Constructing Microchannel Plates from Thin Patterned Laminae

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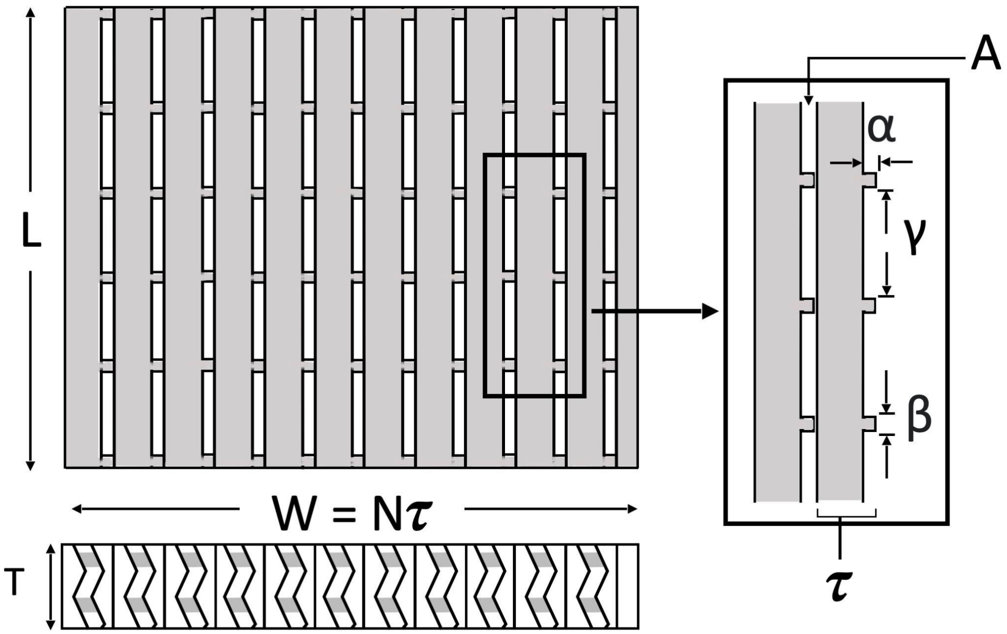
Outline

1. What is a laminar microchannel plate (LMCP™)?
2. Advantages of the laminar design
    a. New substrate materials, new secondary emitting materials
    b. New pore geometries
    c. Potentially cheaper than drawn capillary arrays
3. Gamma ray detection via surface direct conversion in LMCPs, without scintillating crystals or photocathodes
4. Applications in ultra-low-dose PET, shower-max detectors, general MCP-PMTs
5. Questions

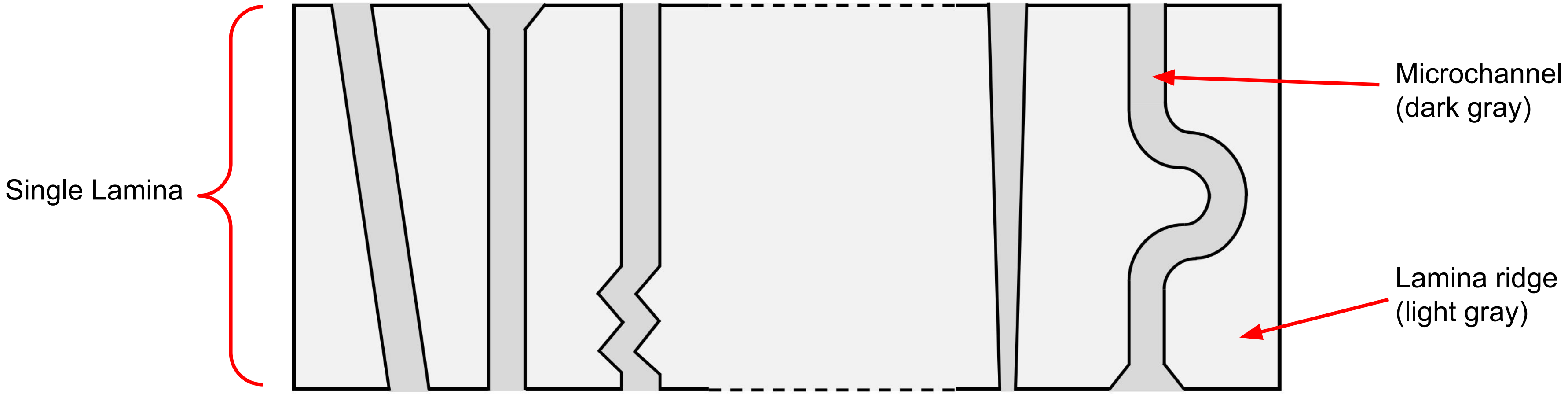
Laminar Microchannel Plates (LMCP)

- LMCPs ≡ thin patterned laminae stacked to form microchannels
- Figure:
  - Not to scale
  - τ: 100 um,
  - T: 1 mm - 2.5 cm
  - L: 20 cm
- Laminae 'ridges' formed via ablation (laser etching, grinding, etc.), additive procedure (3D printing), or molding



