Novel Gamma-ray Detector Approaches for PET

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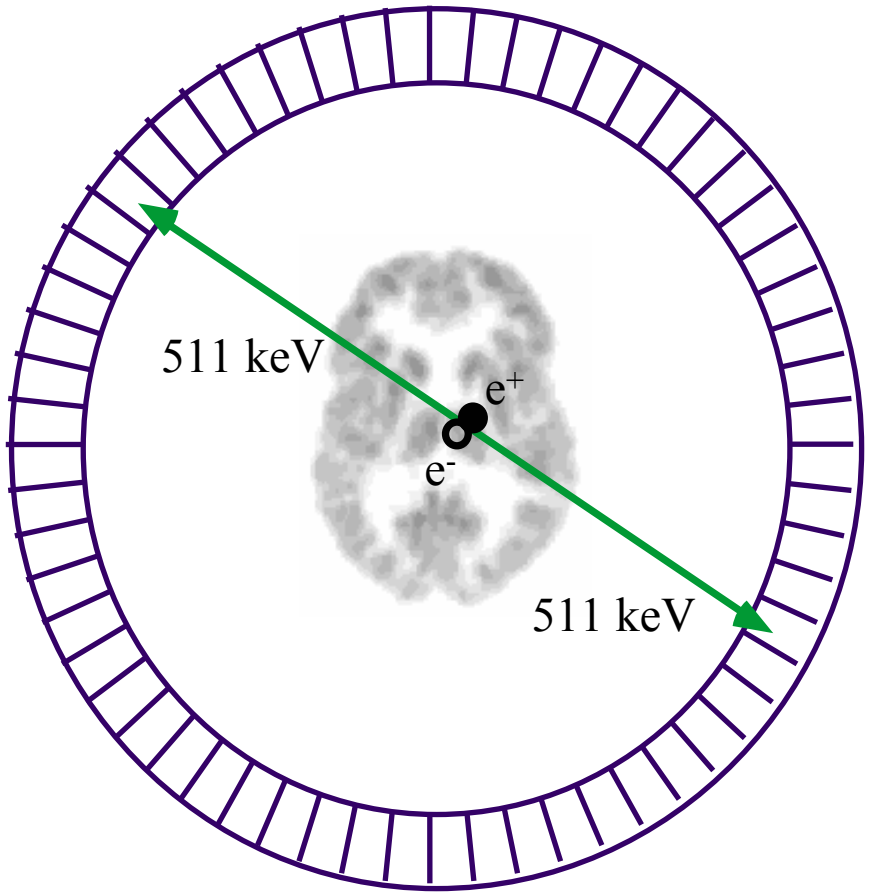
Positron Emission Tomography

- Positron annihilation
  - 2x 511 keV gamma rays
  - 180 degrees apart
  - Line of response
- PET scanner is just a photon counter
  - Gamma-ray *pairs* vs. single gammas
  - Time window ~ 1 ns



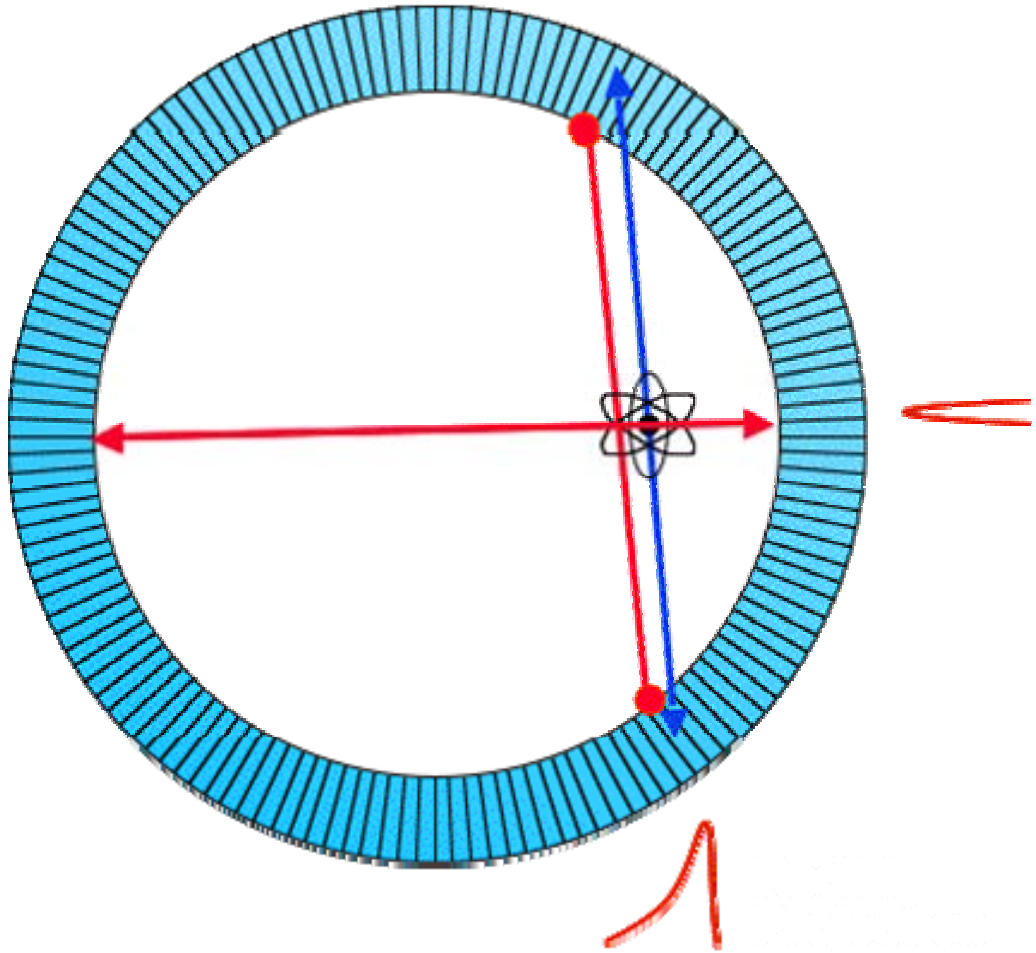
Important Detector Properties for PET

- spatial resolution - in 3D
- efficiency
- time resolution
- energy resolution
- countrate capability
- cost

Important Detector Properties

Spatial resolution

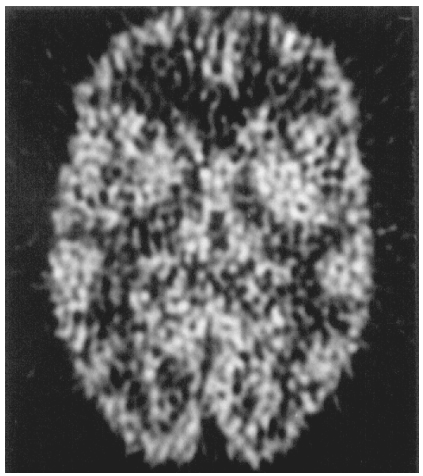
- Detector resolution directly affects image resolution
- Currently ~ 1 - 5 mm
- Depth-of-interaction (DOI)
  - “parallax” ~ crystal length
  - Also ~ FOV dia / ring dia
  - Smaller = cheaper scanner



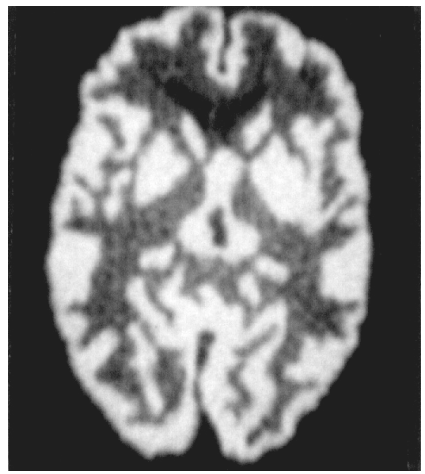
Important Detector Properties

Detection efficiency

- Reduces noise from counting statistics
- Currently > ~ 30% (singles)



1M Events

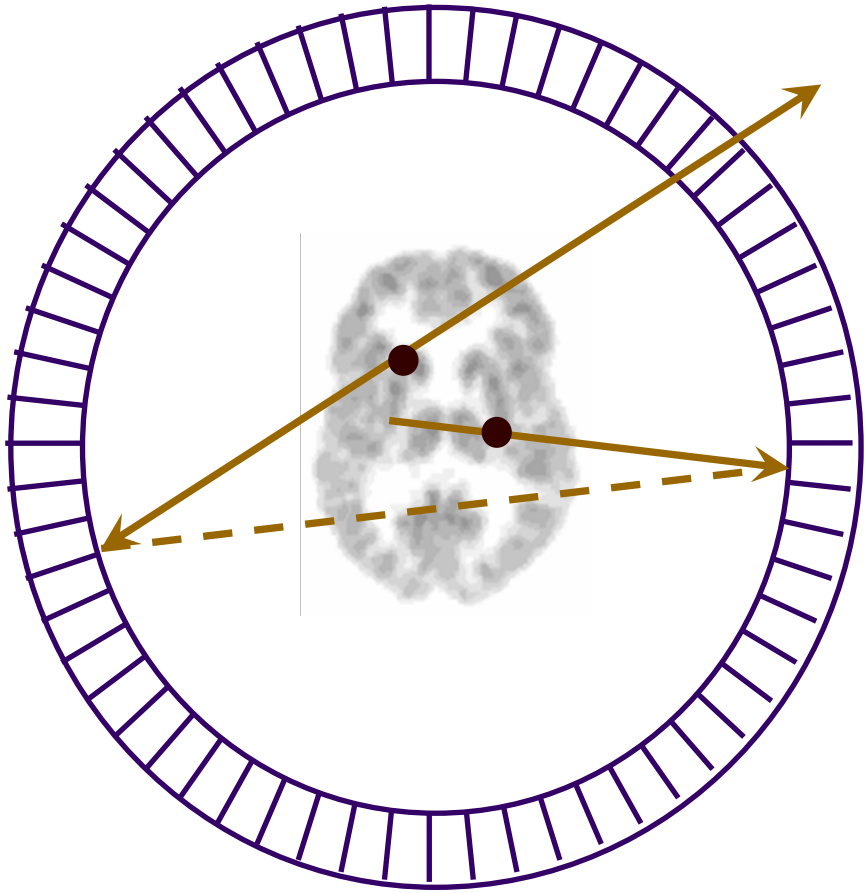


55M Events

Important Detector Properties

Time resolution

- Affects acceptance of random coincidences
- Currently ~ 1 - 10 ns
- Time-of-flight (TOF)
  - c = ~ 30 cm/ns
  - Need << 1 ns resolution



