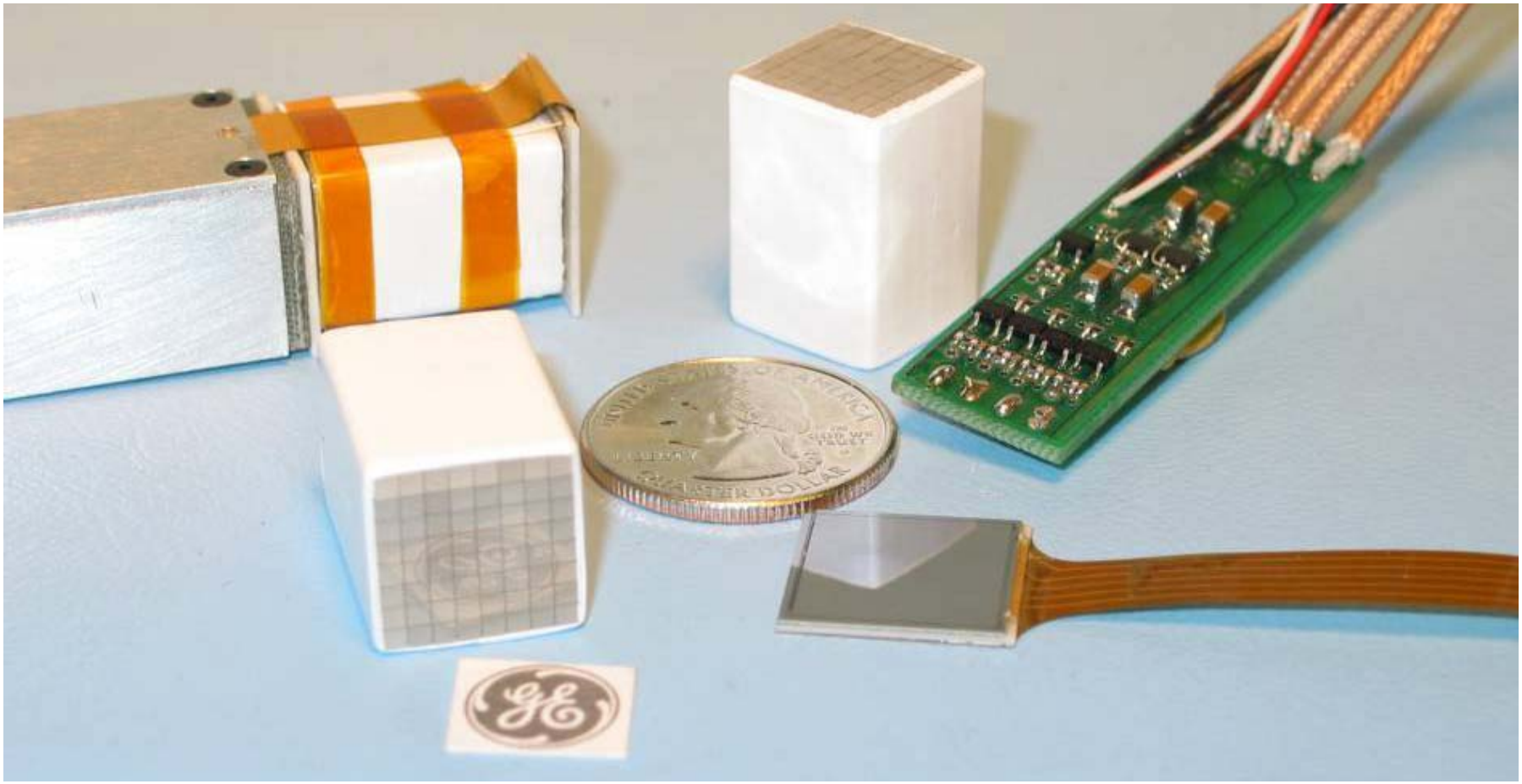
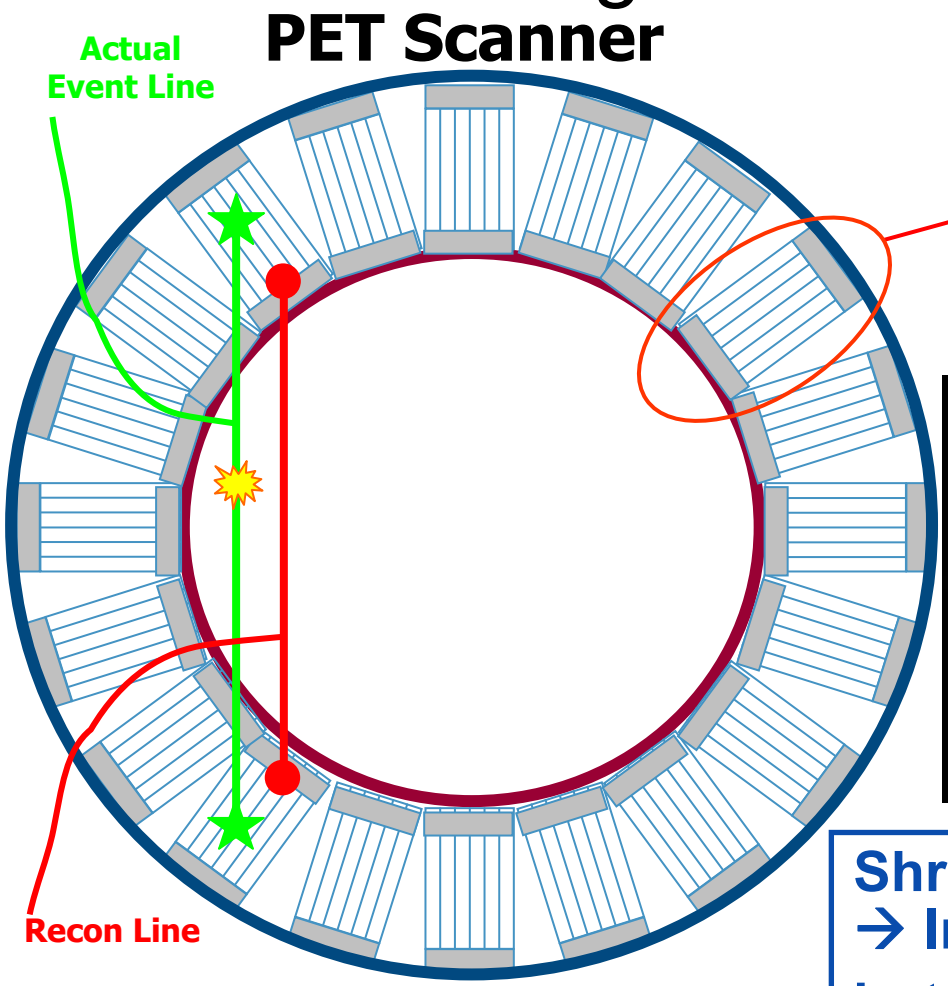
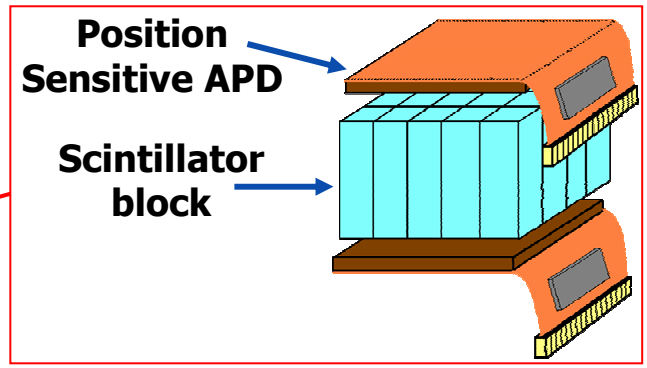
Design of Scintillator Arrays for Dual-End Depth-of-Interaction Encoding Small-Animal PET Detectors