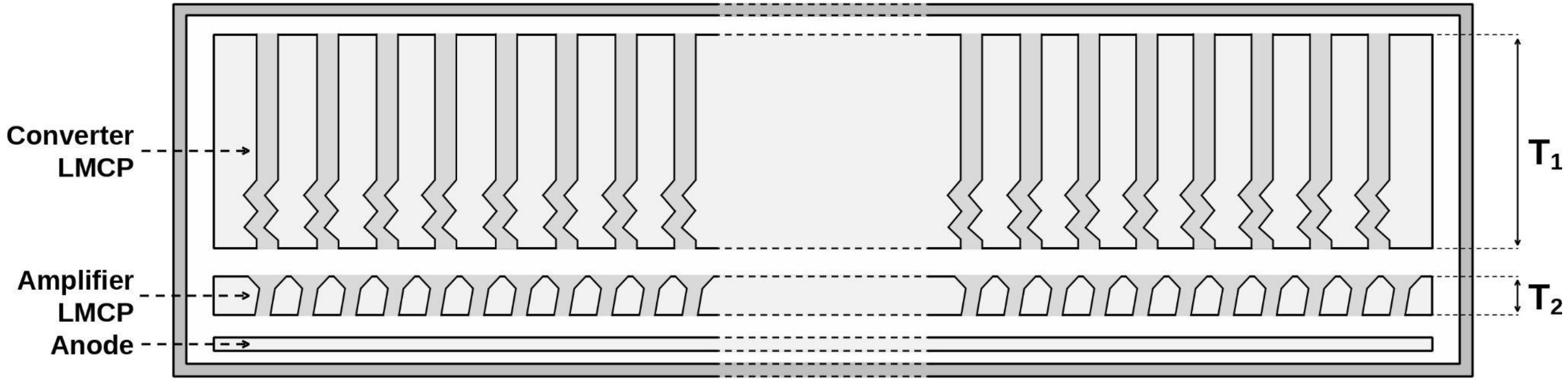
Note: laminae can be patterned on both sides

Advantages of the Manufacturing out of Laminae



- Pore types (left to right): bias angles, entrance funnels, zig-zag features, tapered pores, and curving patterns with exit funnels.
- Advantages:
  - New substrate materials like glasses, plastics, 3D-printed materials, curable polymers, etc.
  - Different geometries allow for different types of pore patterns (above)

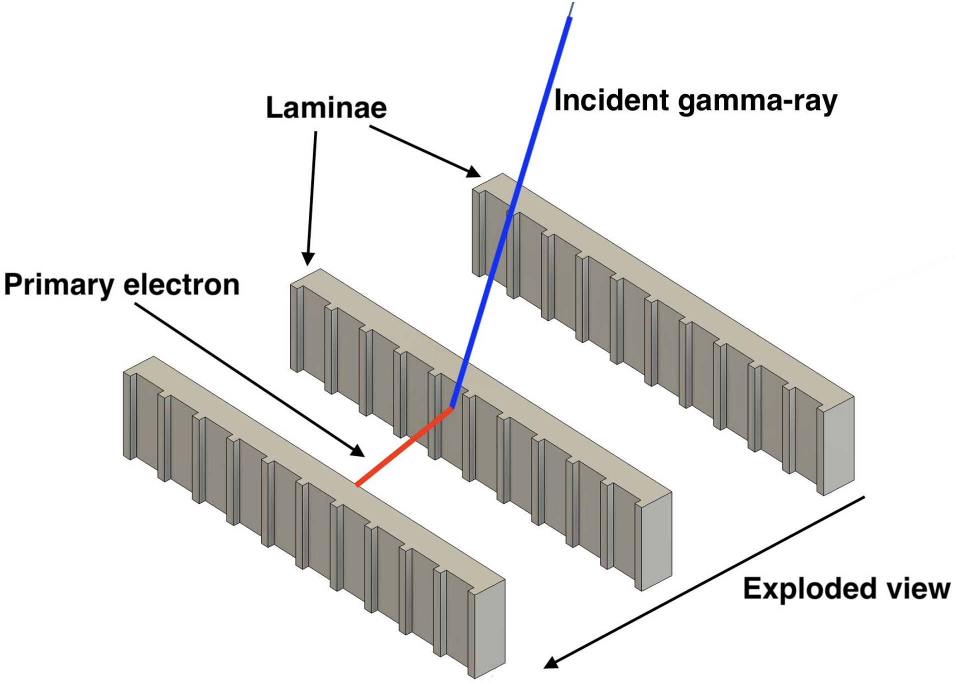
Advantages of Having Access to the Microchannel Pore



- Advantages:
  - New possibilities of secondary emitting coatings (e.g. CVD diamond, tape casting)
  - Non-uniform voltage distributions
  - Variable pore surface textures
  - Sensors/electronics in pores
- In general, the laminar method is a way of manufacturing: with a photocathode, it's still an MCP-PMT

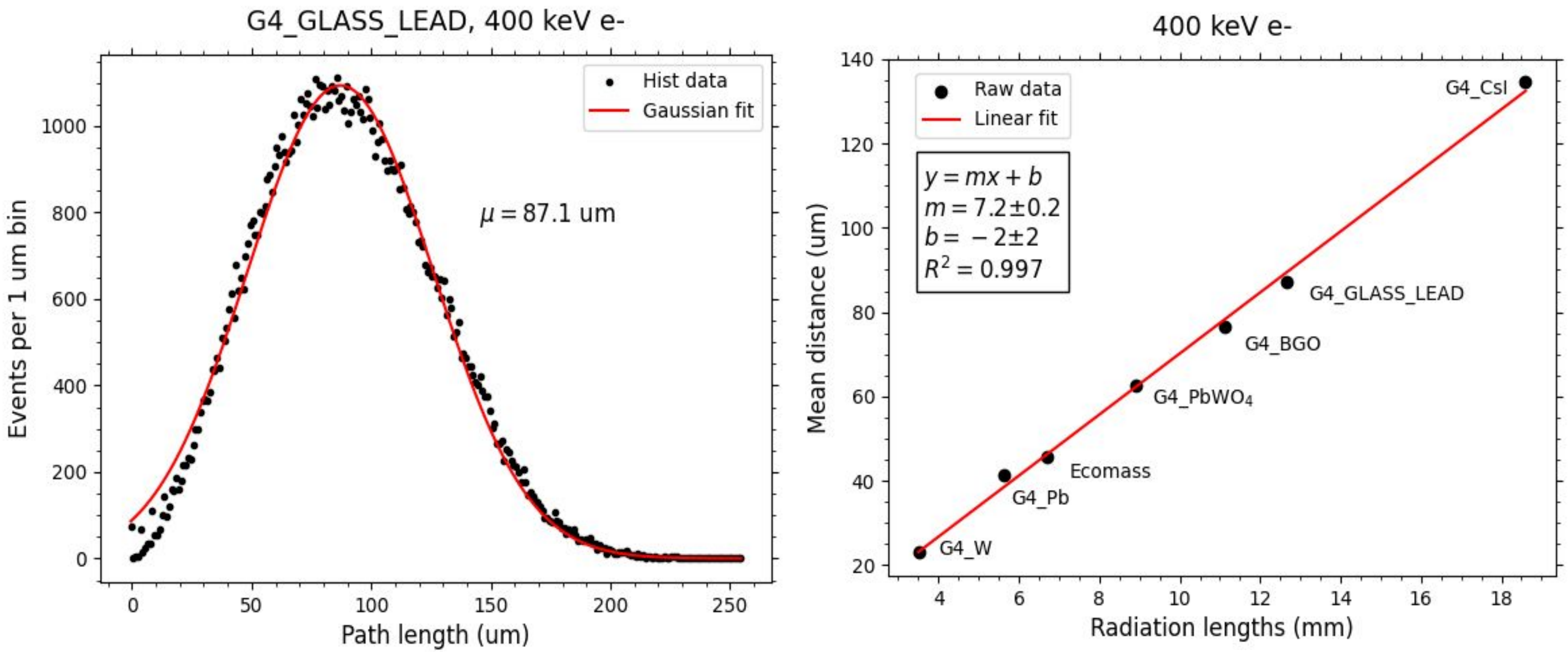
Gamma Ray Detection via Surface Direct Conversion