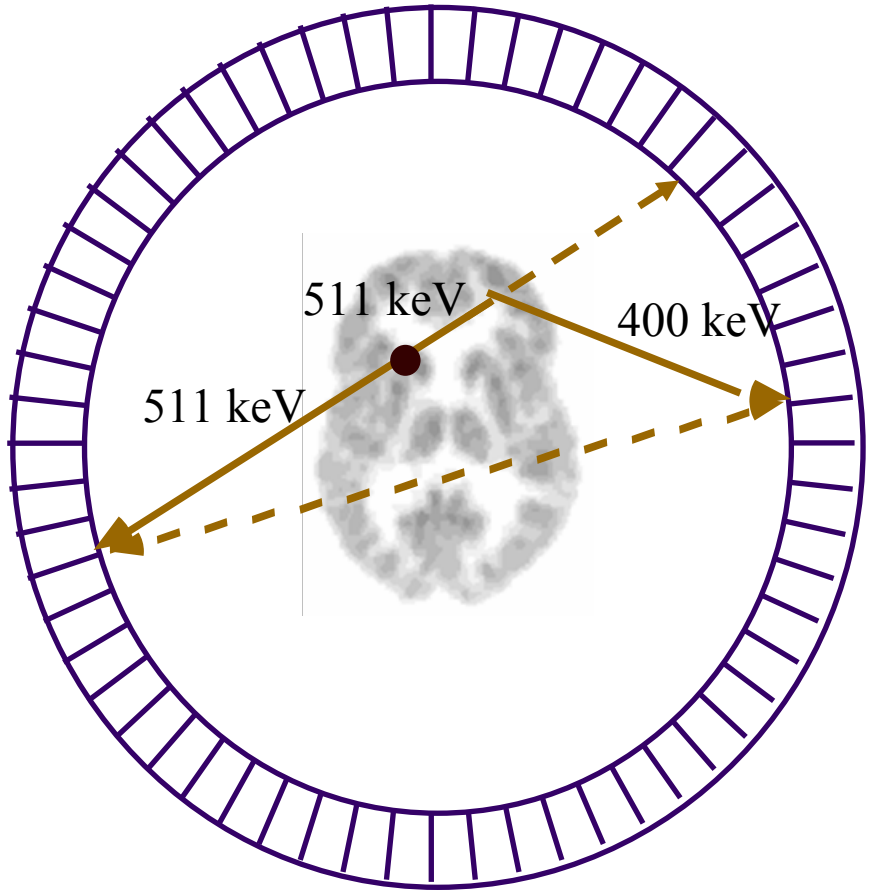
Random (accidental) coincidence

Important Detector Properties

Energy resolution

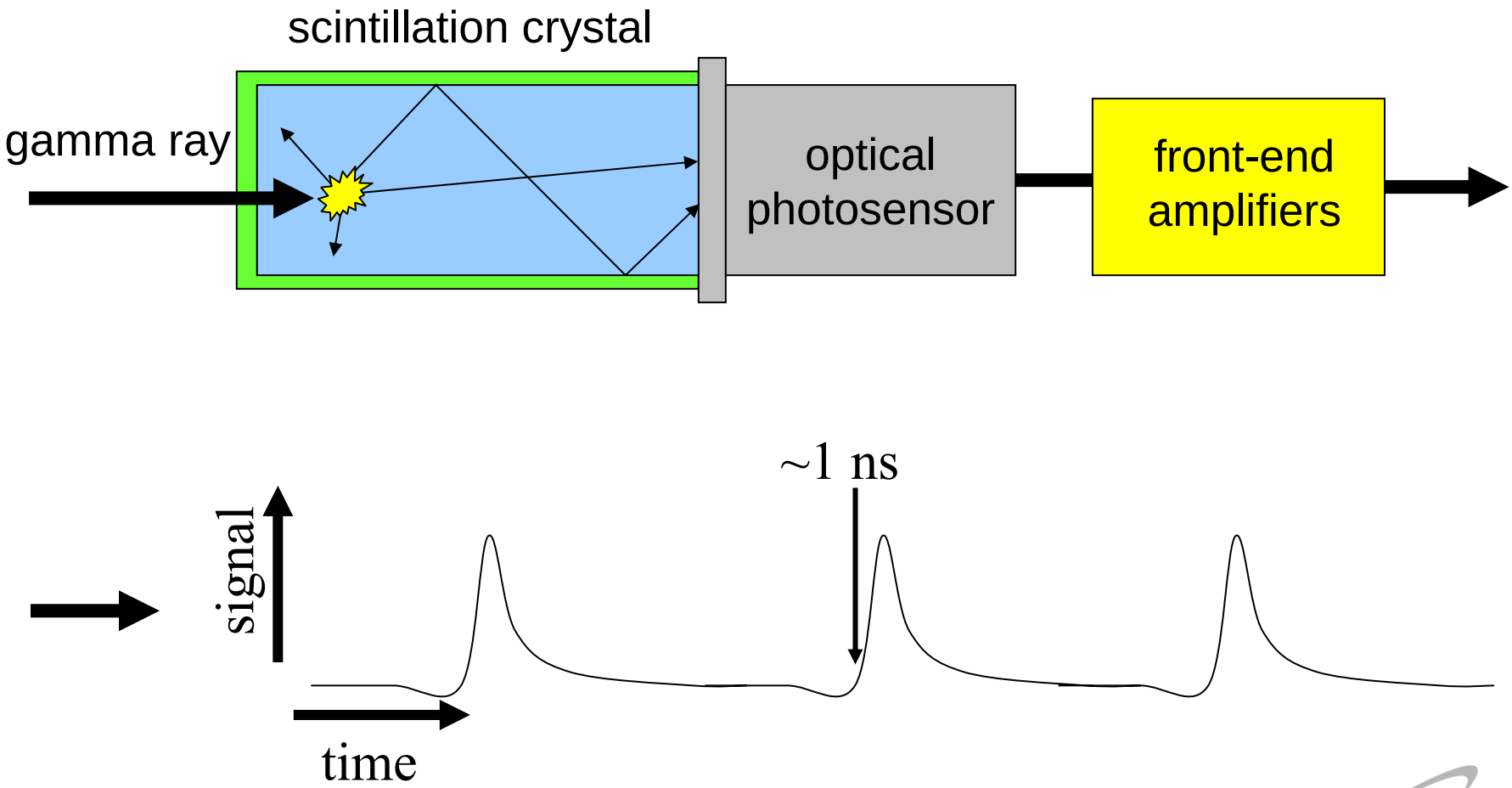
- Scattered gammas change direction AND lose energy
- Affects acceptance of scattered coincidences
- Currently ~ 20% FWHM

- Deadtime
  - Handle MHz count rates



Scatter and Attenuation

Prototypical PET Detector

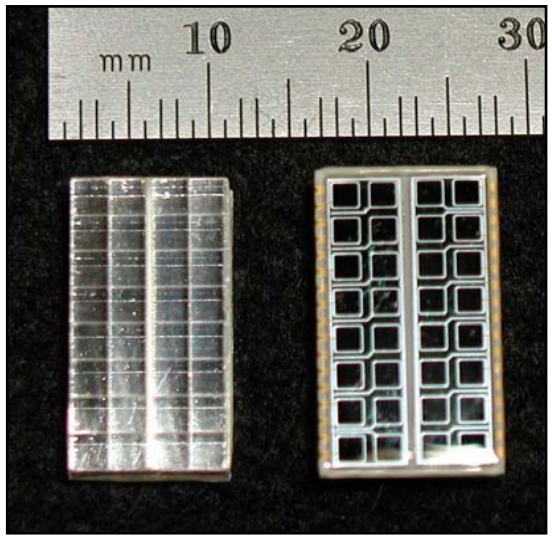


PET Detector Approaches

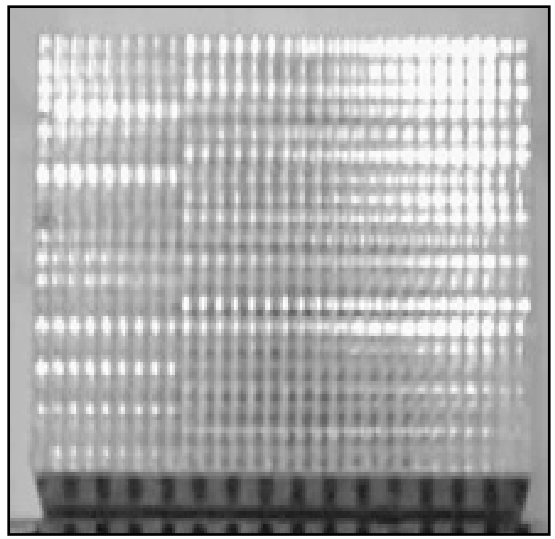
- Scintillators
  - Types - BGO, LSO/LYSO, $LaBr_3$
  - Geometries - pixels, monolithic
  - Photosensors
    - Types - PMT, PS-PMT, APD, SiPM
    - Geometries - light-sharing block, 1:1 readout
- Solid state
  - CZT, CdTe, Si
- Other
  - Pb converters and ionization - straws, RPCs

different tradeoffs

Traditional Approach



RatCAP LSO crystal array – crystals are 2x2 mm^2 in cross-section

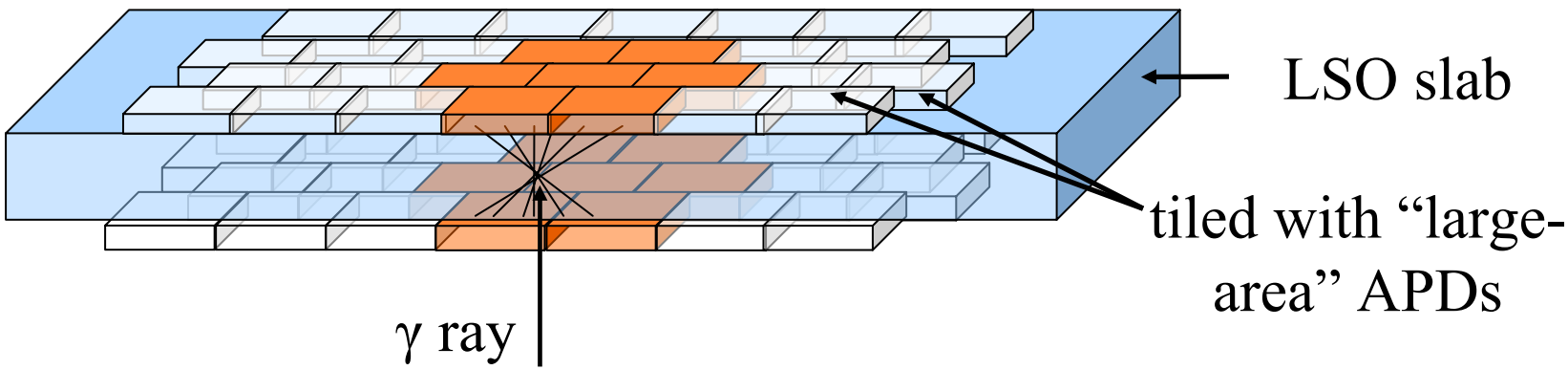


0.5 mm^2 LSO crystal array – J. Stickel et al., 2007

Approaches of BNL Imaging Physics Group

- RatCAP - pixels with 1:1 APD readout
  - Need many elex channels - ASIC
  - No ADC needed, no “position decoding” error
- Monolithic - light-sharing with APDs
  - Catching on - UWash, UPenn, Delft
- CZT
  - Stanford, UCDavis

Monolithic scintillator w/ APD readout



Potential Advantages

- Simpler design
- Improved sensitivity
- High spatial resolution
- Depth-of-interaction measurement
- *Scalable* resolution
- Fewer readout channels, reduced cost
- Simultaneous PET and MRI?**