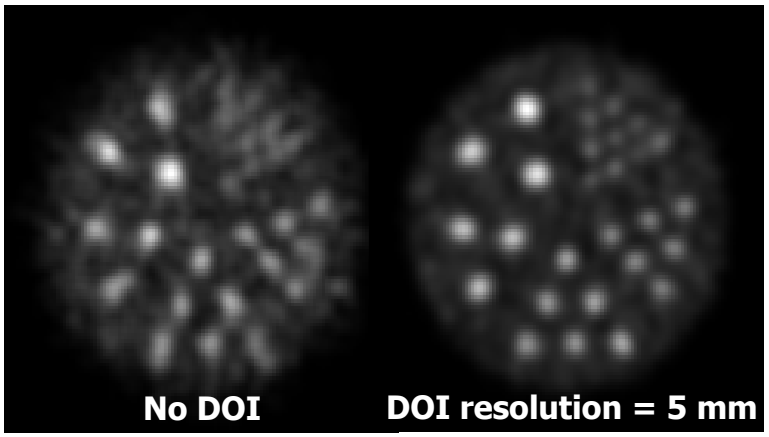


Kent Burr, Adrian Ivan, Don Castleberry, Jim LeBlanc
Detector Technology Lab, GE Research

Challenges in Small-Animal PET







Shrink the bore and use long crystals → Increase sensitivity

but …

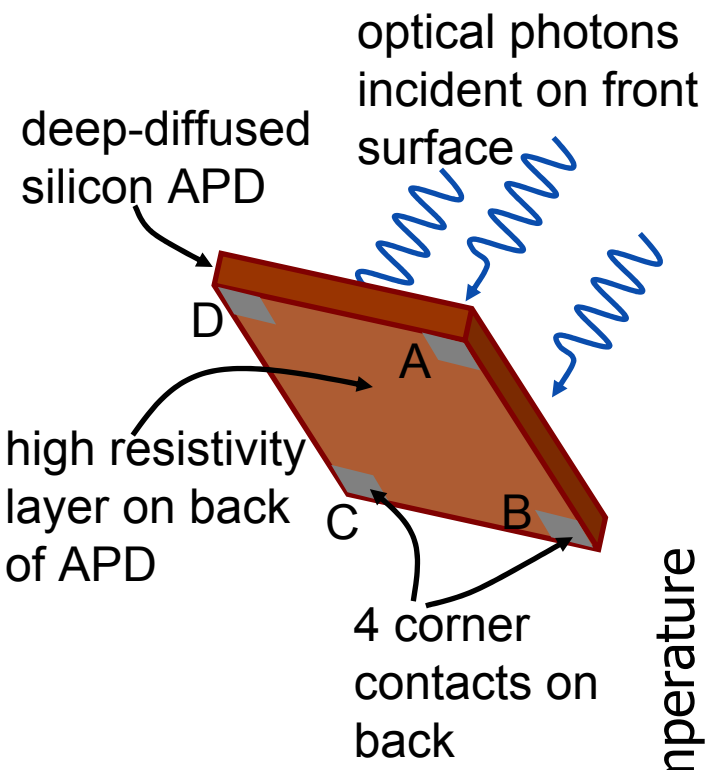
Parallax error → Lose resolution

3D Position Information Breaks Inverse Relationship between Sensitivity and Resolution