- Background:
  - We have experience with low-Z liquid scintillators for PET.
  - Is there a way to remove the optical components (scintillation crystals, photocathode) of a PET scanner?
- Solution: surface direct conversion
- 511 keV gamma ray interacts in LMCP substrate via Compton or photoelectric effect -> can produce e- that generates cascade in the pore
- Takeaway: gamma ray detection with no scintillator/photocathode



*Note: figure not to scale

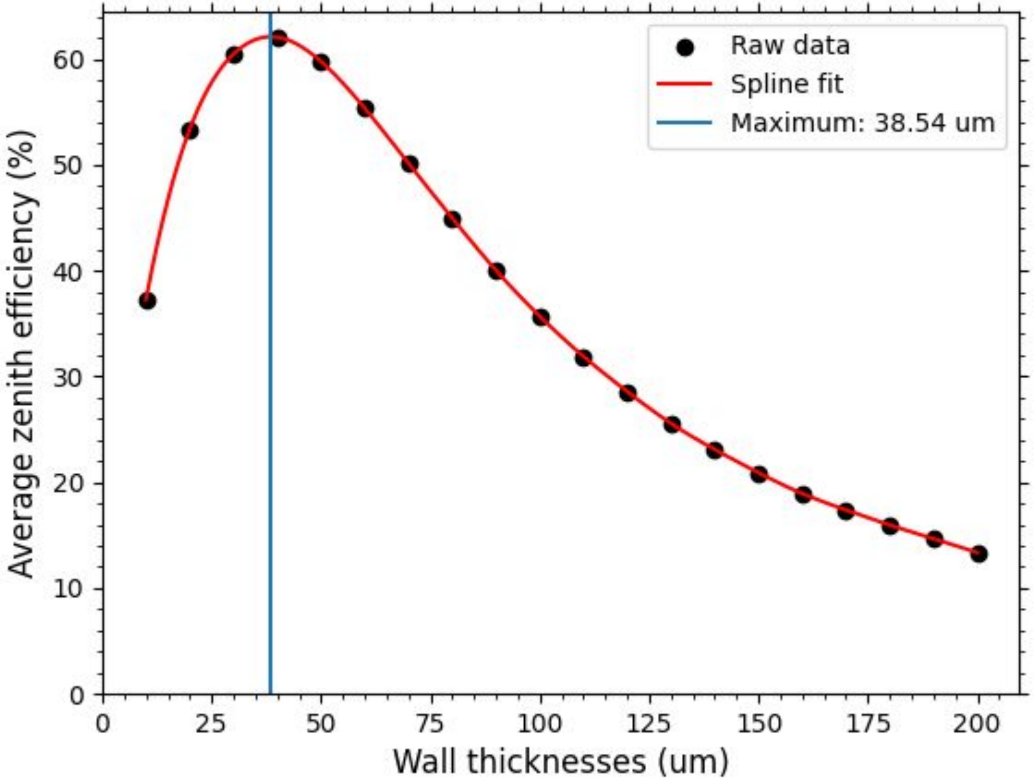
Maximum Feature Size for Surface Direct Conversion



- Surface direct conversion is only possible if electrons can escape the channel wall
- Geant4 simulations show electron mean distance traveled is linearly related to radiation length
- Feature size for a given material cannot be larger than the mean distance traveled by ~400 keV electrons (the high-end of primary electron energy from 511 keV gamma rays)