** Talk: Maramraju et. al., M05- 3

** Poster: Ravindranath et. al., M10-56

Detector Design

single LYSO crystal and a large-area avalanche photodiode from Hamamatsu

Hamamatsu S8664-55

Active area = 5x5 mm^2

Gain ~200

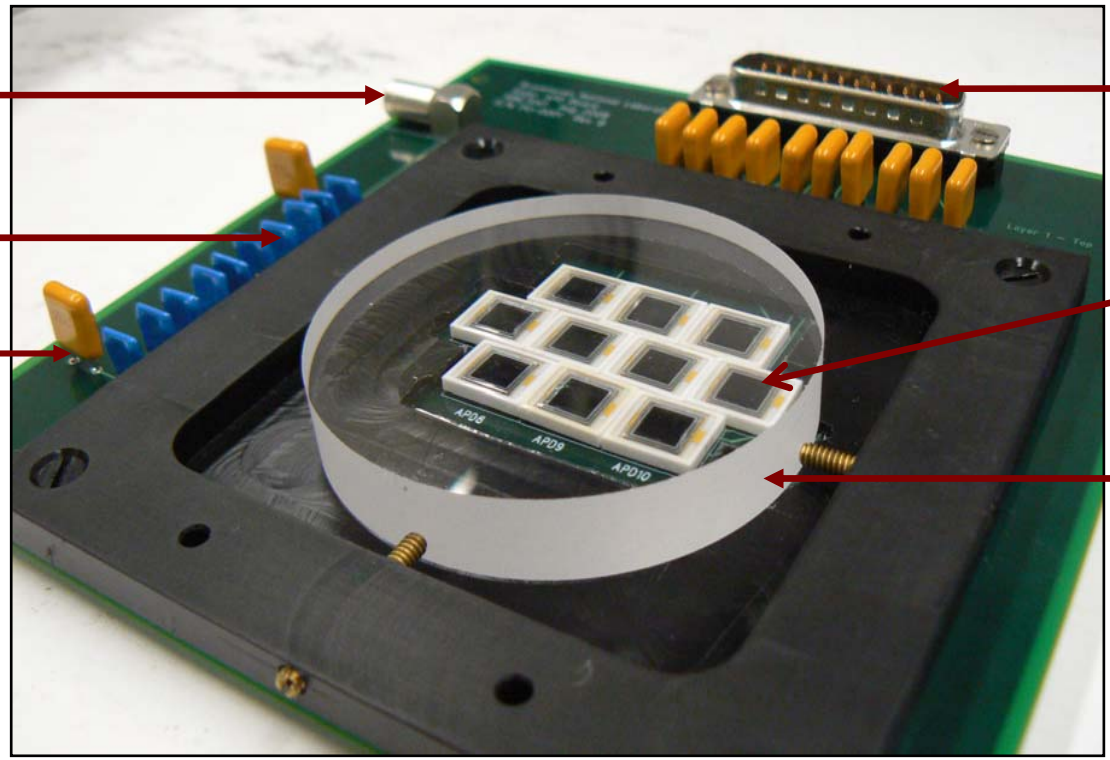
Dark Current ~70 nA

Capacitance = 80 pF

Quantum Efficiency = 70 %

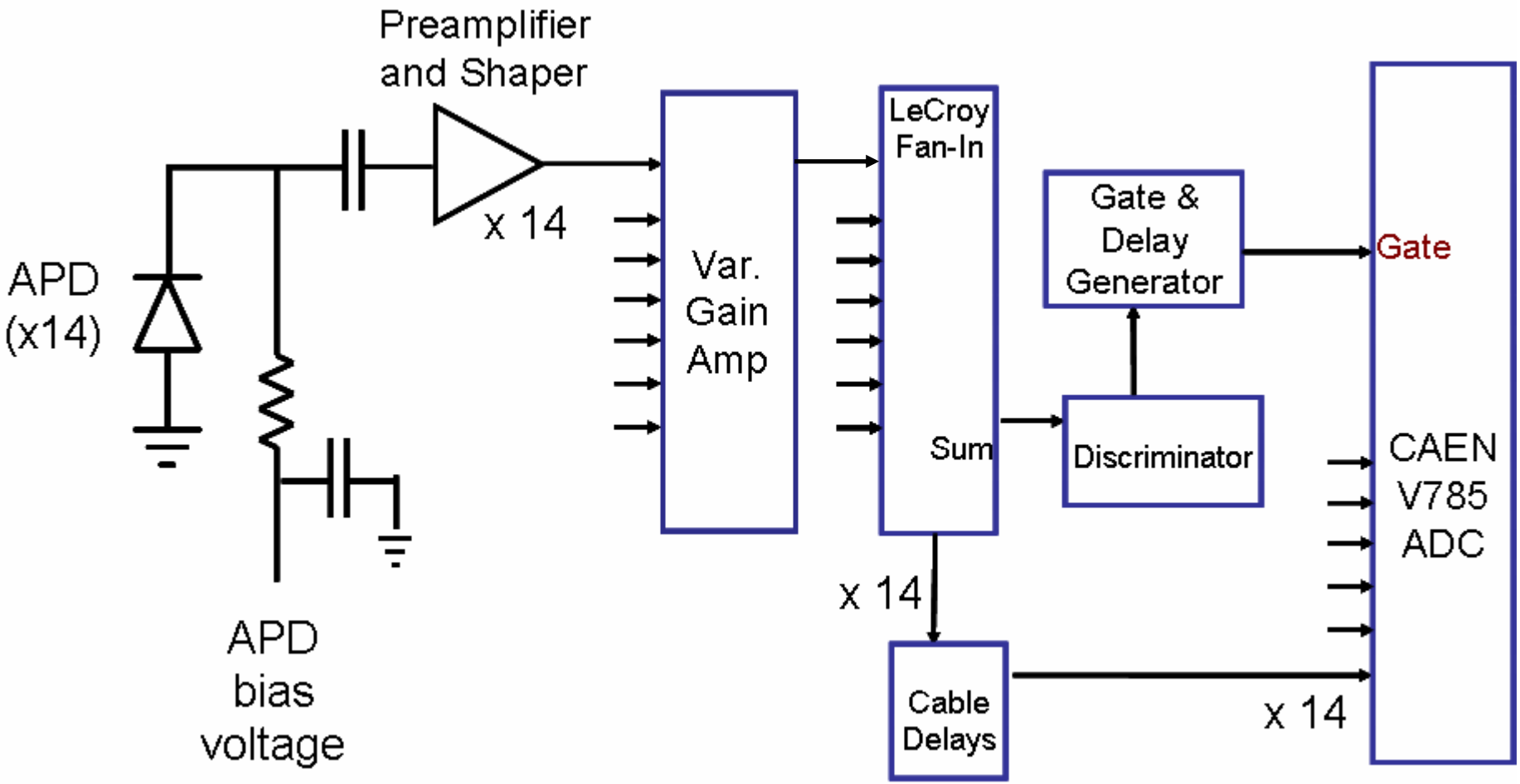
Fractional active area ~ 25 %

Assembled Detector



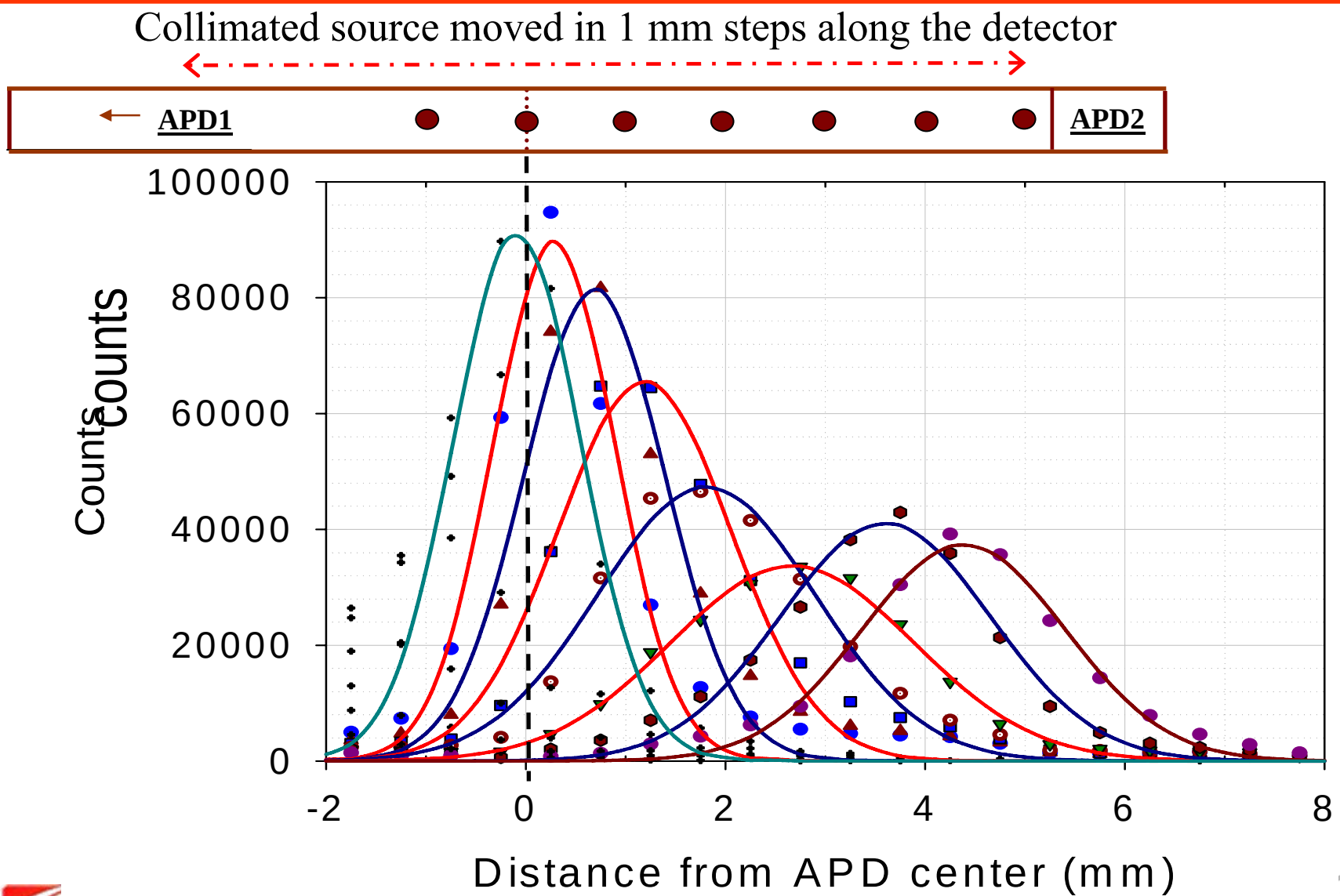
an identical board containing APDs is mounted on the other side of the crystal