*animated

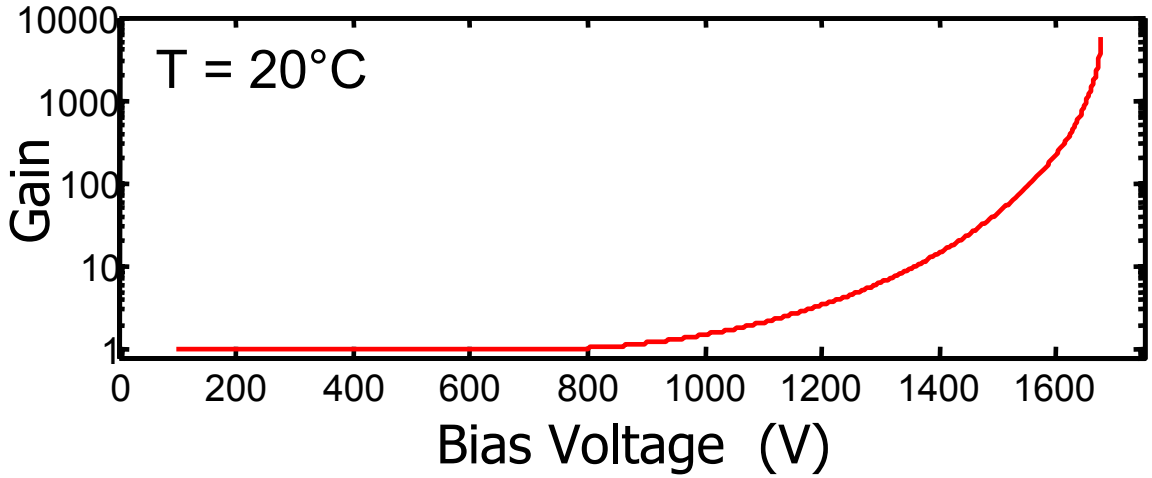
imagination at work

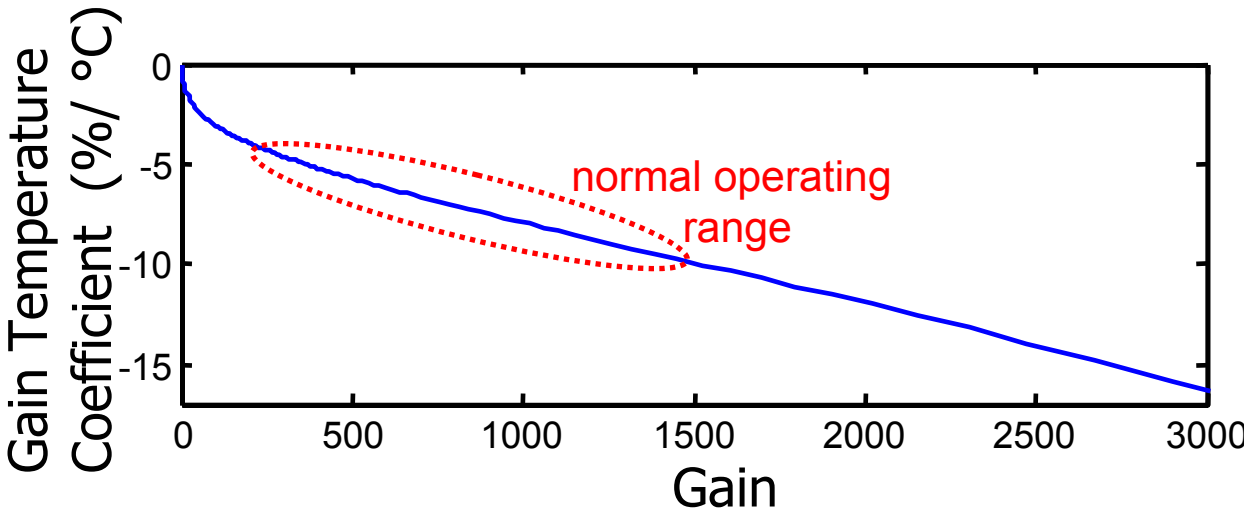
Position Sensitive APD* introduction



$$x = \frac{(A+B)-(C+D)}{(A+B+C+D)}$$

$$y = \frac{(A+D)-(B+C)}{(A+B+C+D)}$$





*PSAPDs manufactured by Radiation Monitoring Devices, Inc., Watertown, MA, USA.