Optimizing Channel Wall Thickness

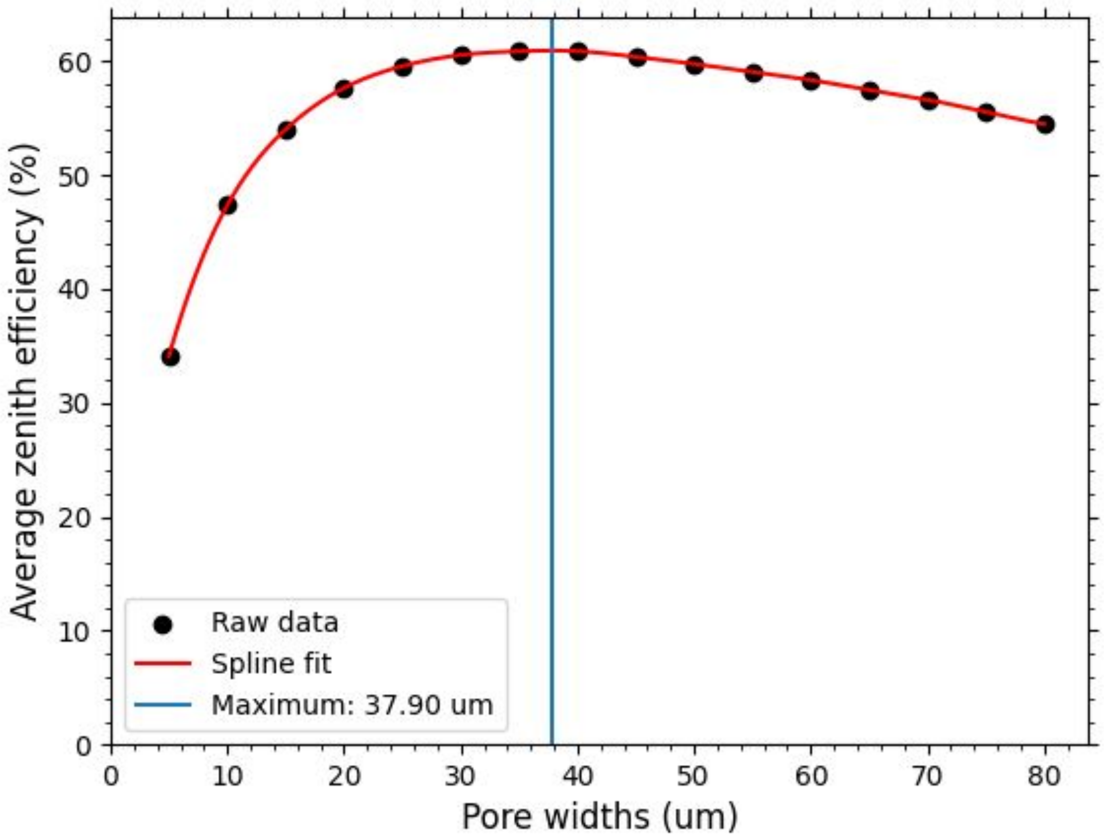
- Efficiency ≡ fraction gamma rays that produce primary electrons that traverse a pore wall
- Efficiency of primary e- to secondary e-? Still researching
- Competing contributions: substrate per unit volume vs. distance e- can travel
- Maximum efficiency at ~40 um wall thickness



Geant4 simulation of 2.54-cm (1-in) thick NIST lead glass LMCP with 50-um wide square pore

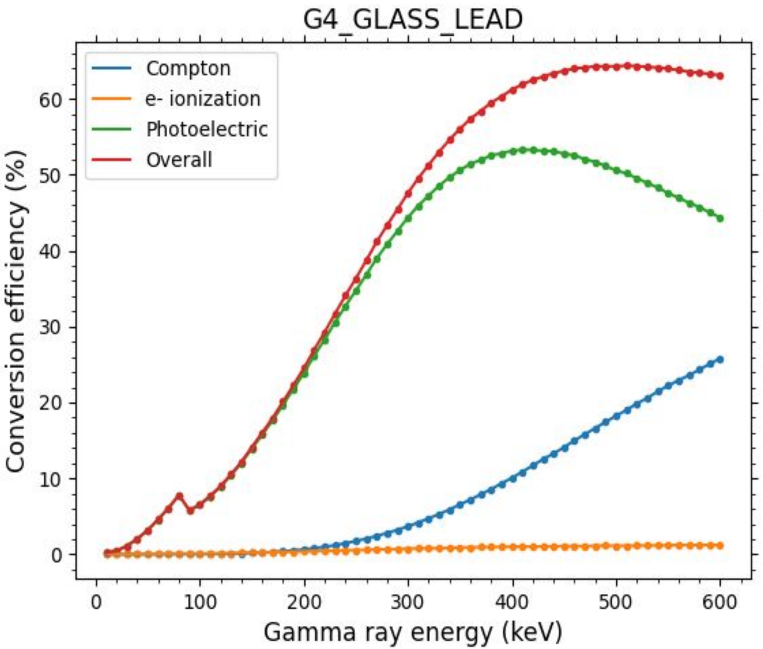
Optimizing Pore Width

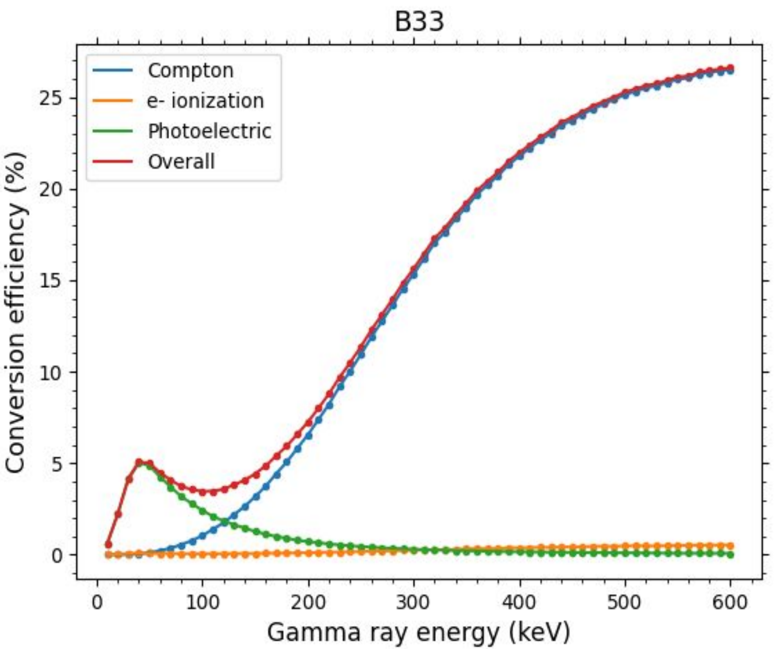
- Similar competing processes: substrate per unit volume vs. surface area to volume ratio
- Maximum efficiency at ~40 um pore width
- Flatter maximum -> can afford to use slightly narrower or wider pores



