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

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Overview

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

- 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)
- “Surface” component is important: 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 $\equiv$ 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 $\approx$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 cm³ (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 be 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


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
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 in³ 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](image)
Why Remove Optical Conversion?

- Optical conversion is a step between gamma ray and electron cascade where gamma ray is converted into optical photons for 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
- Converter LMCP presents hardest timing challenge
- Solution: break single converter LMCP into multiple sub-modules with smaller thickness, but similar total converter length

\[ \Delta t \equiv \text{time of arrival of first secondary} \]
What is the HGMT time resolution? (continued)