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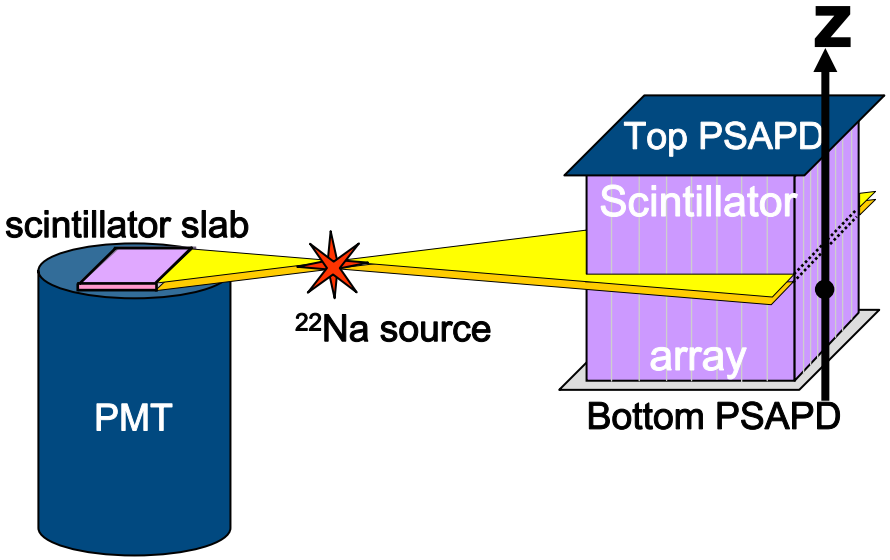
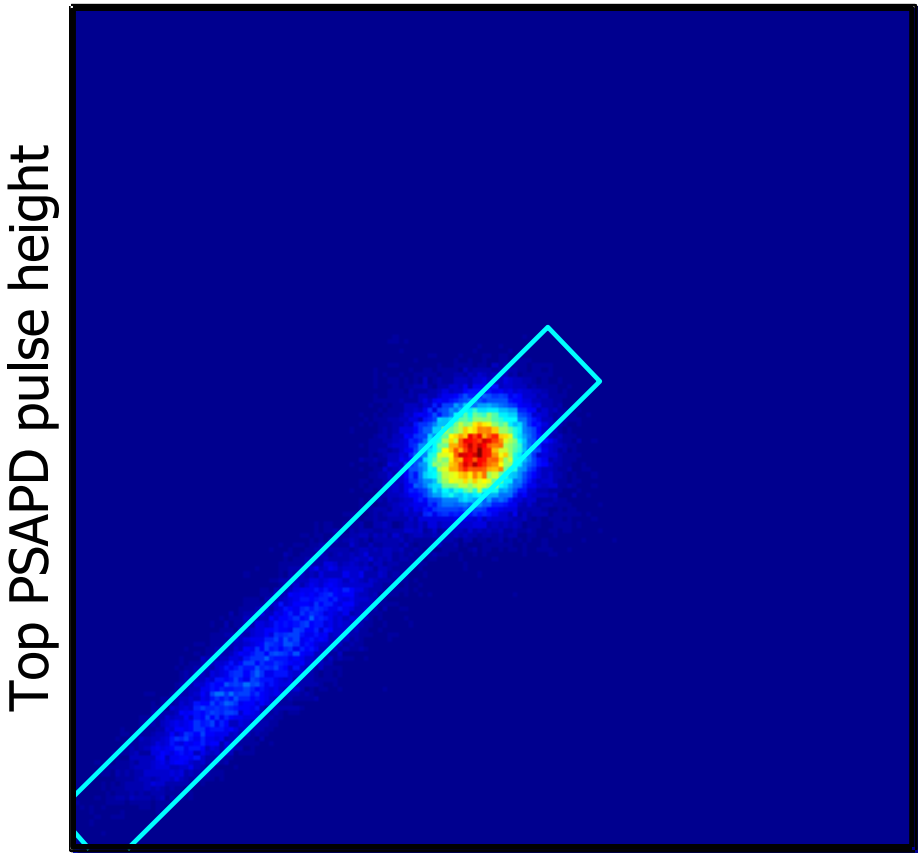
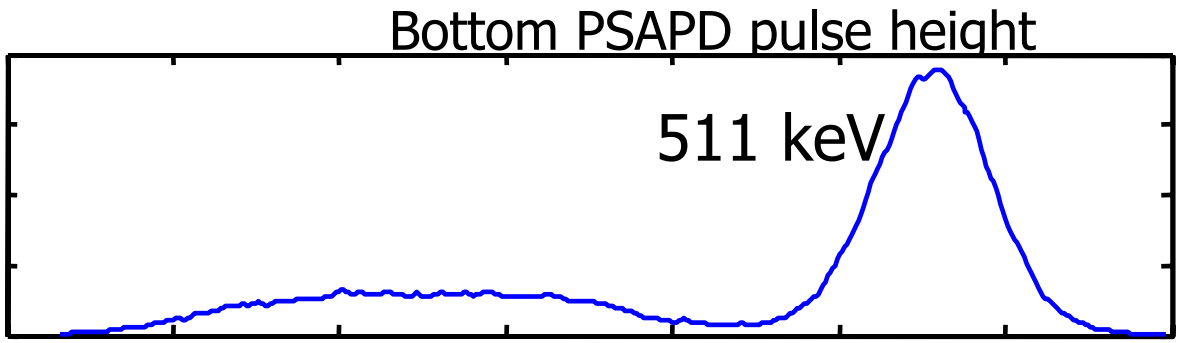
Depth-of-Interaction Illustration



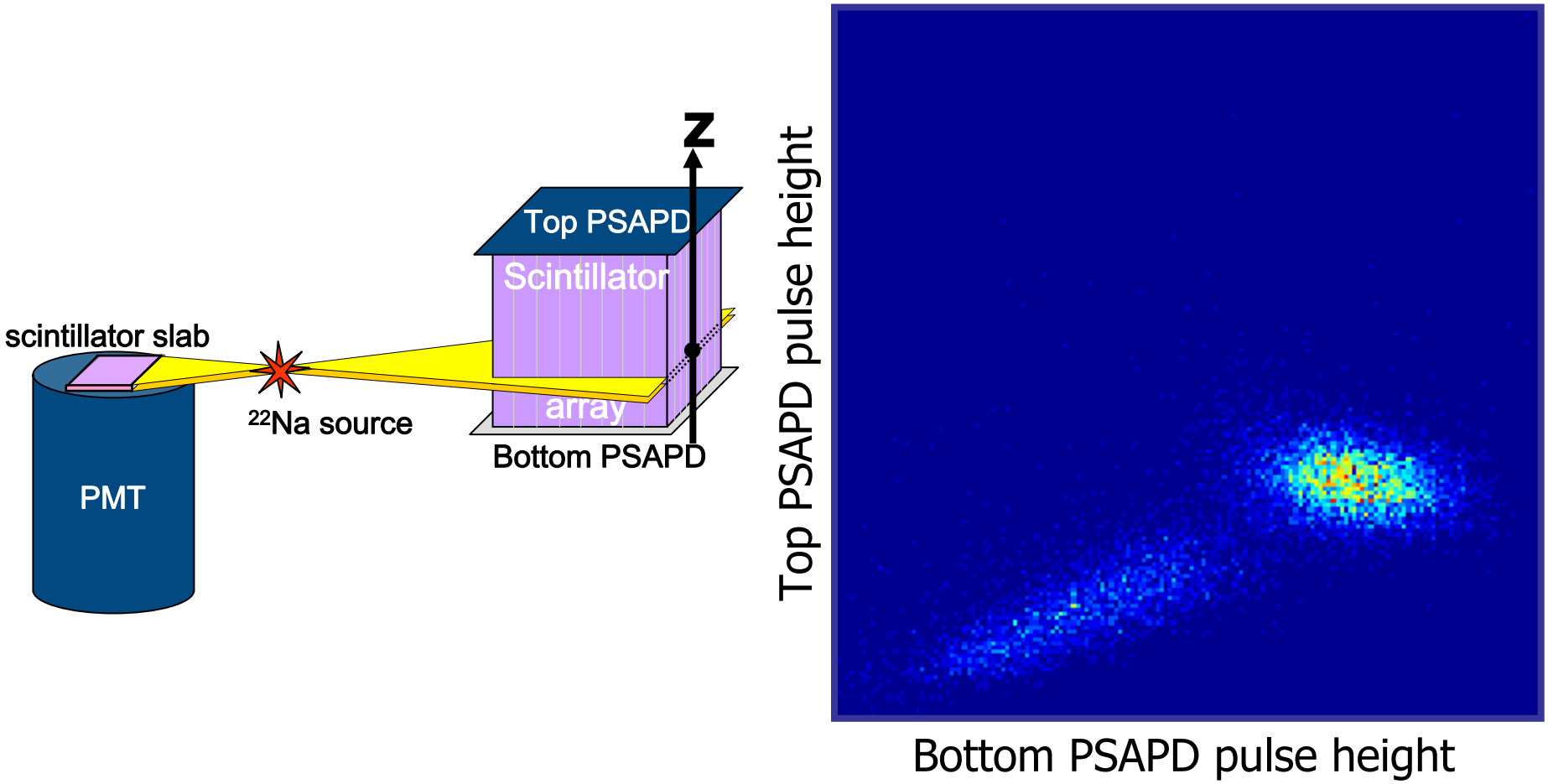
DOI = 0mm
(center of crystals)