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

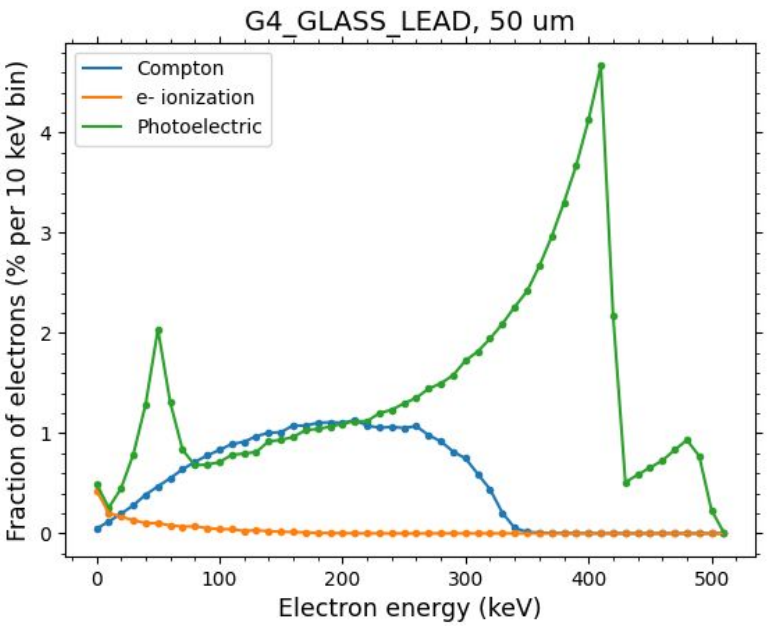
Relative Interaction Processes

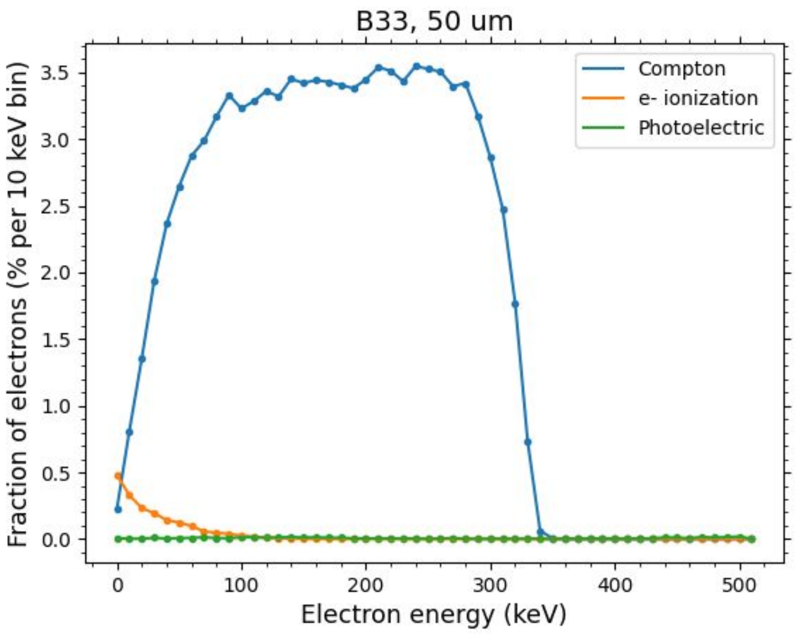




- Geant4 simulation of conversion efficiency vs. gamma ray energy in 1-in thick LMCP with 50 um wall/pore widths for different processes (500k gamma rays at each energy step)
- B33 = Schott borosilicate glass
- Changing LMCP material can be used to select for certain interactions in the substrate (Compton vs. photoelectric)

Surface Direct Conversion: Electron Energy Spectra

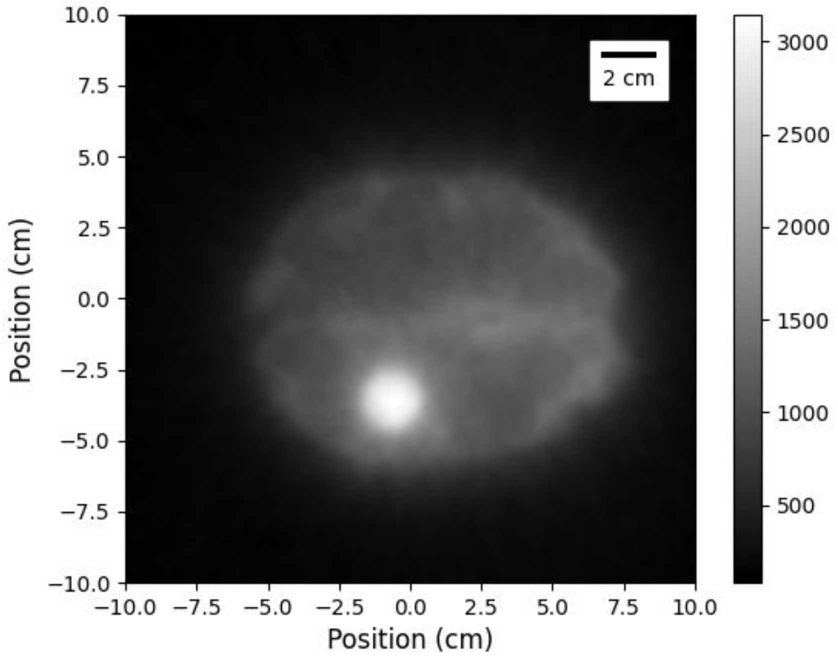




- Histogram of electron energies from Geant4 simulation of 1-in thick LMCP with 50 um wall/pore widths for 500k 511 keV gamma rays
- Energy of primary electrons depends on the generating process, and thus the substrate material -> secondary emitting coatings can be optimized for different processes

