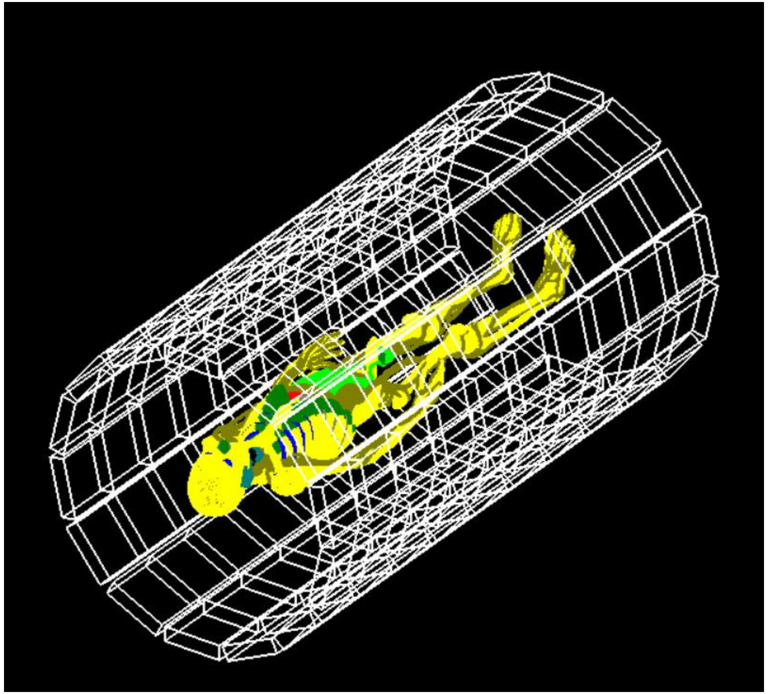
HGMT Mechanical Configuration

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



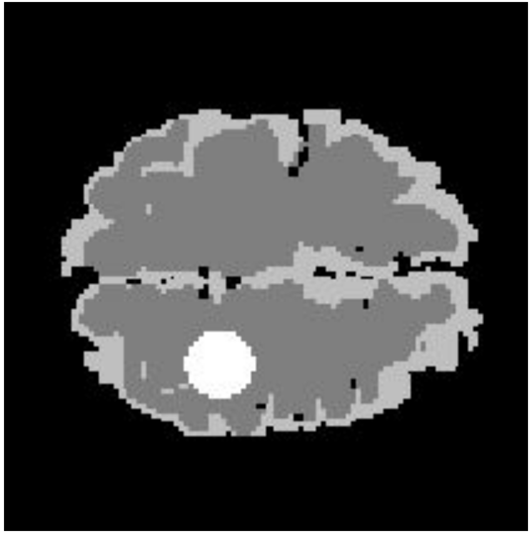
TOPAS Simulations of HGMT-based PET

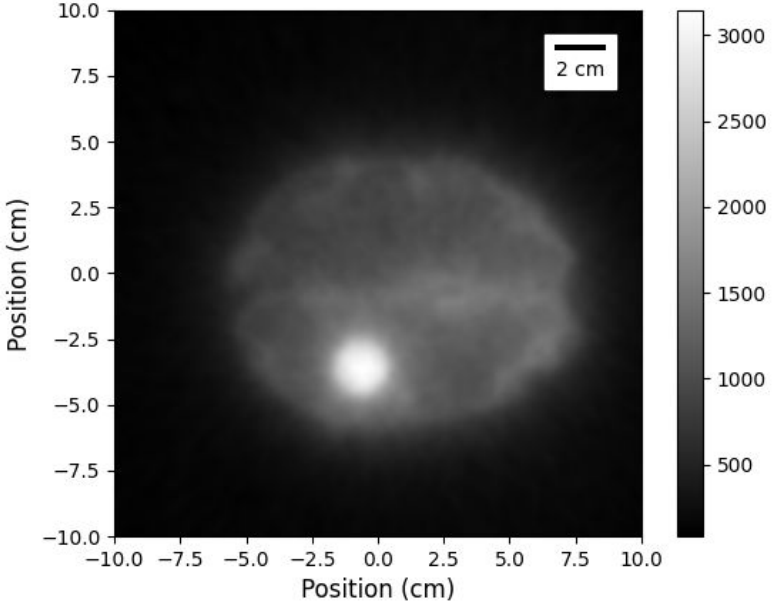




- XCAT phantom in the detector from TOPAS: 2 m long, 45 cm bore radius, 5 cm thick
- HGMTs shown are rectangular, but can curved, non-planar, or with varying thickness
- Directionality of pores can vary with position