*animated

Depth-of-Interaction Illustration



*animated

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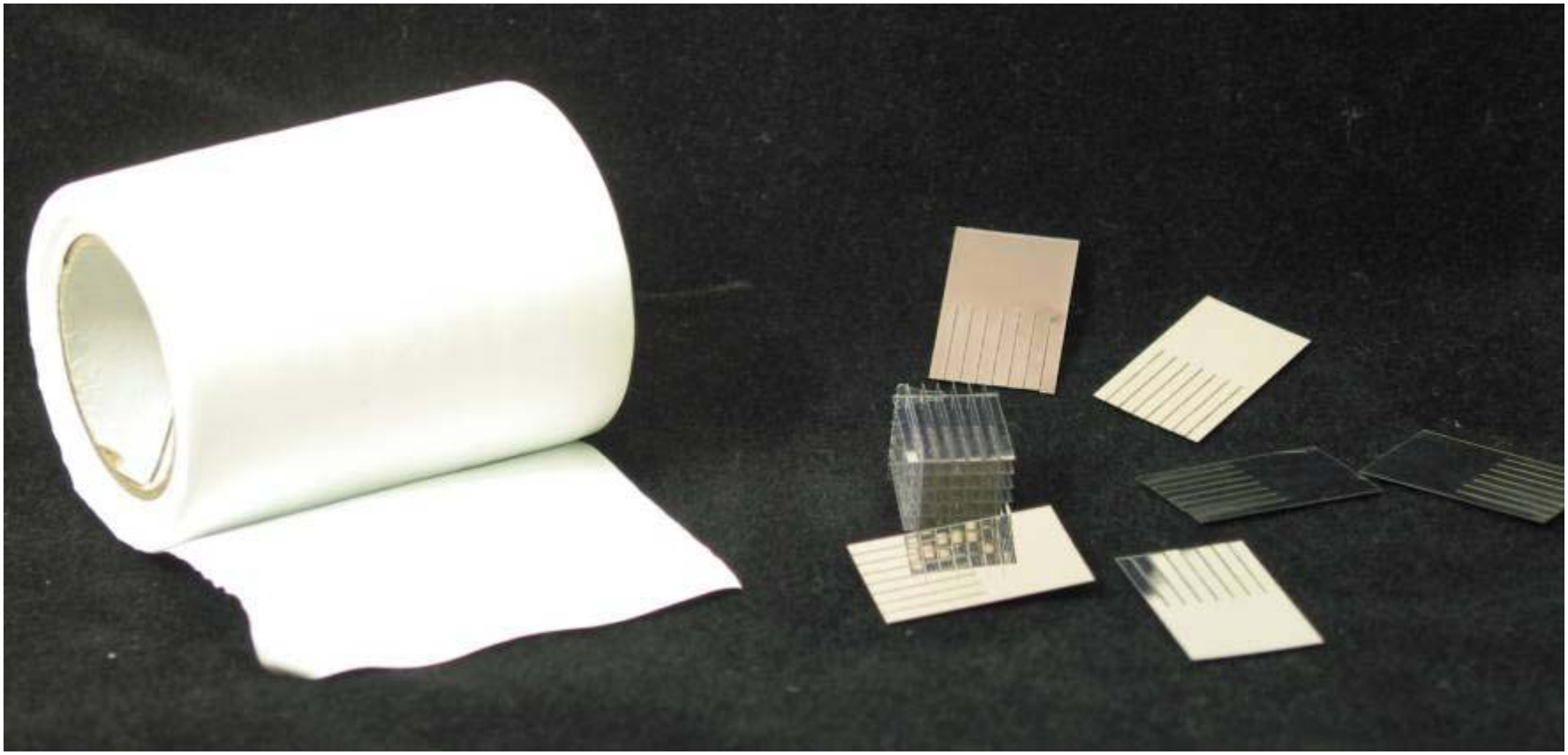
Scintillator Array Design