Applications for LMCPs

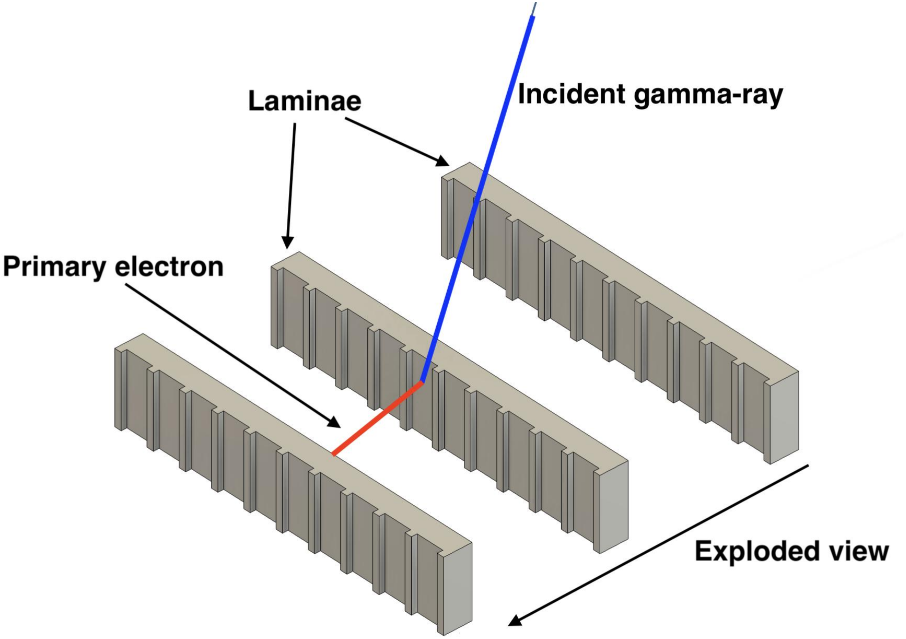
- As MCPs in conventional MCP-PMTs
- Packaging a surface direct converting LMCP with an amplifying MCP and anode: hi-res gamma ray multiplier tube (HGMT)
    - See C. Poe HGMT talk in the Calorimetry Session
- Large market for HGMTs: time-of-flight PET, has potential to decrease radioactive dose by 100x, opening opportunities for routine and early screening for cancer and disease in underserved groups
- Other uses: shower max detectors, rare kaon decays



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

Summary

- LMCPs provide a new method of manufacturing MCPs out of thin, patterned laminae
- LMCPs have the advantage of new pore geometries, new secondary emitting coatings, new substrate materials, and cheaper cost
- LMCPs have applications in MCP-PMTs and gamma ray detection through surface direct conversion (PET, shower-max detectors)



Surface direct conversion in an LMCP

Thank you

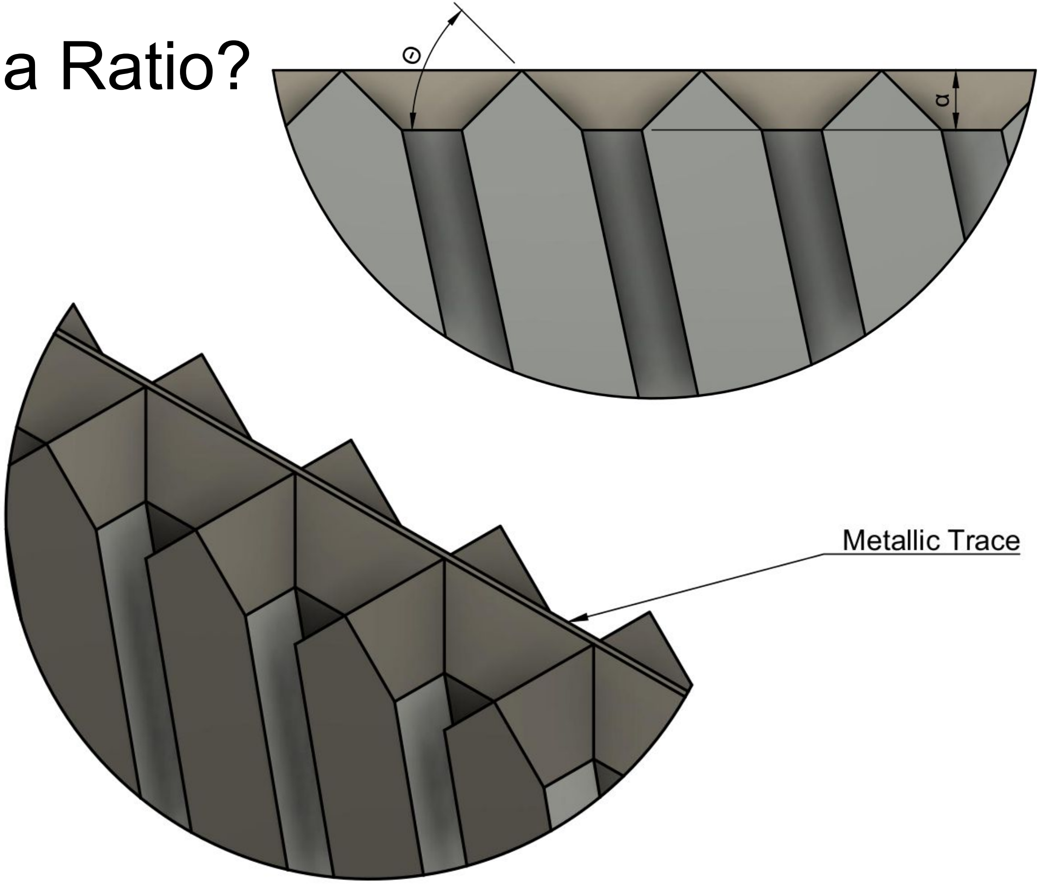
References

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.

What About the Open-area Ratio?