TOPAS Simulations of HGMT-based PET (continued)

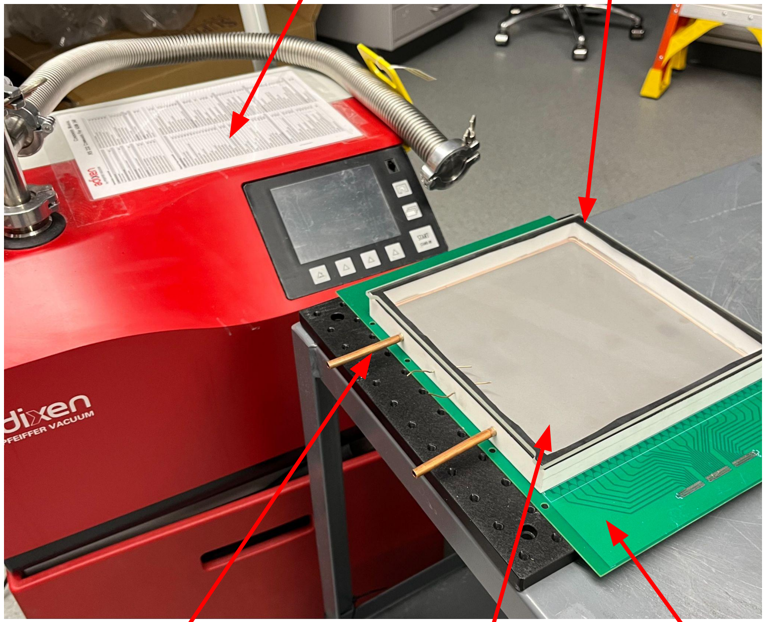




- Left: cross section of the XCAT brain
- Right: cross section of the XCAT brain imaged by the HGMT scanner in TOPAS
  - 1/100th dose, compared to benchmark 10 min, 8.25 kBq/mL (white matter), 33 kBq/mL (gray matter), 99 kBq/mL (lesion) - Hoffman brain activities
  - 100 ps FWHM timing resolution, 1 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 Amplifier LMCP Testing Setup

- Contacting vendors to produce laminae (glass, plastics, etc.)
- Preliminary test setup (courtesy P. Scheidt)
- Pumped vacuum enclosure using multi-purpose leak detector
- Capacitively-coupled stripline anode readout through nichrome bottom plate (PSEC4/LAPPD electronics)
- Customizable enclosure window
  - Beta button sources
  - Gamma ray button sources + thin high-Z plates for direct conversion



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 scintillating crystals and photocathodes
- TOPAS simulation results of HGMT-based TOF-PET indicate 100x reduction in dose
- Have began to find LMCP manufacturers and create testing setup