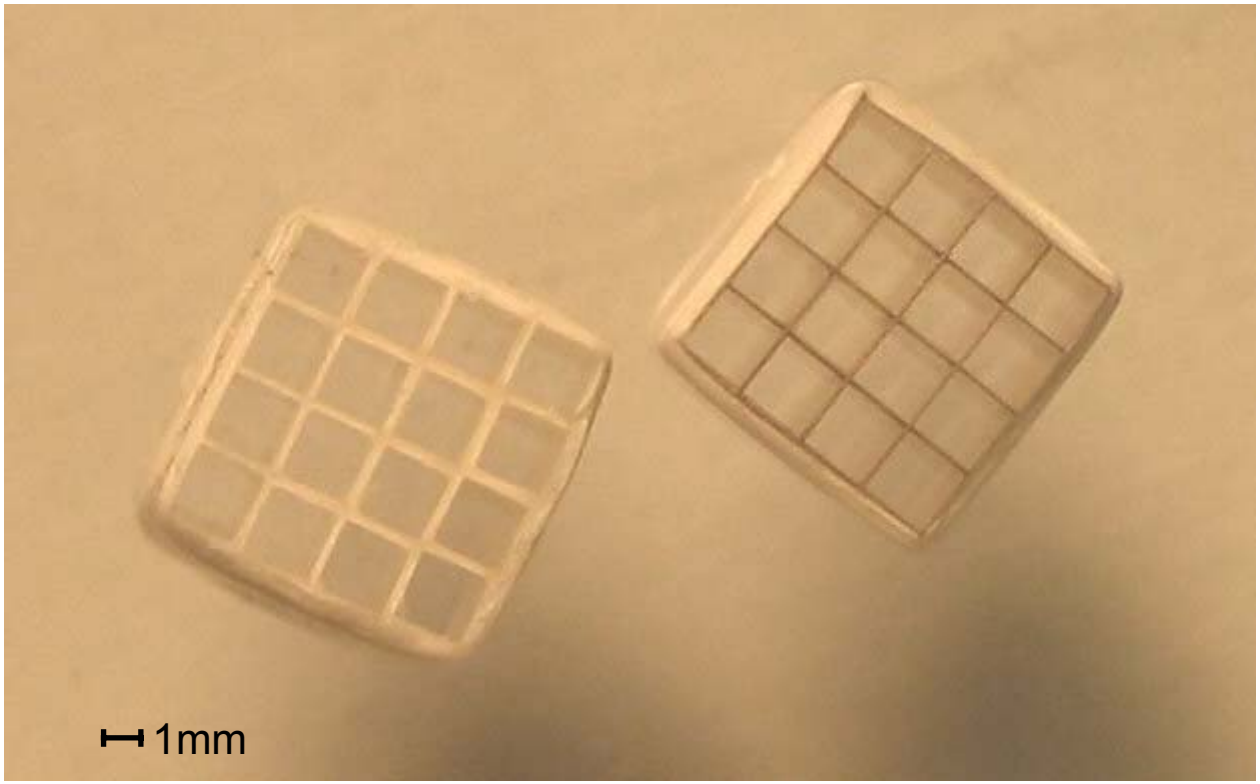
scintillator array attribute	**selection**	**reason**
scintillator material	*mixed lutetium silicate*, MLS	high light output, high density & Z, fast decay
array size, crystal dimensions	8x8 array, 1.65mm x 1.65mm x 22mm	PSAPD size, resolution, sensitivity, crystal cutting capabilities
reflector material	• **Teflon tape** • **VM2000** (3M Corp.)	**experimental**
crystal side surface roughness	• ***P*** (polished, 7nm *rms*) • ***M5*** (lapped with 5μm grit, 16nm *rms*) • ***M10*** (lapped with 10μm grit, 700nm *rms*) • ***M20*** (lapped with 20μm grit, 1000nm *rms*)	**experimental**

reflector material



Teflon VM2000

reflector material



Teflon

- best light collection
- time-consuming to assemble
- well-known problems with reproducibility, shrinkage, wicking, etc.

VM2000

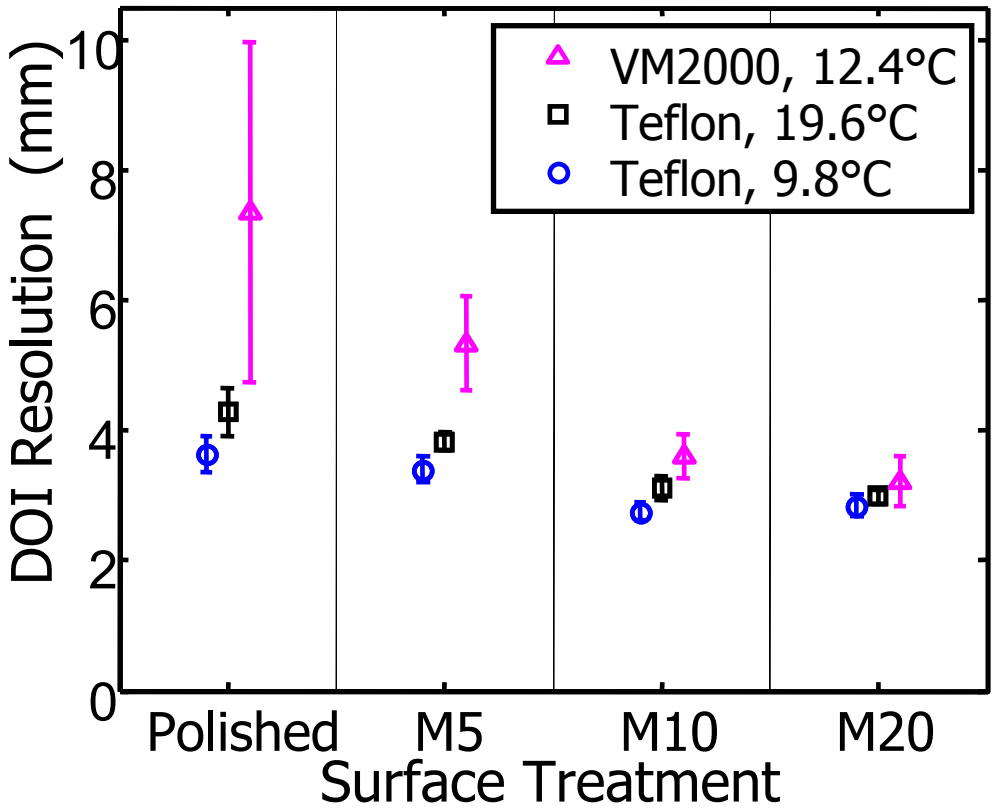
- laser cut film
- much faster assembly
- improved reproducibility
- reduced dead-space
- somewhat reduced light collection efficiency (~75% of Teflon)