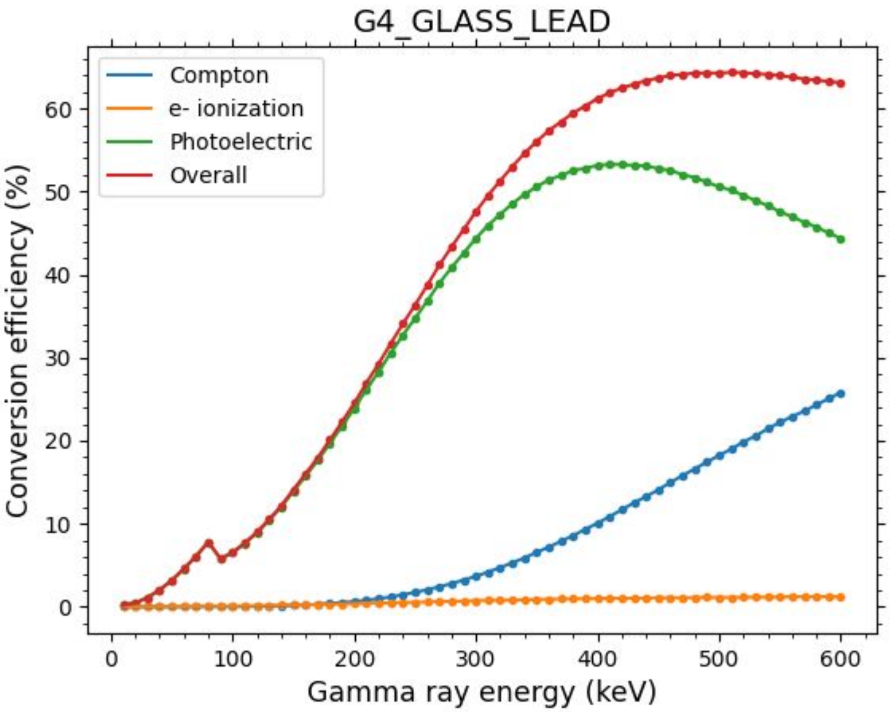
- Hard for LMCPs to have walls as thin as glass capillary MCPs
- Solution: funnels
- Figure: square funnels during patterning for a single lamina
- Alternative: circular funnels before lamina coating



DETAIL E (300:1)

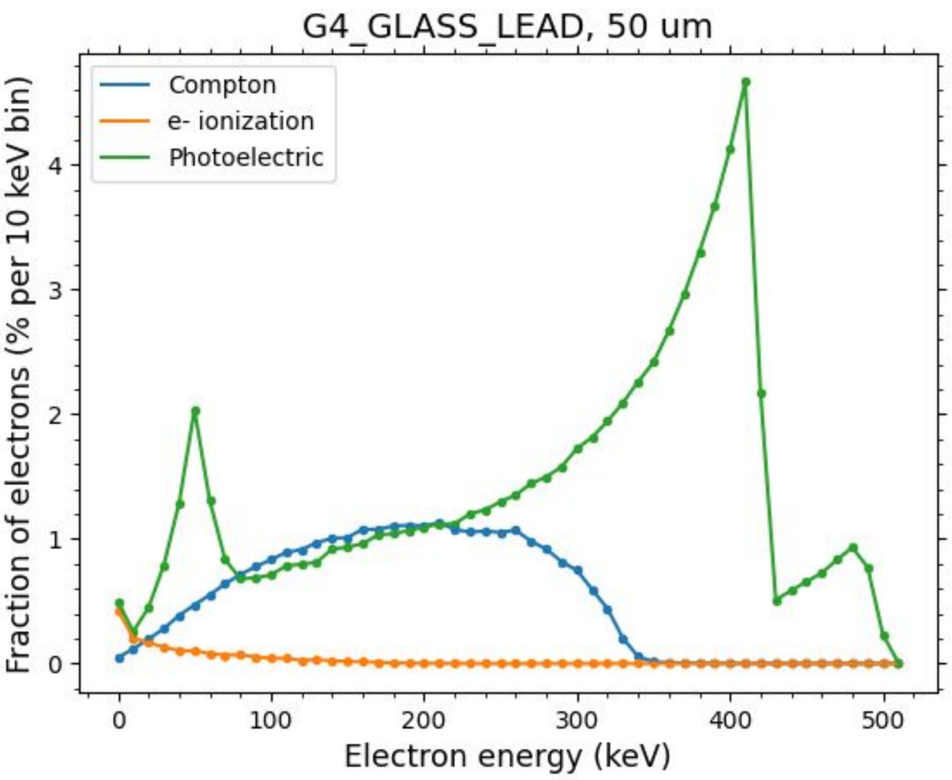
What are the energies of primary electrons?

- 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?

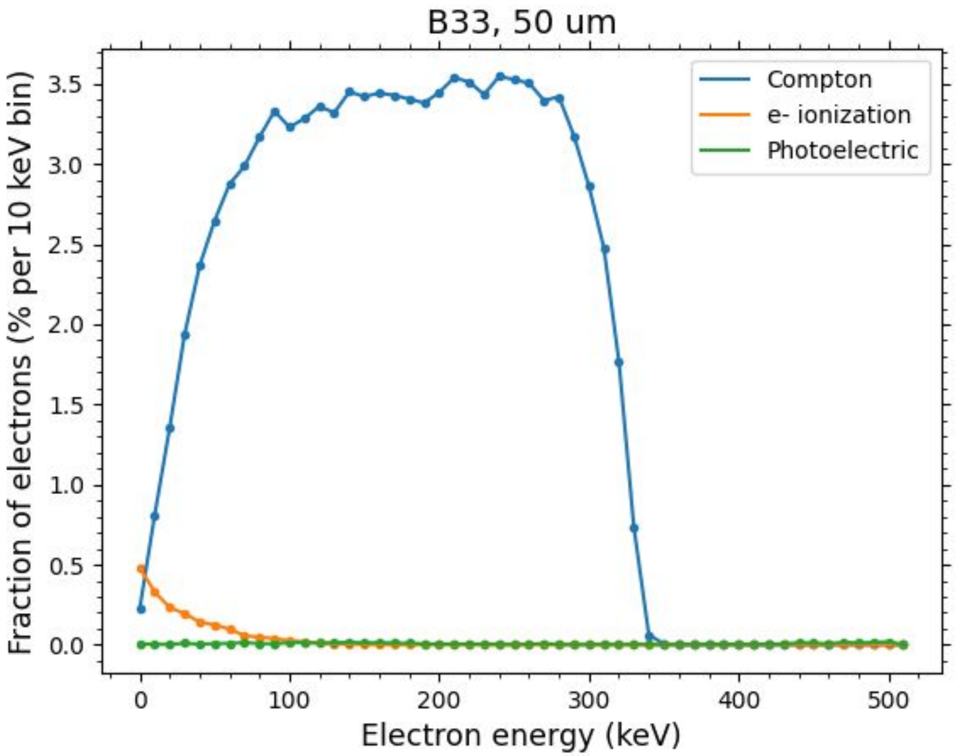
- Still an active area of research for our group
- Couple of advantages of LMCP for primary to secondary conversion:
  - Primary electrons are expected to traverse a pore wall twice
  - Different substrates can shift the energy of primary electrons (Compton vs. photoelectric)
  - Open pores allow for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