Thank you

References

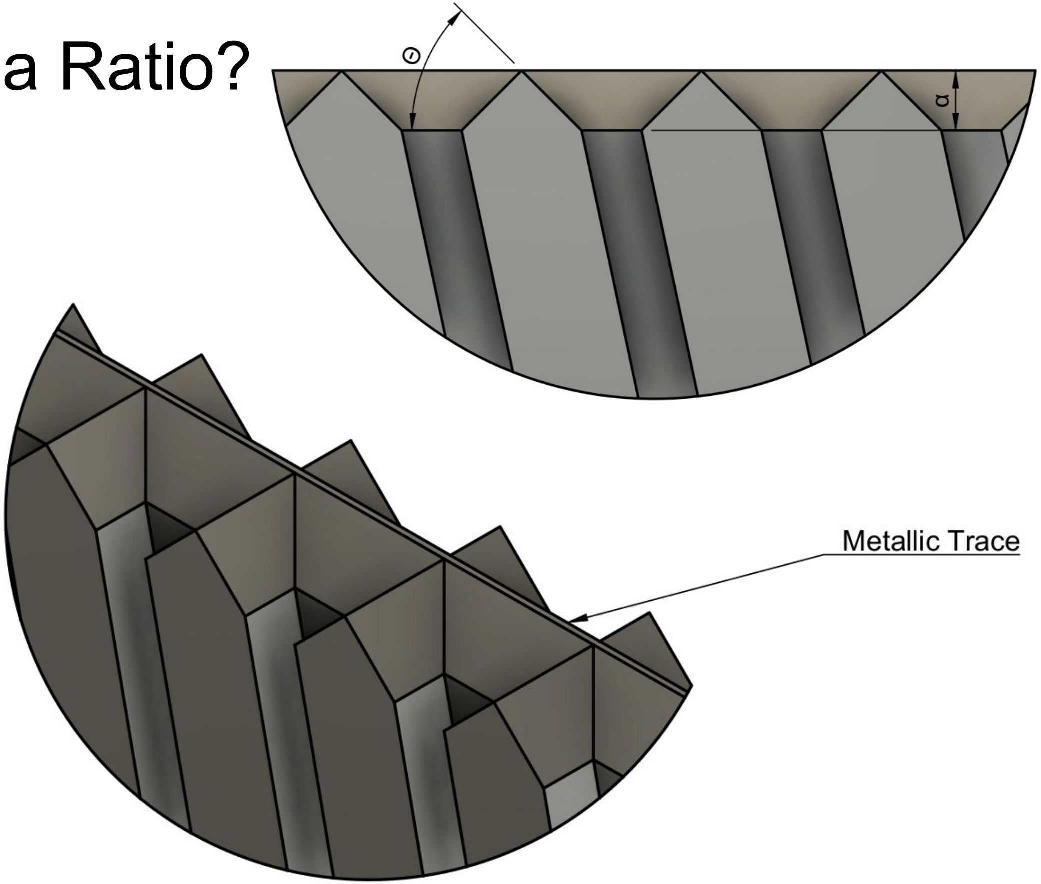
K. Domurat-Sousa, C. Poe, H. J. Frisch, B. W. Adams, C. Ertley, and N. Sullivan. Surface direct conversion of 511 kev gamma rays in large-area laminated multichannel-plate electron multipliers. *Nucl. Instrum. Methods*, 1951055:168538, 2023, https://doi.org/10.1016/j.nima.2023.168538.

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?

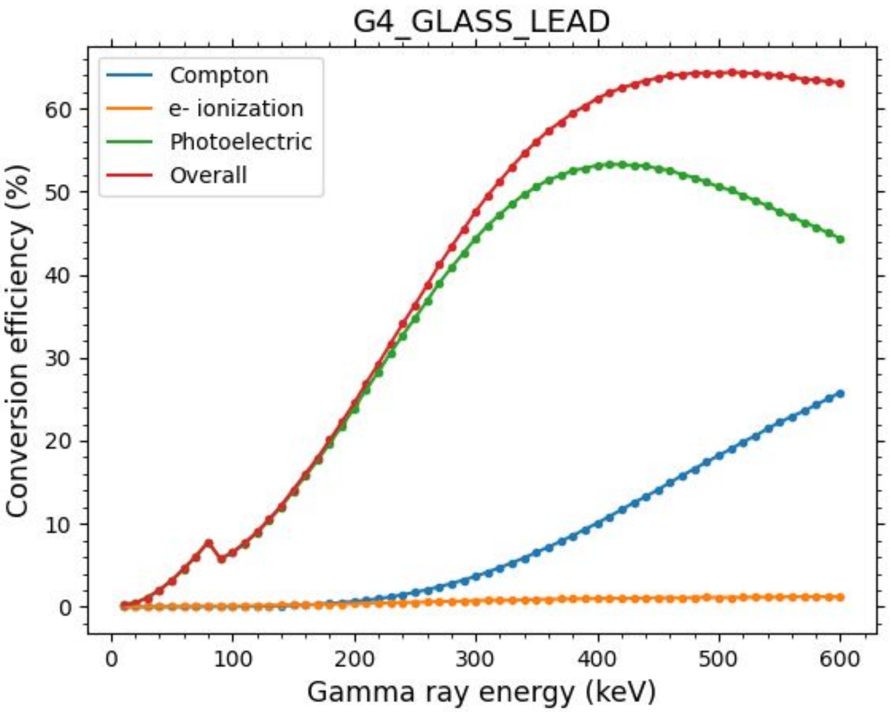
- Hard for LMCPs to have walls as thin as glass capillary MCPs
- Solution: funnels
- Figure: square funnels during patterning for a single lamina
- Alternative: circular funnels before lamina coating



DETAIL E (300:1)