Readout Electronics



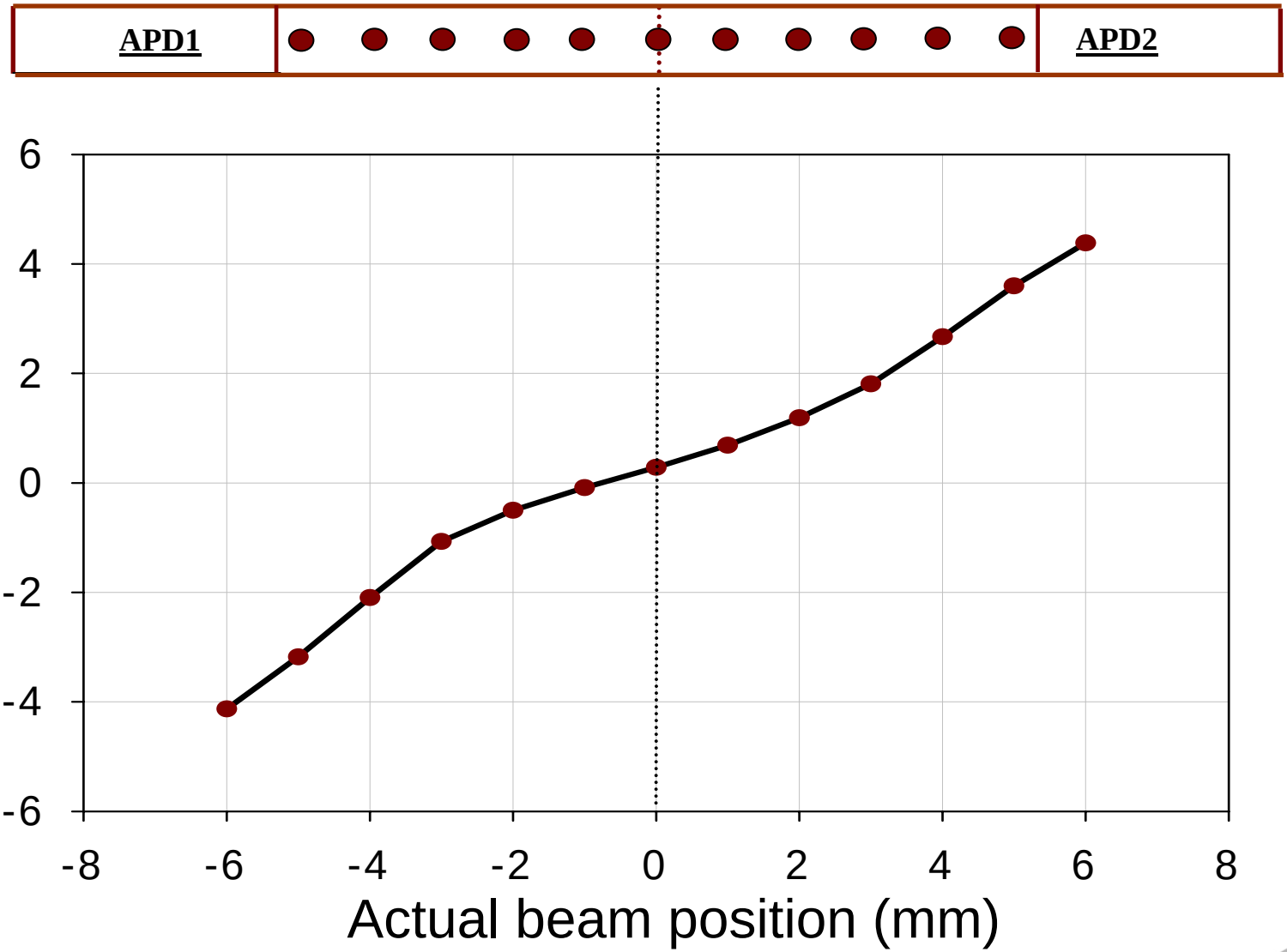
Initial Characterization

Experimental



Linearity
Central APD

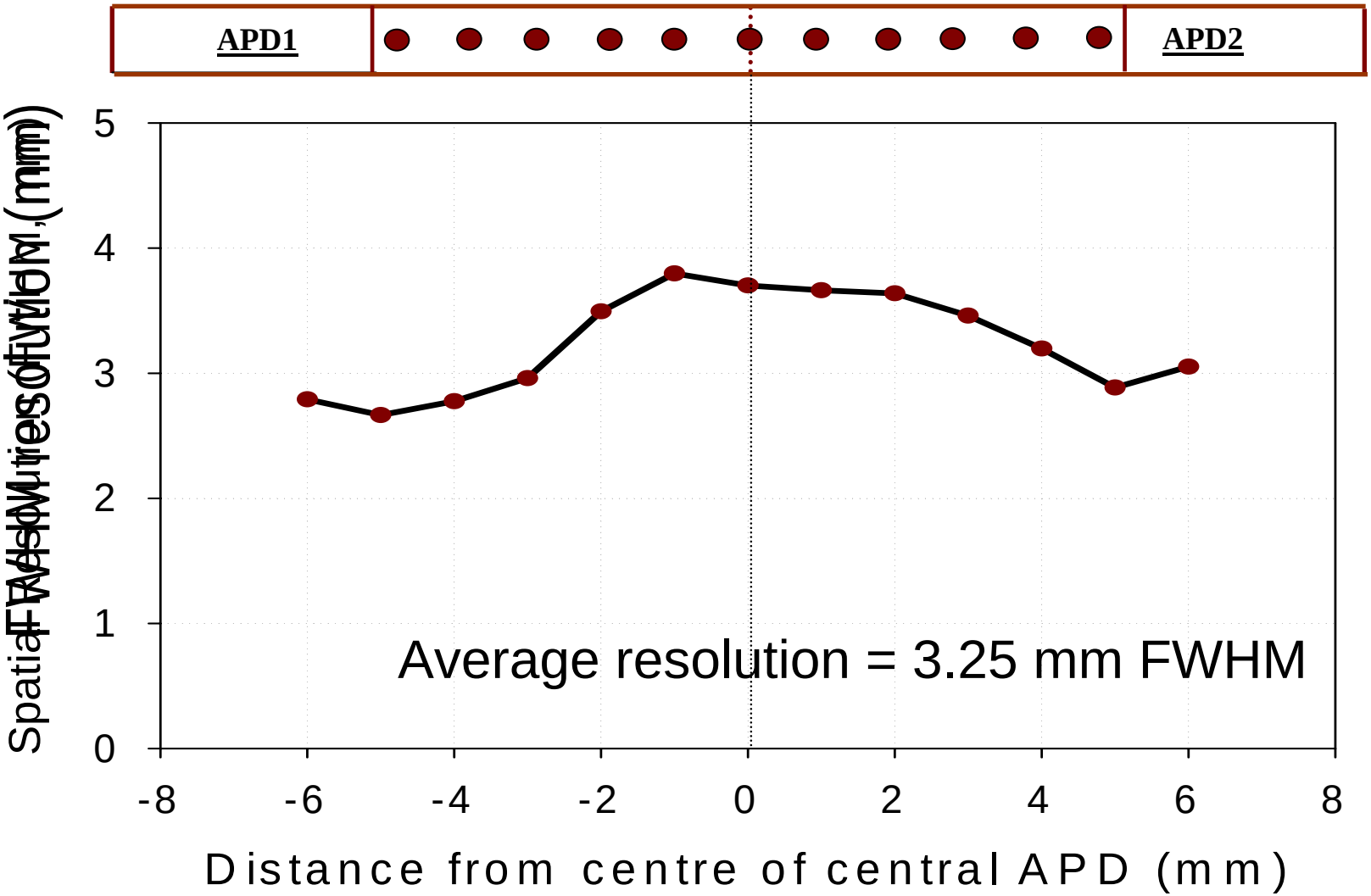
Experimental



Spatial Resolution

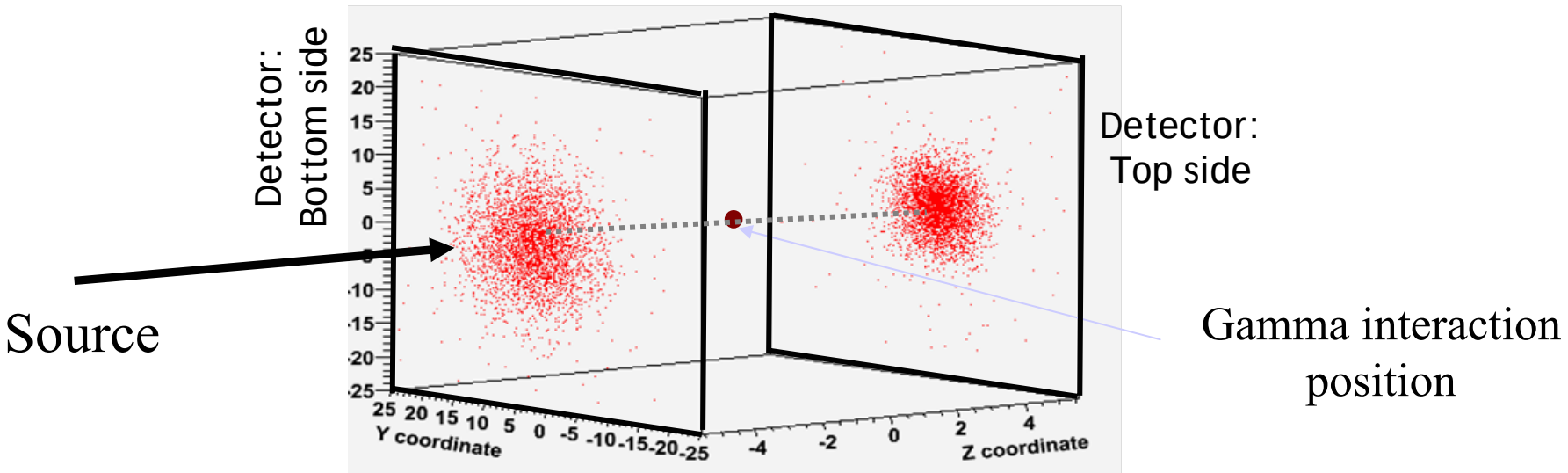
Central APD

Experimental



Depth of interaction

Simulation



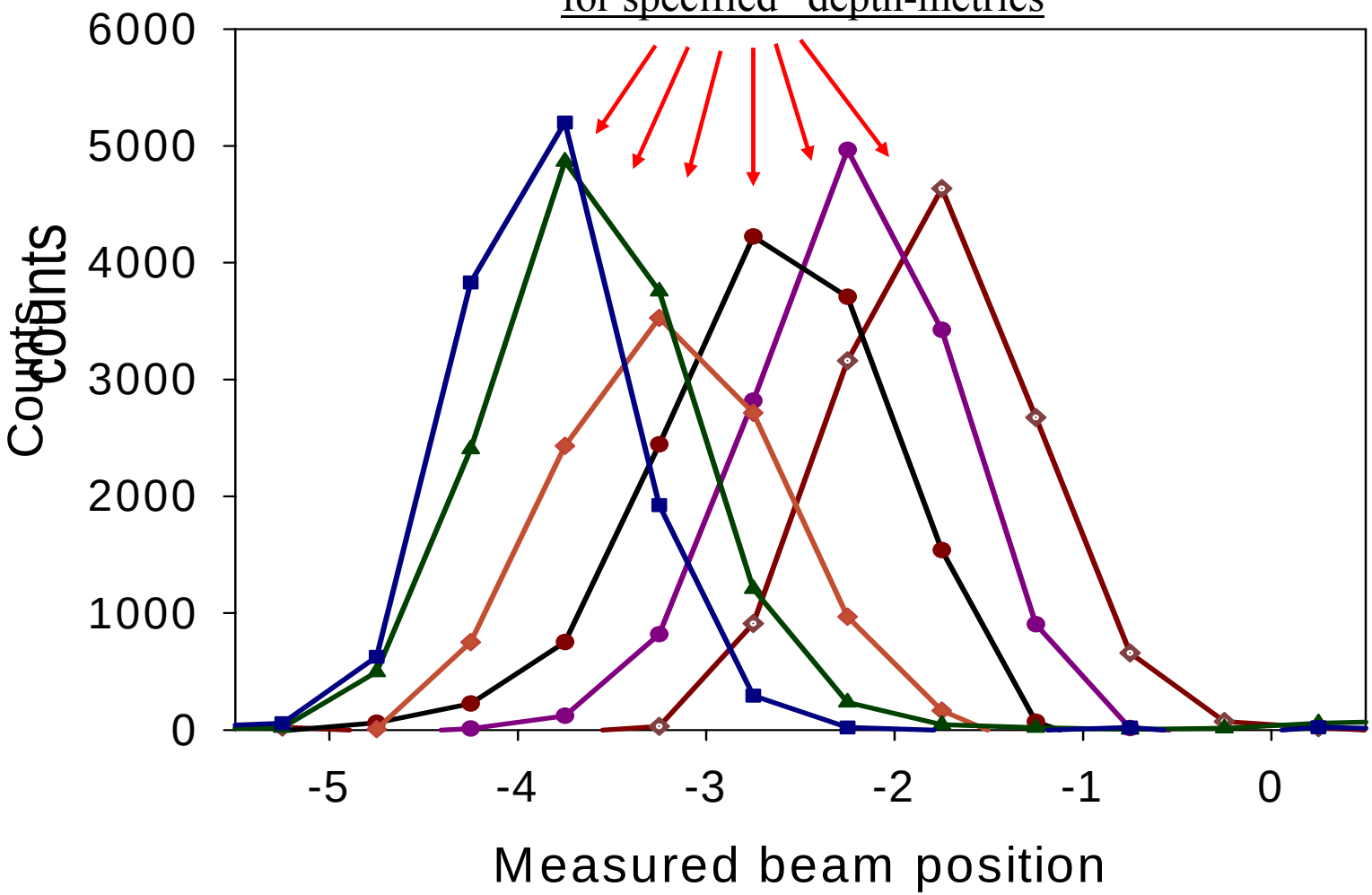
Depth of Interaction = Ratio of dispersion of signal on both sides

"depth-metric"

Measuring DOI

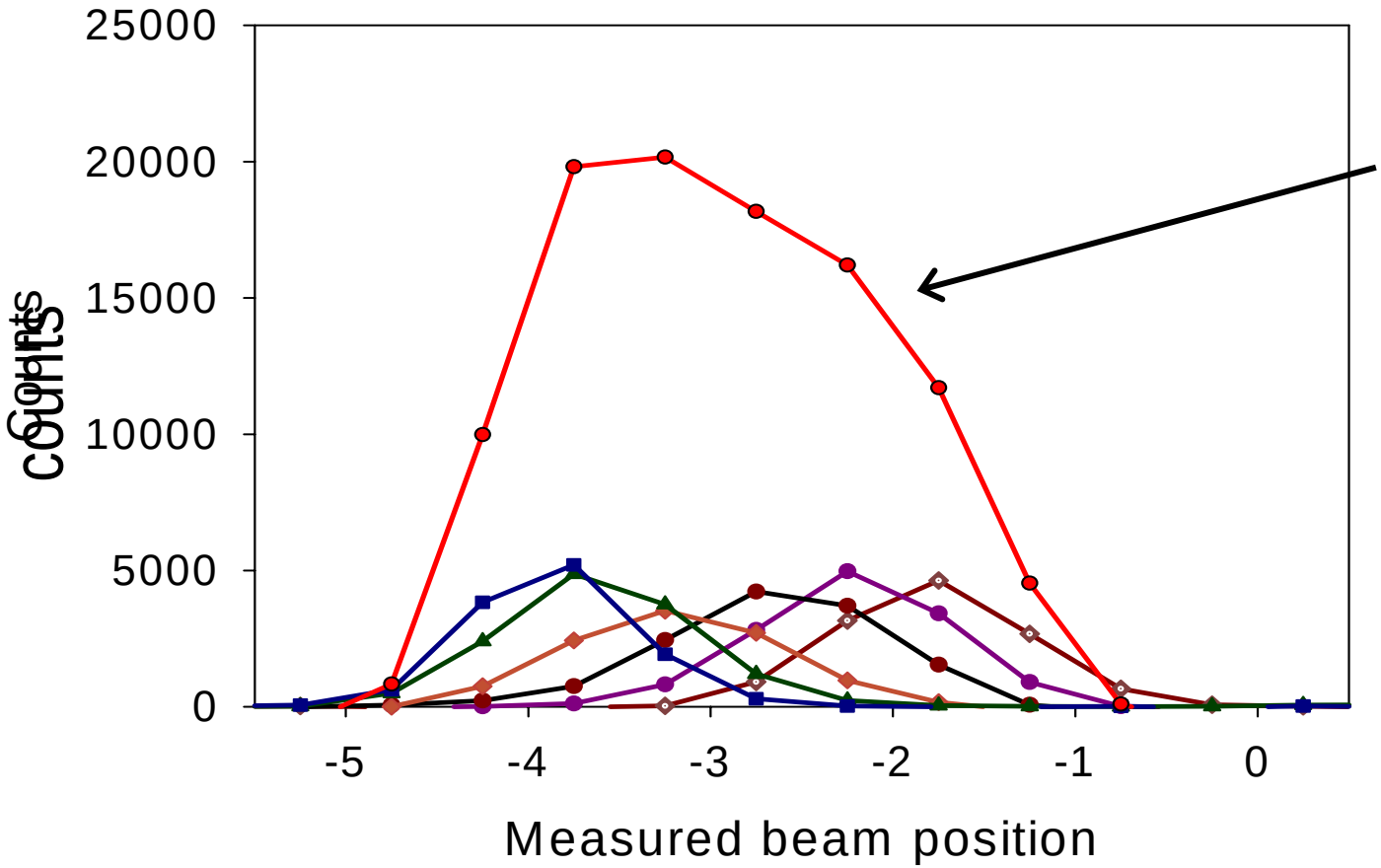
Experimental

Histogram of the measured transverse beam position for specified "depth-metrics"