Energy spectrum of primary e- from 511 keV gamma rays

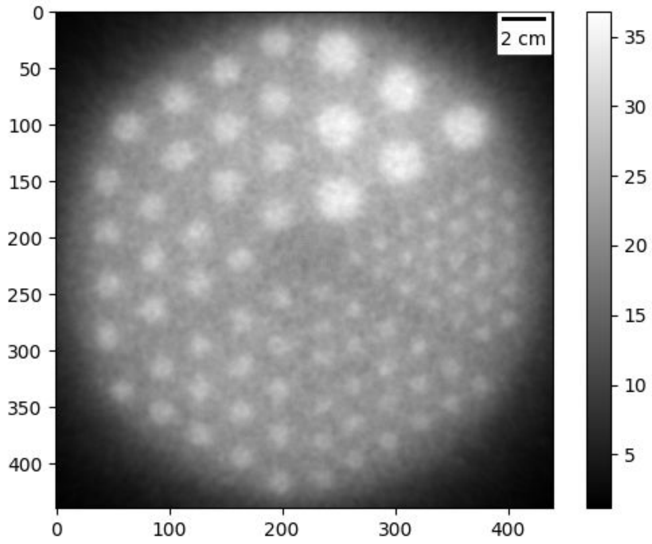
How is a ~450 keV e- converted into a cascade? (continued)

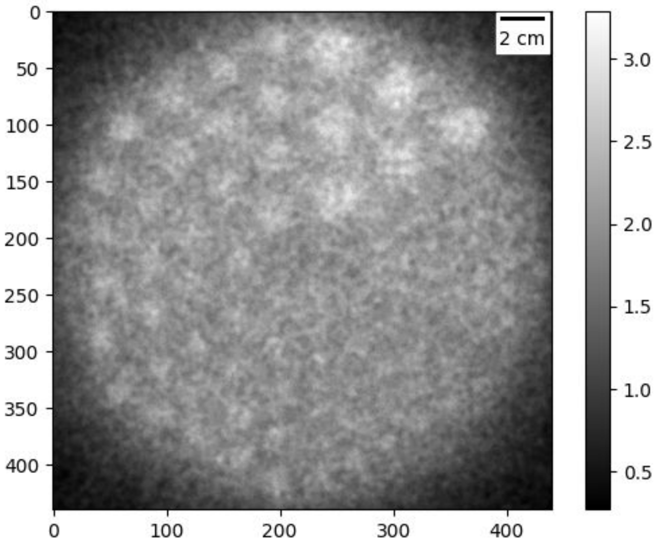
- Comparison to B33, a Schott borosilicate glass (low-Z)



Energy spectrum of primary e- from 511 keV gamma rays

What is the HGMT energy resolution?

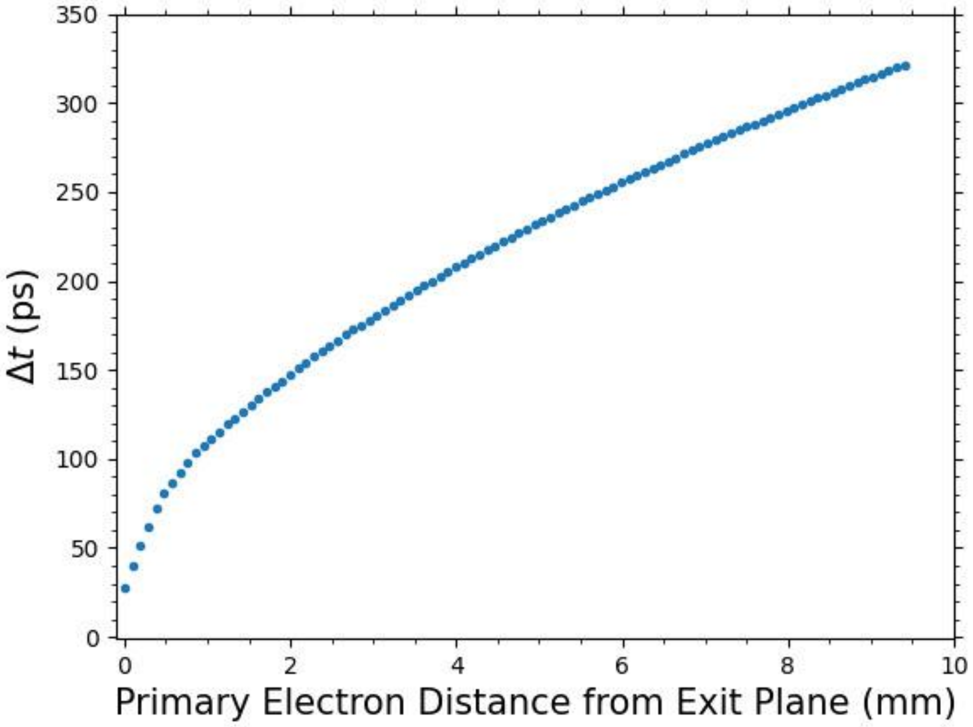




- Still an active area of research
- However, in PET, not having good energy resolution may not be as large of an issue:
  - Simulation results do not have energy resolution->no cuts on in-patient scattering
  - In-patient scatters are a low-frequency background (see Domurat-Sousa arXiv:2305.07173v1 or K. Domurat-Sousa's talk in the Calorimetry Session)
  - 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)