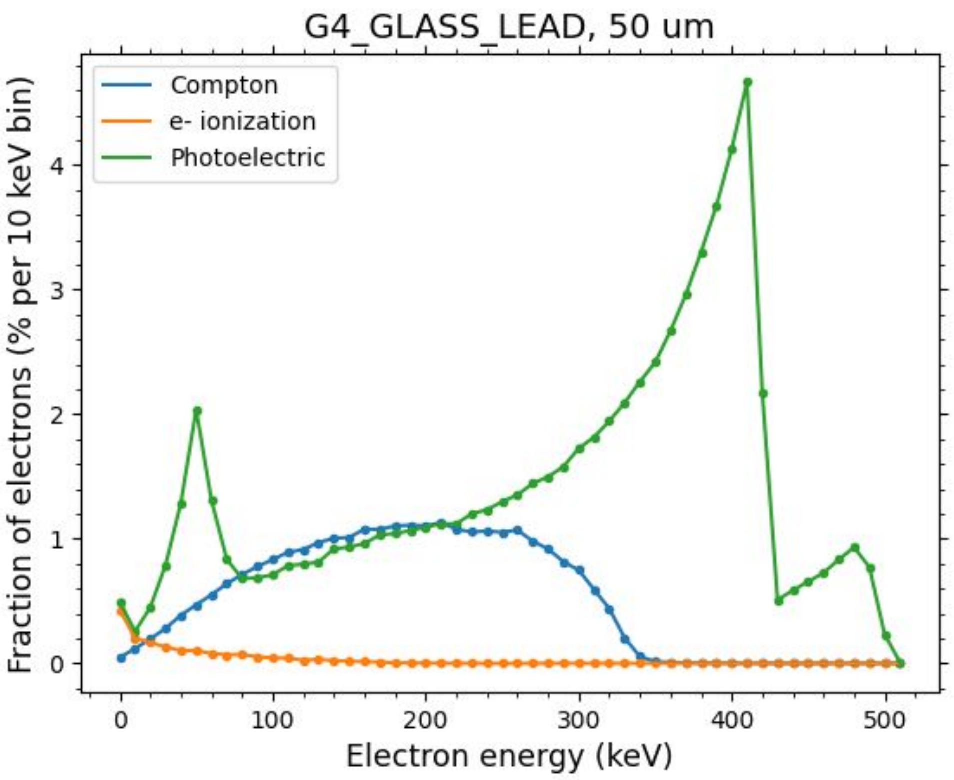
What are the energies of primary electrons?

- 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
- 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



How is a ~450 keV e- converted into a cascade?

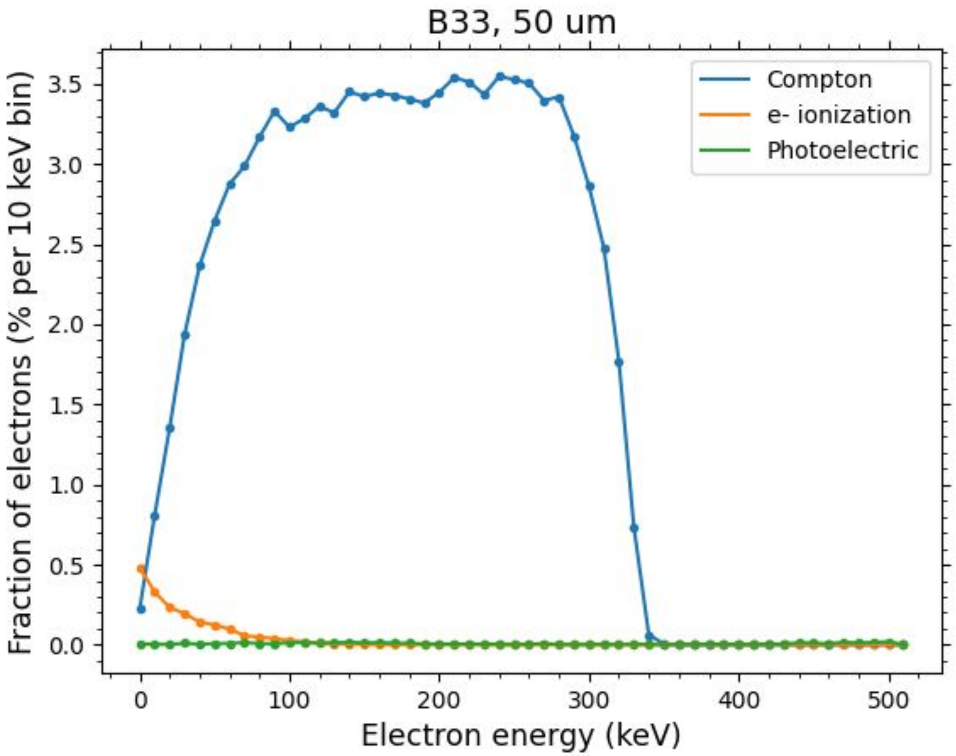
- Still an active area of research for our group
- Couple of advantages of LMCP for primary to secondary conversion:
  - Primary electrons are expected to traverse a pore wall twice
  - Different substrates can shift the energy of primary electrons (Compton vs. photoelectric)
  - Open pores allow for new secondary coatings