Measuring DOI

Experimental



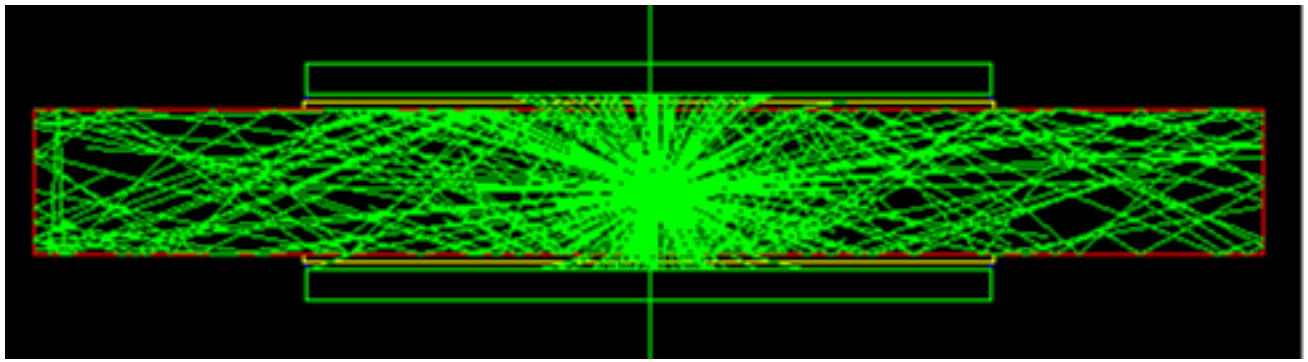
Histogram of the measured beam position without using the "depth metrics"

Suggests we can: a) measure "depth of interaction"

b) improve the transverse spatial resolution

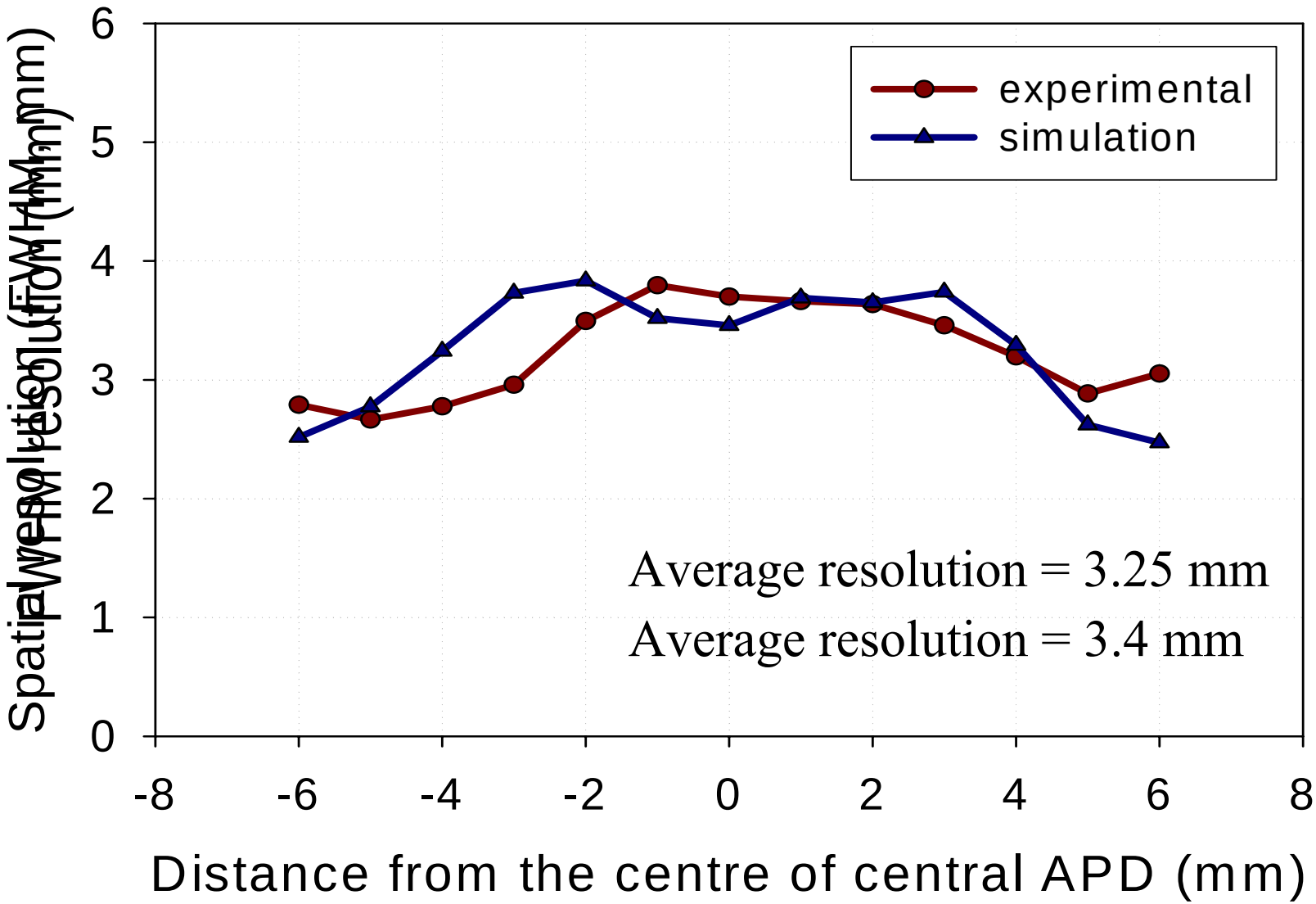
Monte Carlo simulation

GATE – "**Geant4** Application for Emission Tomography"



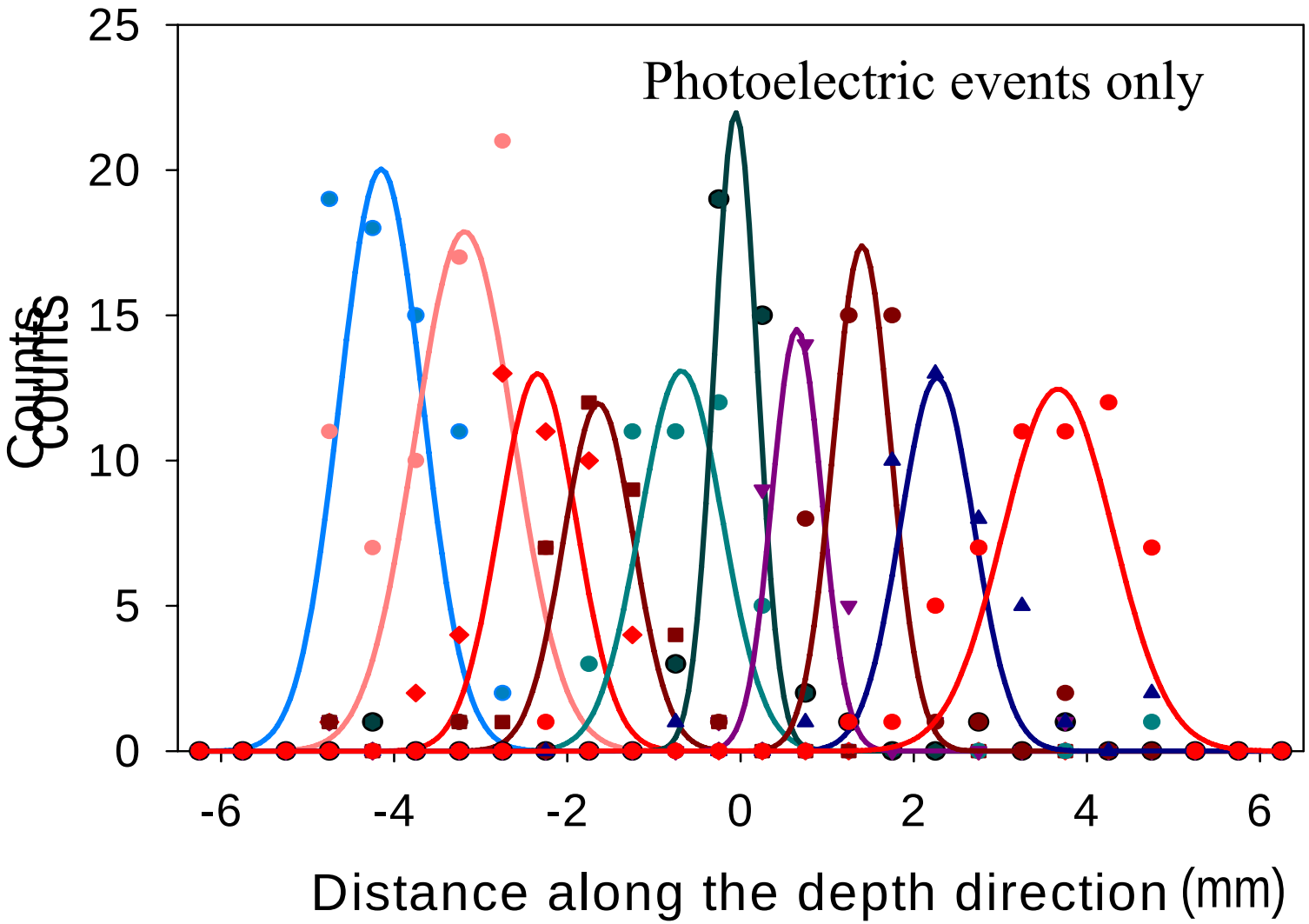
LSO light yield = 26,000 photons/MeV
LSO intrinsic resolution ~ 10 %
APD quantum efficiency = 70 %
APD gain = 200
APD excess noise = 2.2
Electronic noise = 2500 e- rms