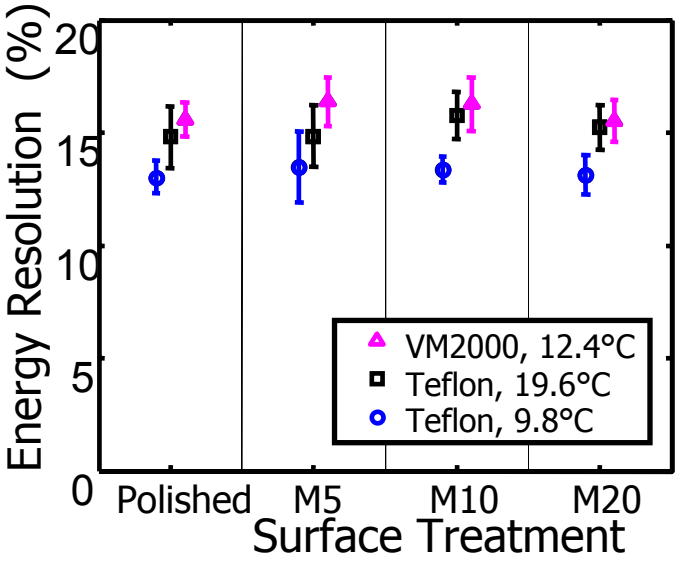
Scintillator Array Experiments

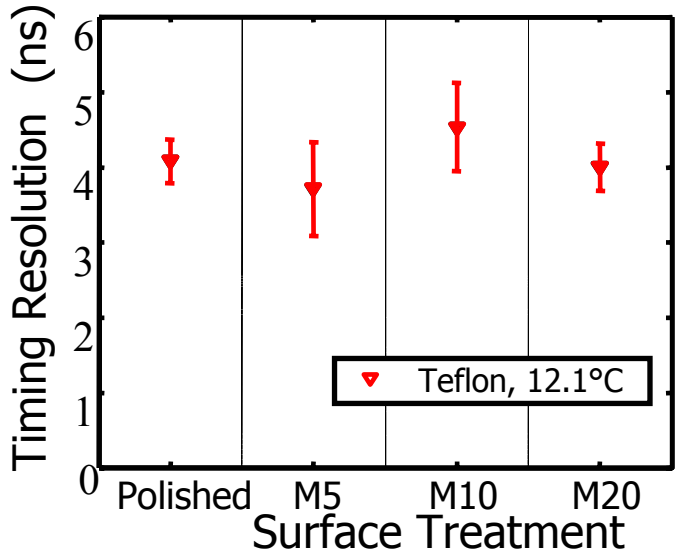
- 4 different surfaces
(P, M5, M10, M20)
- 2 reflector materials
(Teflon, VM2000)
- 5x5 array of crystals
(parallel data acquisition under identical conditions)
- 1.9mm x 1.9mm x 20mm MLS crystals
- 14mm x14mm PSAPD
- arrangement chosen so that:
    - each row and column have at least one of each crystal type
    - central 3x3 of array has at least two crystals of each type
    - "black" crystal used for unambiguous identification of crystals
    - each corner crystal has different surface
    - each 2x2 in corner has one crystal of each type, except for corner that has "black" crystal

P	Black	M20	M10	M5
M10	M20	M5	P	M20
M5	P	M20	M10	M5
P	M5	M10	M20	P
M20	M10	P	M5	M10

Scintillator Array Experiments: Results







Roughening the surface improves DOI …

… without degrading energy resolution and timing resolution.