Energy spectrum of primary e- from 511 keV gamma rays

How is a ~450 keV e- converted into a cascade? (continued)

- Comparison to B33, a Schott borosilicate glass (low-Z)



Energy spectrum of primary e- from 511 keV gamma rays

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 underserved populations (rural, young, elderly) requires good sensitivity at low dose
- Simulation results show that HGMTs accomplish this

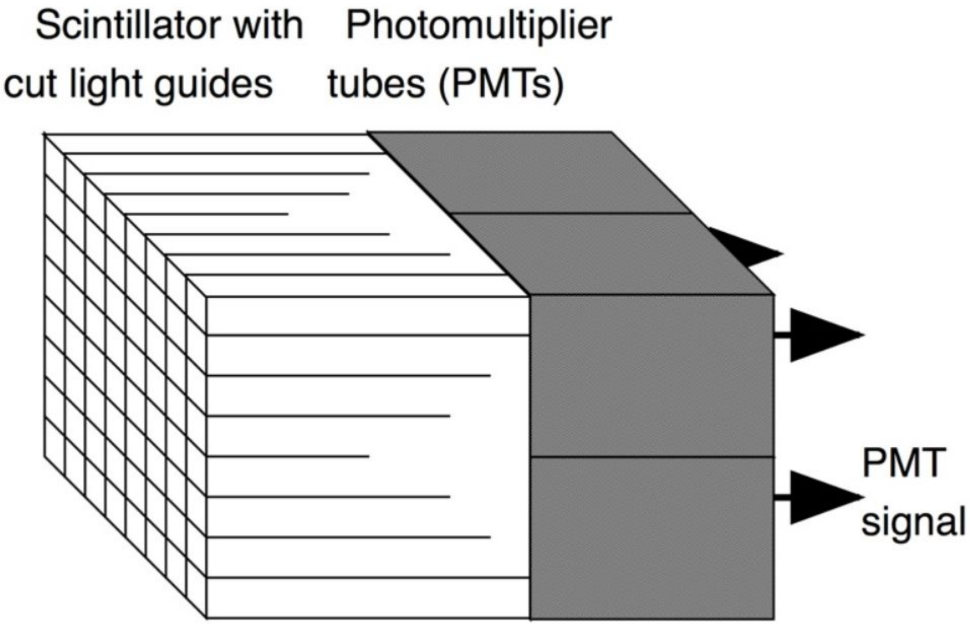
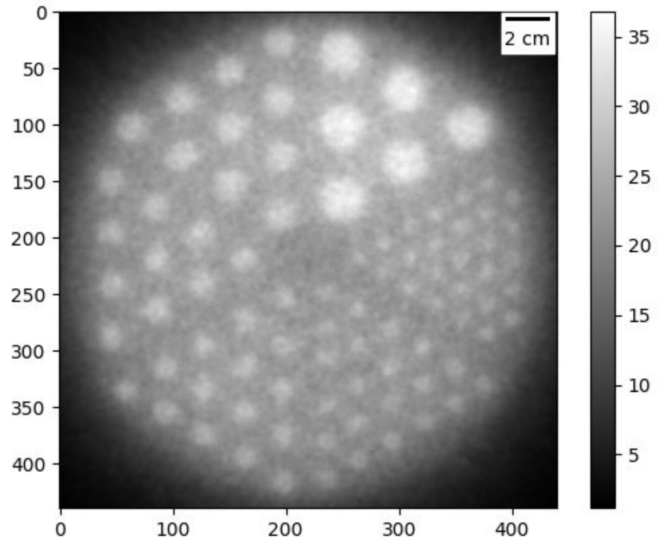
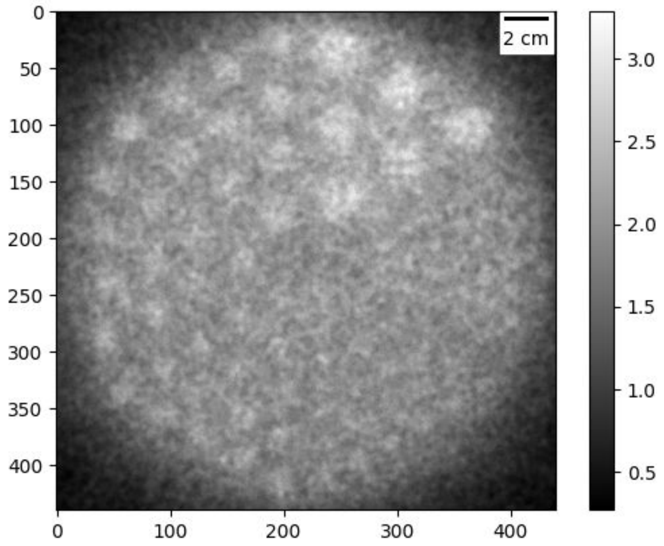