Spatial resolution



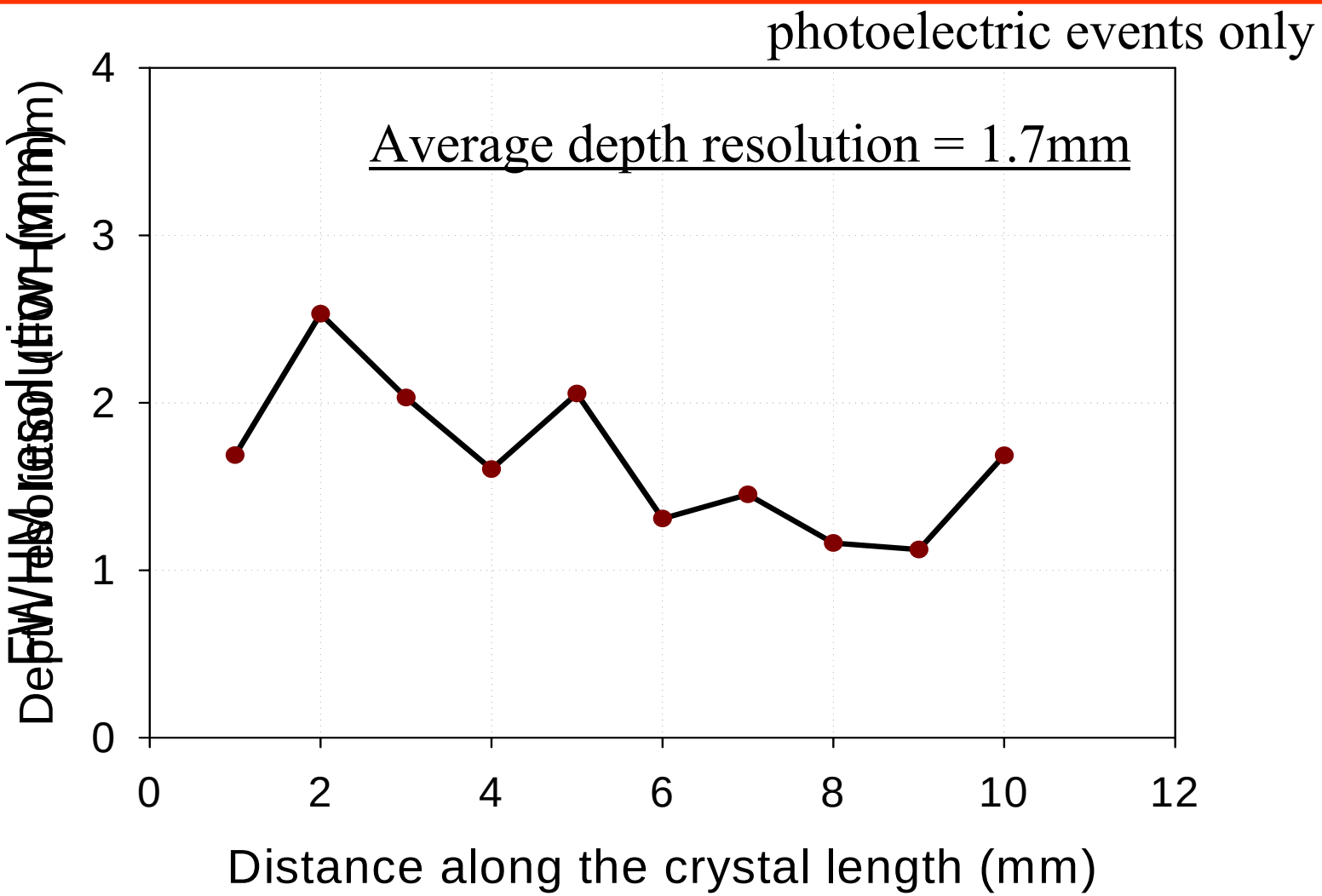
More DOI

Simulation



More DOI

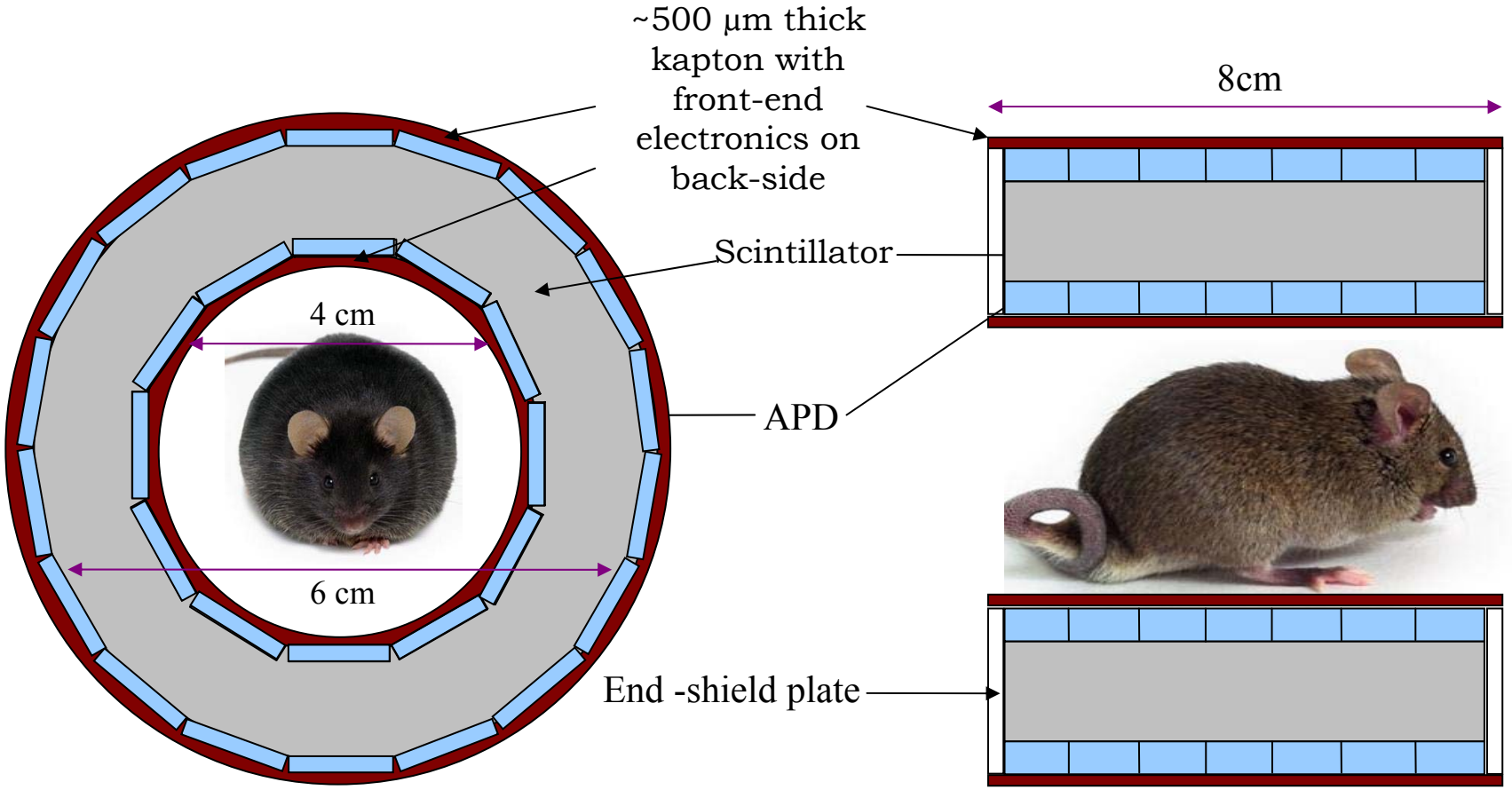
Simulation



Summary

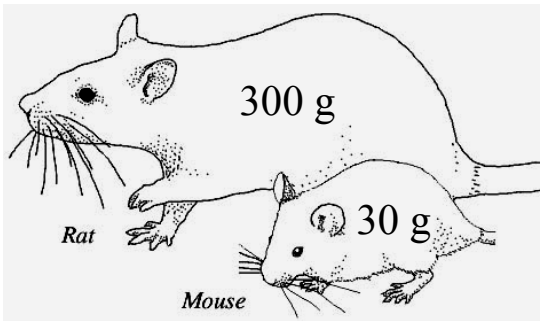
- Future work
  - Measure DOI resolution - not so easy
  - Implement ML positioning algorithm
  - Measure/optimize timing
  - Better scintillator? - LaBr3
  - Better photosensor - higher packing APD, SiPM
- Lessons learned
  - Perseverence pays!
  - Improvements in scintillator, APD, coupling, front-end elex, daq, processing

Potential application



CZT for Ultra-High Resolution PET

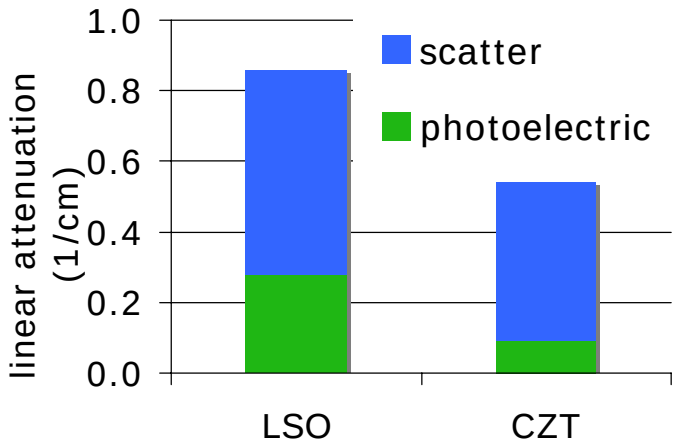
- Transgenic mouse models
  - 2007 Nobel Prize in Medicine
  - facilitate PET with these models



- Human
  - micrometastases in human cancer
  - more accurate quantitative brain studies

Cadmium Zinc Telluride

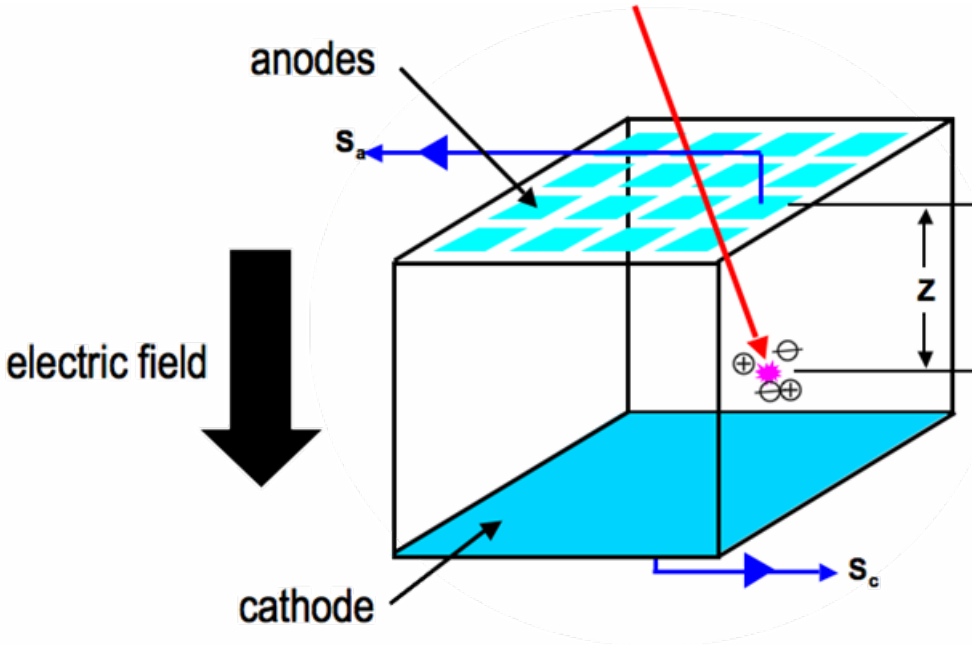
- Advantages for PET
  - No photodetector, room temperature
  - Spatial resolution
  - Depth resolution - parallax
  - Energy resolution - Compton kin
  - MR-compatible(?)

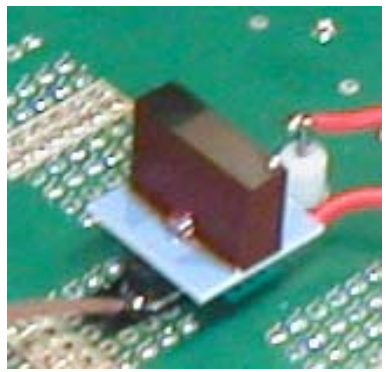


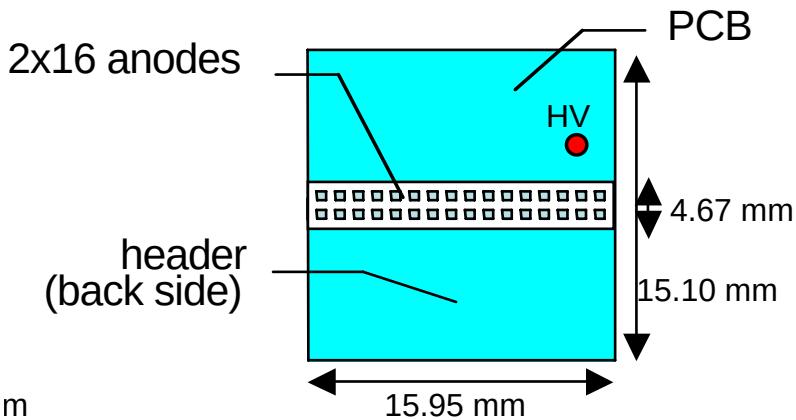
- Challenges
  - Detection efficiency - ~3x < LSO
  - Slow charge collection - randoms
  - Yield/cost - new competition

CZT Pixel Detector

- 3D spatial resolution
- eV Products 16 x 2 anodes on 1 mm pitch



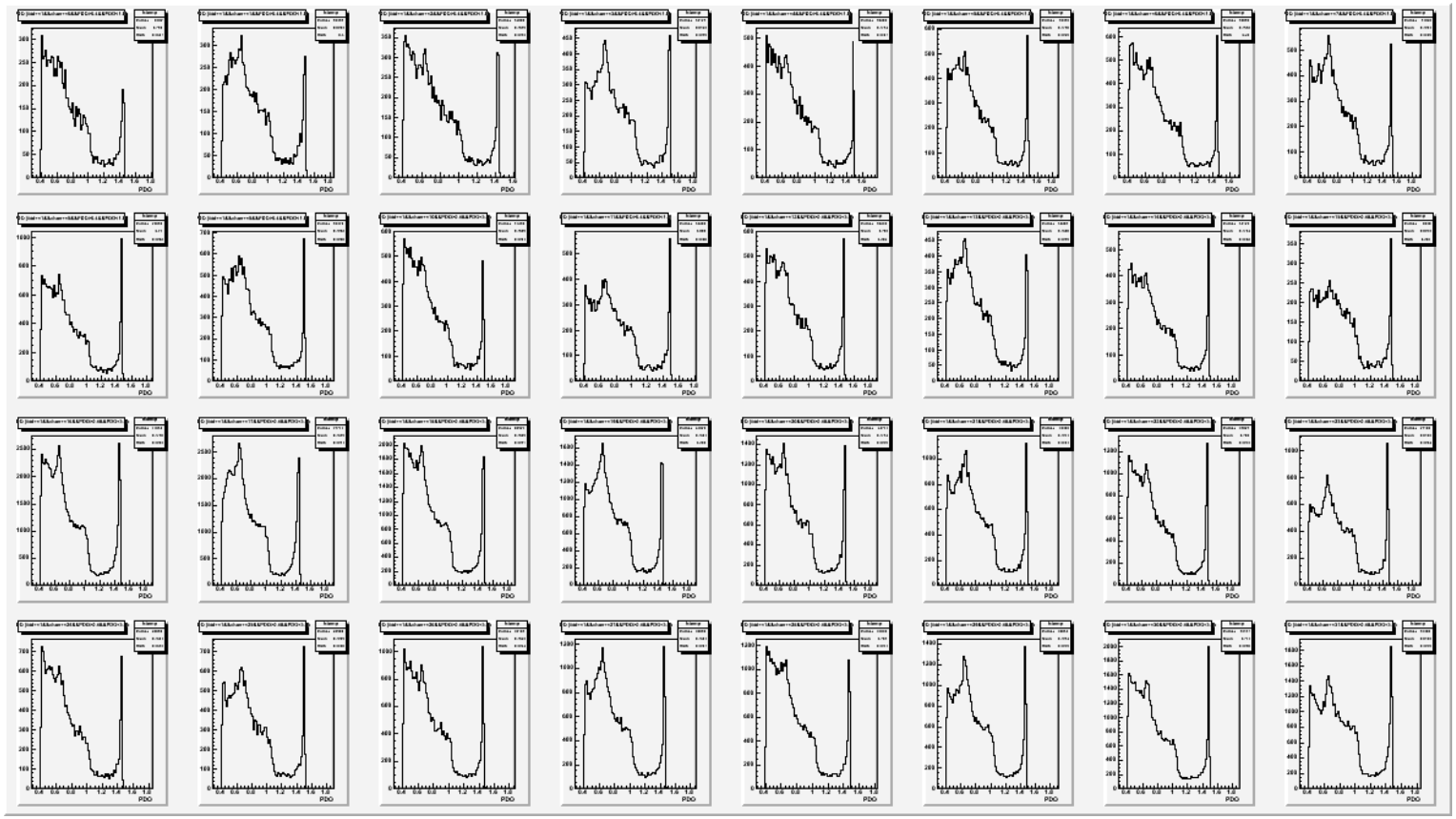




m

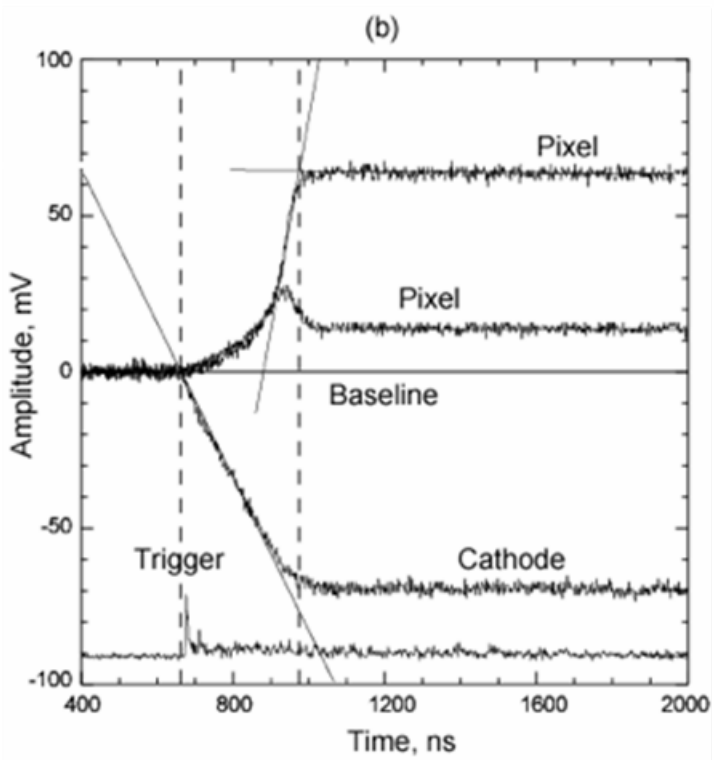
Detector Performance

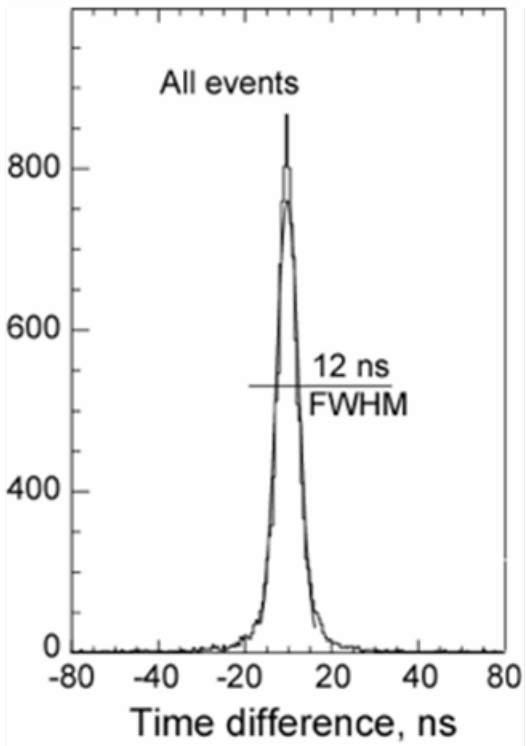
- Energy resolution from one detector
  - < 2 % FWHM on all anodes



Detector Performance

- Potential time resolution ~10 ns FWHM

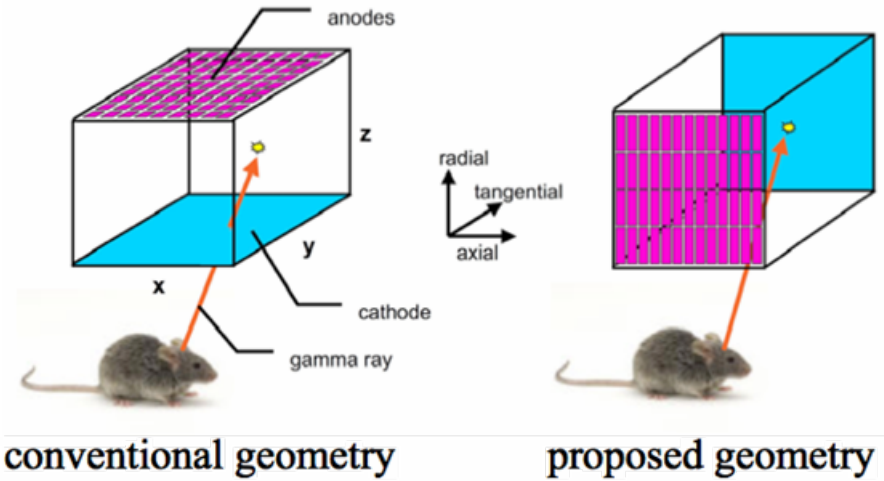


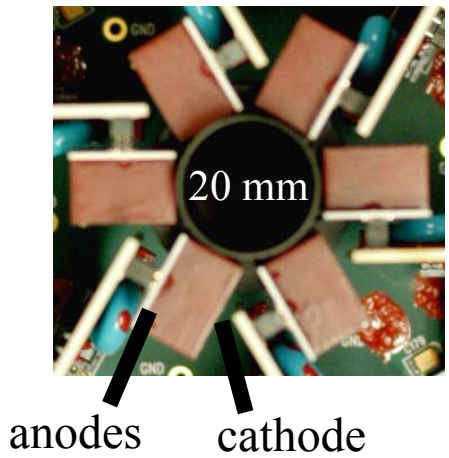


A. Bolotnikov

Prototype design

- Novel geometry
  - Optimal use of cathode-anode resolution
  - Increase “depth” without drift time/trapping/HV issues

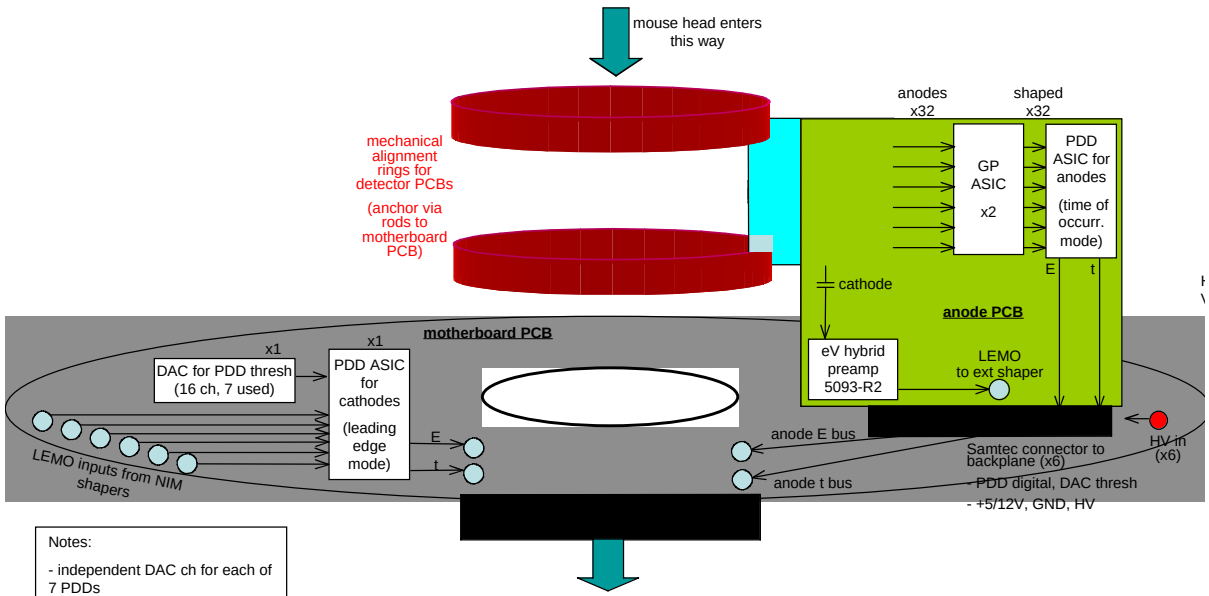


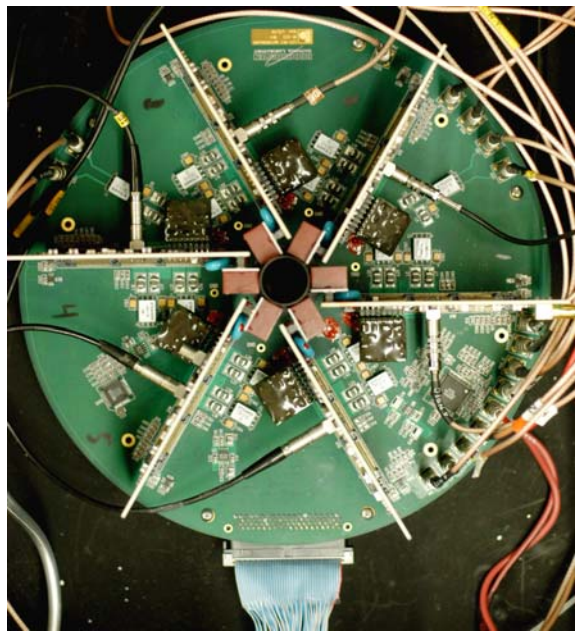


- Limitations of prototype
  - Timing - off slow shaped anode signal only
  - Sensitivity - one plane only

Electronics

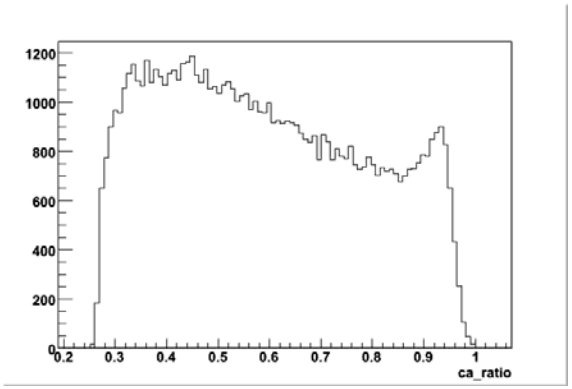
- circular motherboard + 6 detector boards (Pratte, Cui, Fried, Dragone)
- anodes: GP ASIC preamp and shaper (1.2 us)
- cathodes: Cremat preamp and shaper (2 us)
- energy peak-hold + discr + TAC: PDD ASIC (DeGeronimo)
- ADCs and data acquisition: MIOS (Fried)
- 1500 V, LLD = 450 keV