Figure from: R. Schmitz, A. Alessio, P. Kinahan, *The Physics of PET/CT Scanners*, 2013

What is the HGMT energy resolution?

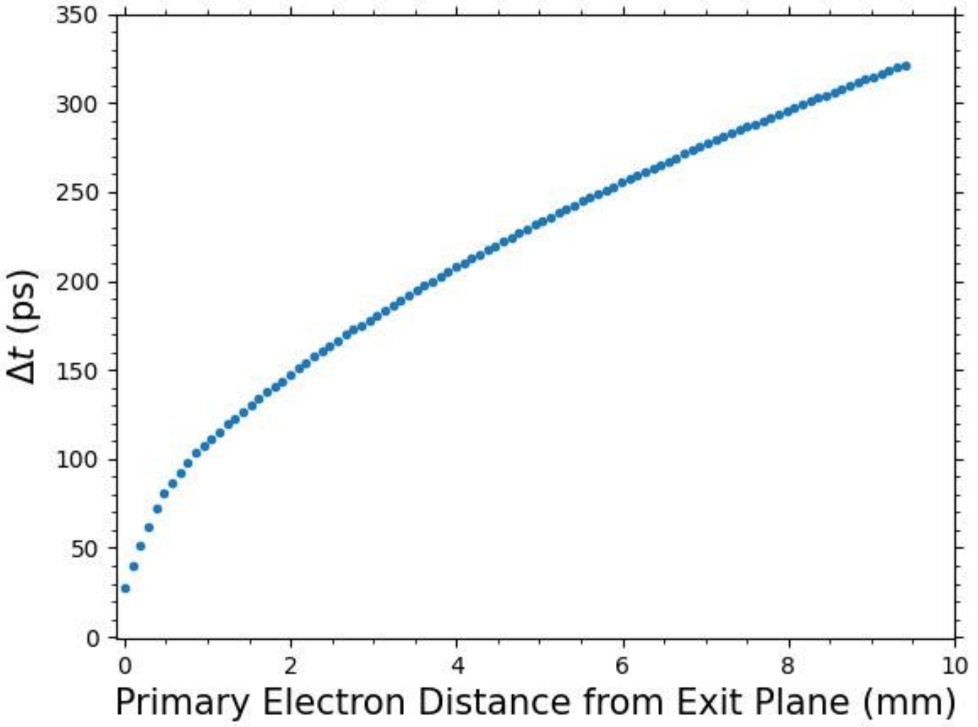




- Still an active area of research
- However, in PET, not having good energy resolution may not be as large of an issue:
  - Brain simulation results do not have energy resolution->no cuts on in-patient scattering
  - In-patient scatters form a low-frequency background (see Domurat-Sousa arXiv:2305.07173v1)
  - Some clinical settings may benefit from some PET, rather than no PET
- Left: Derenzo imaged by LYSO scanner simulation., right: only mis-ID lines-of-response

What is the HGMT time resolution?

- Determining time resolution similar to that of MCPs
- PSEC4 and stripline anodes provide very fast time resolution on the digitizing side
    - See [E, Oberla, PhotoDet 2012, vol 158, 15 Jun 2012.]
- Converter LMCP presents hardest timing challenge
- Solution: break single converter LMCP into multiple sub-modules with smaller thickness, but similar total converter length



Δt ≡ time of arrival of first secondary

What is the HGMT time resolution? (continued)