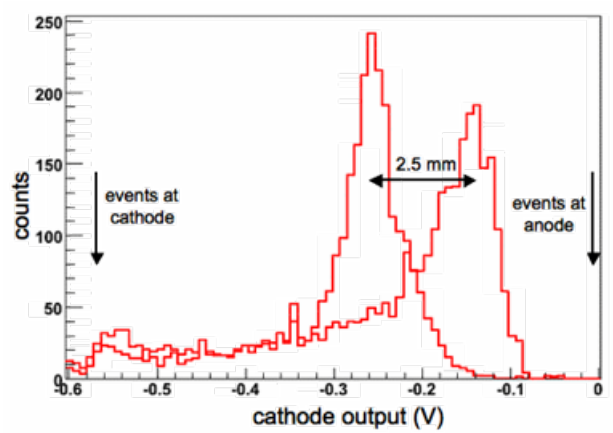


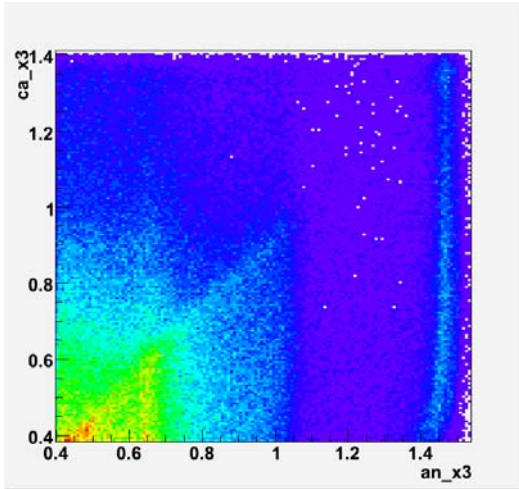


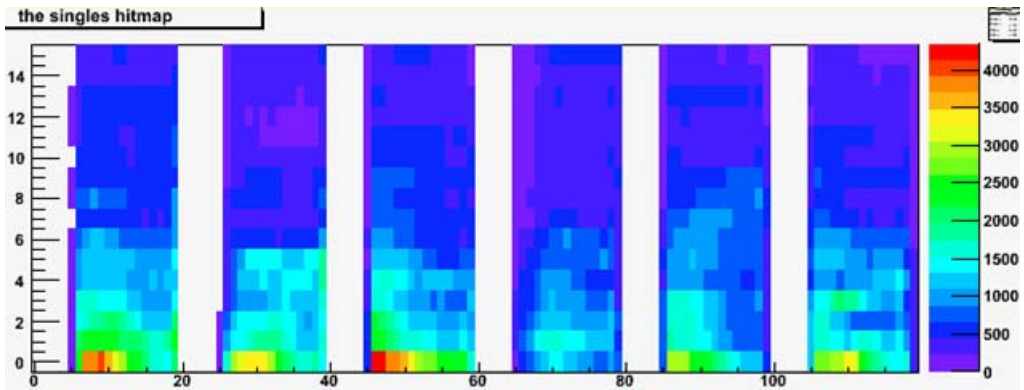
“Depth” response

- C/A binned into 20 bins = ~ 0.5 mm per bin



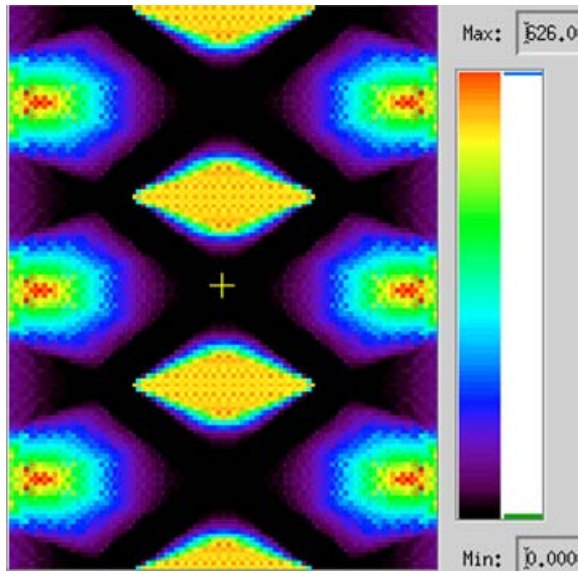






Data processing

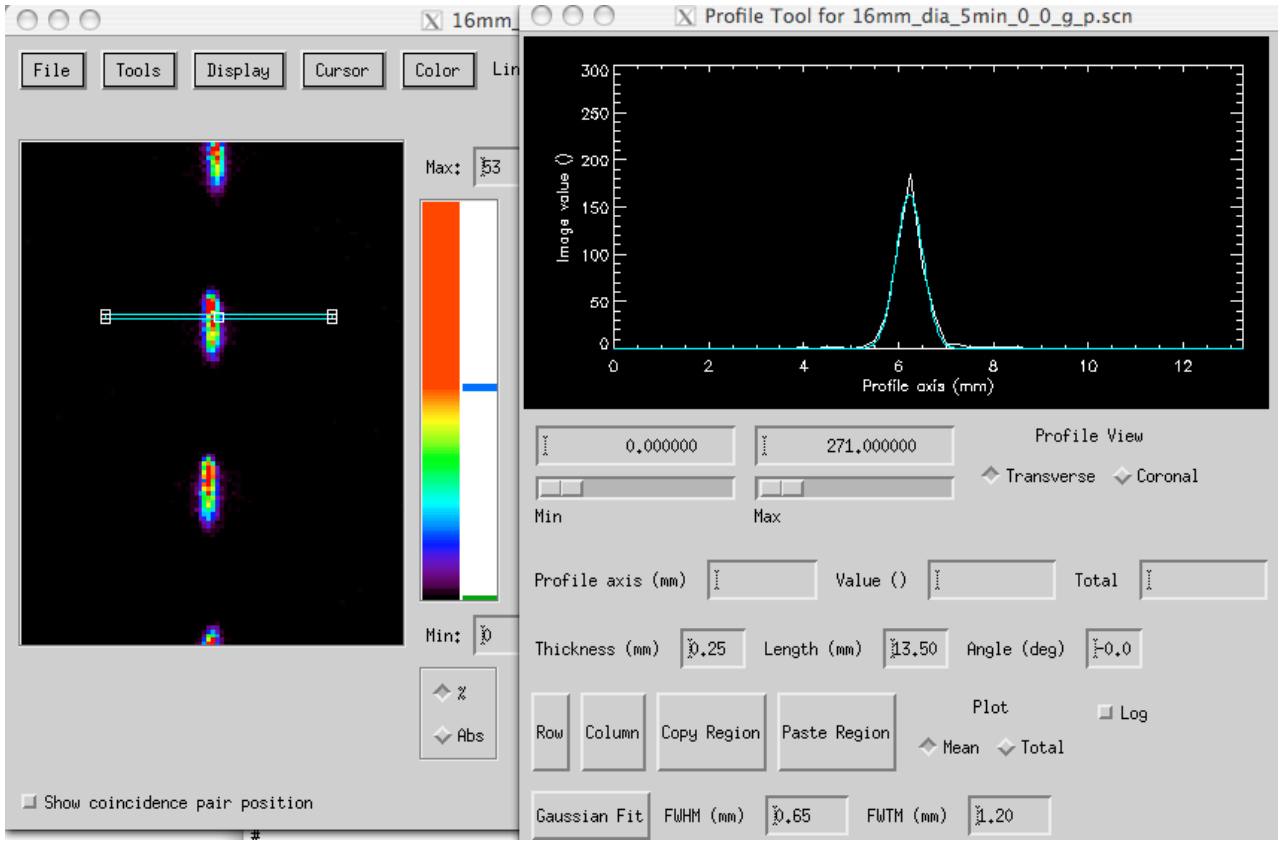
- Coincidences
  - tau = 300 ns window (anode time only)
  - Prompt and delayed windows



- Sinogram sampling
  - 0.25 mm in r
  - 91 r x 120 phi
  - Gaps, nonuniform sampling

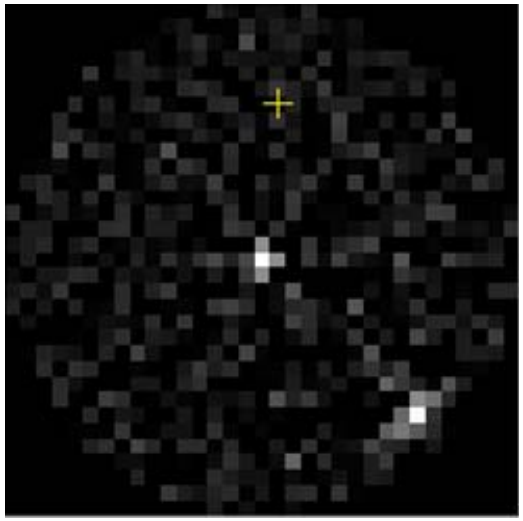
- Image reconstruction
  - 0.5 mm voxels, 33x33 voxels, one plane only
  - MLEM
    - *measured* system matrix (~800 voxels)
    - 0.25 mm dia., 30 uCi Na-22 source

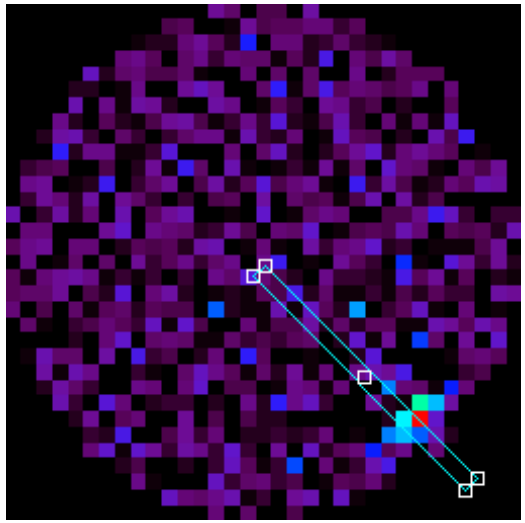
Sinogram Resolution

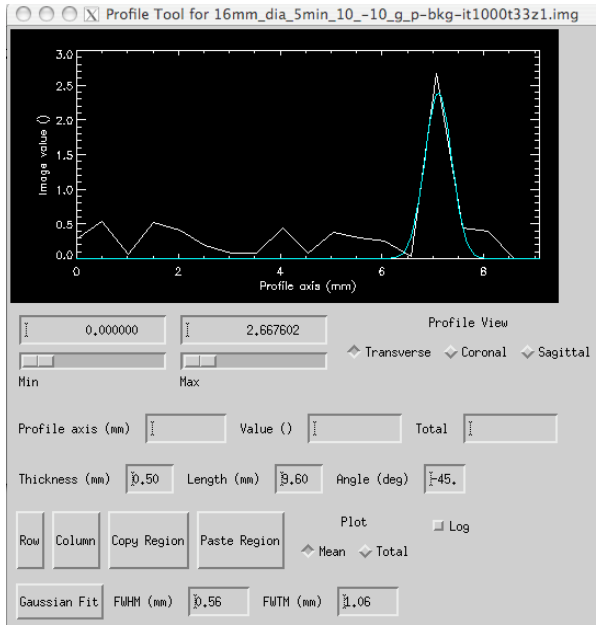


- 0.65 mm FWHM
- 1.20 mm FWTM

Image Resolution



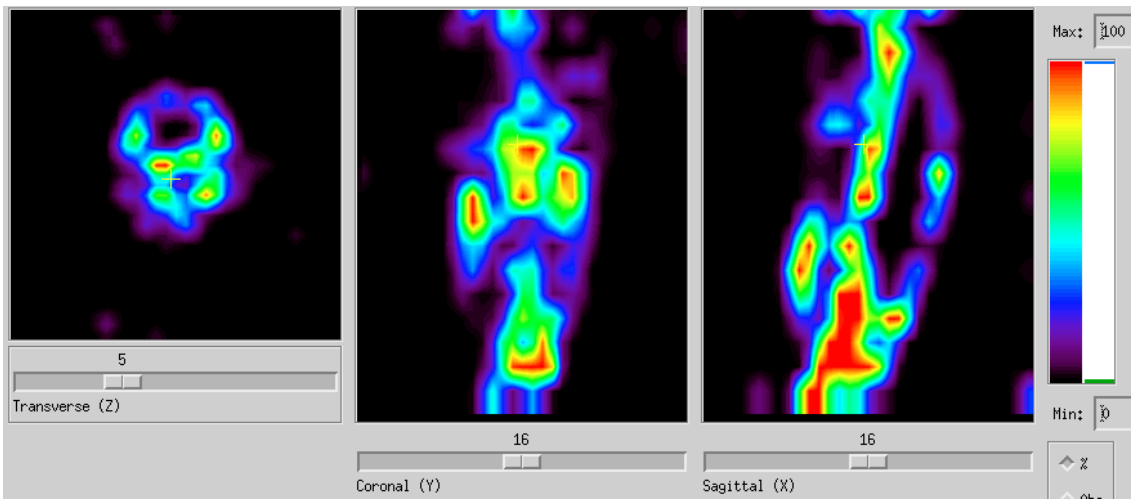


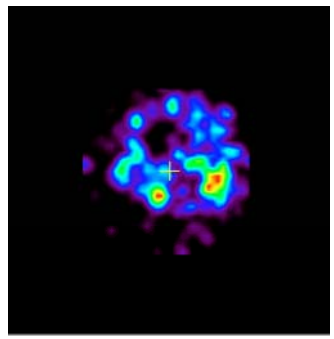


- point source in warm background
- image resolution averages for 0 & 7 mm radius:
  - radial 0.73(1.38) mm FWHM
  - tangential 0.85(1.56) mm FWHM

Animal Data

- ^{18}F-fluoride mouse skull bone scan
  - 1.5 mCi, 1 hr uptake
  - RatCAP scan, then CZT PET scan
  - 1 mm FWHM post-smoothing for CZT
  - high randoms ~50%





Next steps

- Increase/optimize HV
- Improve depth reponse and measure depth response directly
- Improve timing
- Measure sensitivity
- Lower threshold to recover detector scatter
- Mouse brain data - raclopride

Acknowledgements

- Srilalan Krishnamoorthy
- Dohyun Kim
- JF Pratte

- RatCAP group
- Instrumentation

- DOE, NIH