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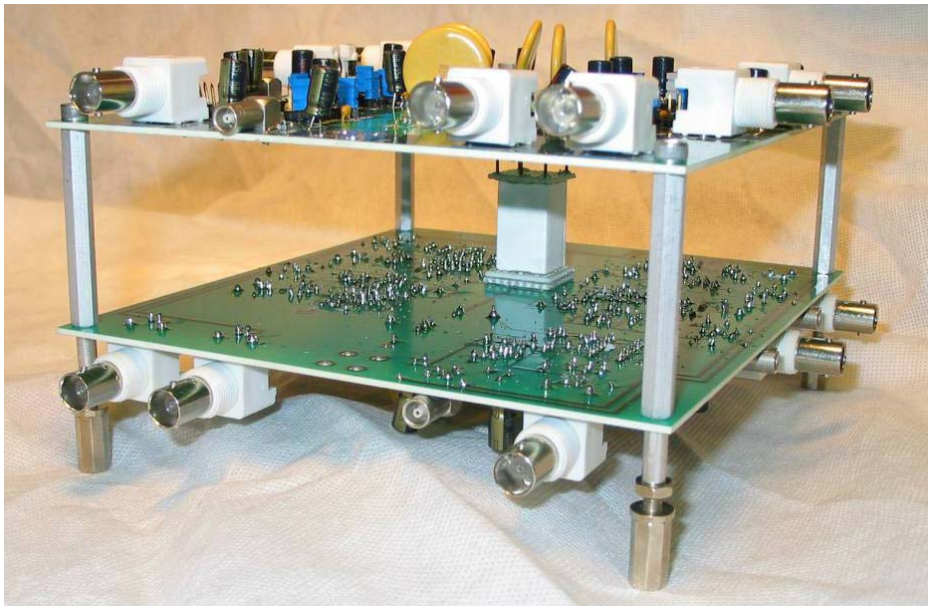
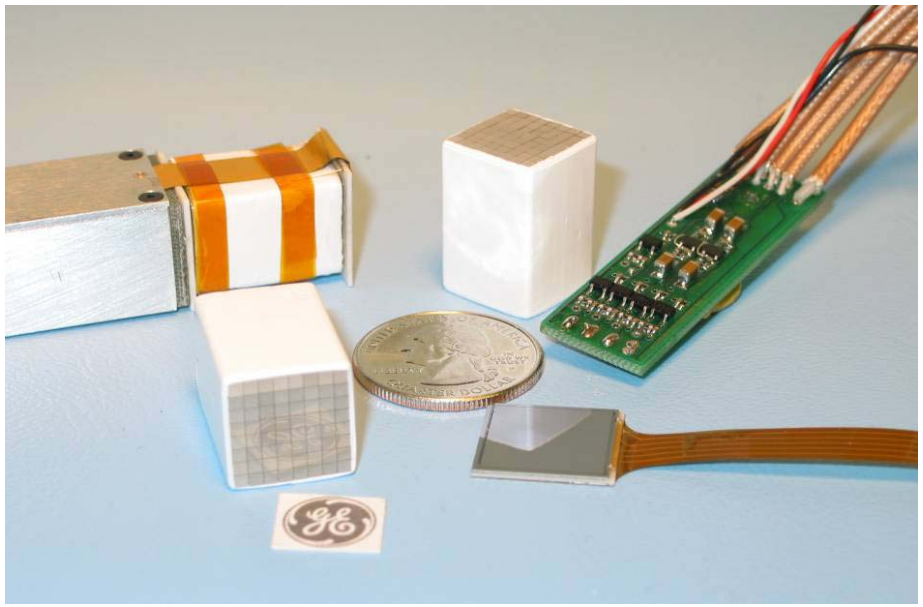
Detector Evolution





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*animated

Detector Specifications

PSAPD

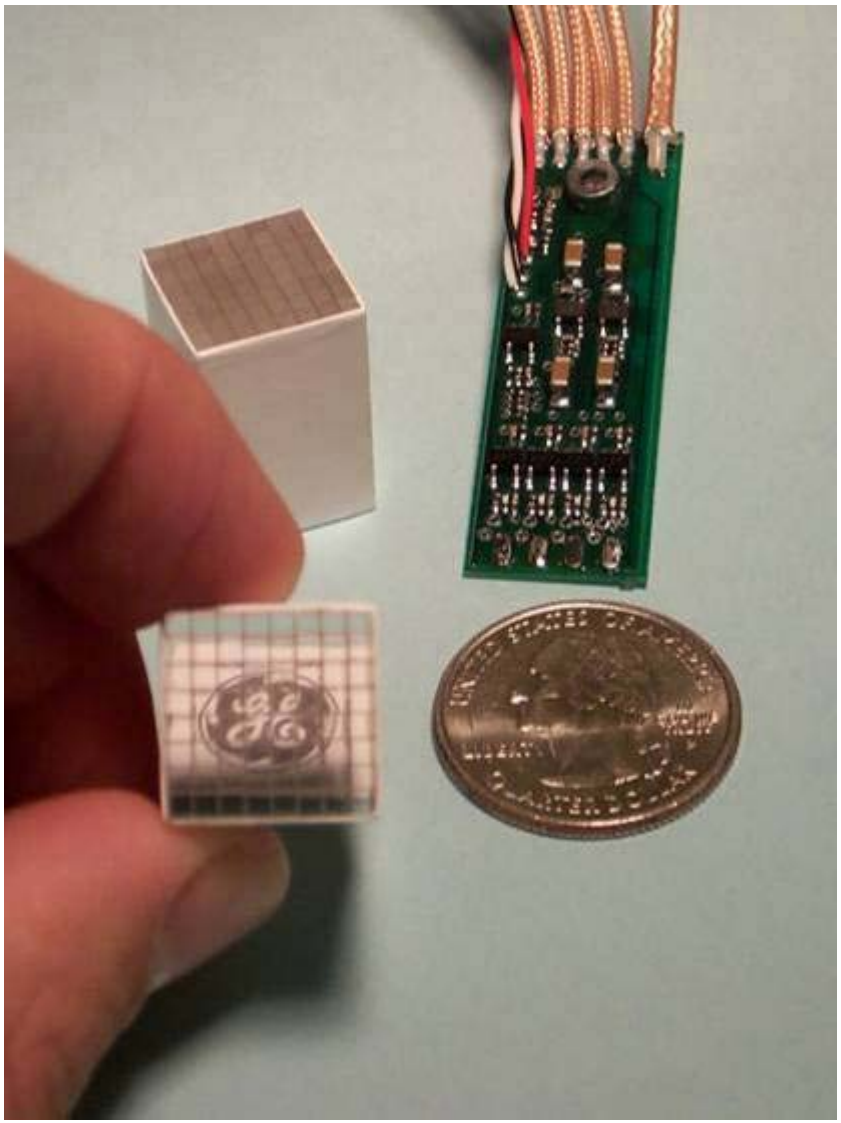
- 14 mm x 14 mm active area
- operated at 10°C and -1630V
- gain ~950
- leakage current ~1μA

Scintillator array

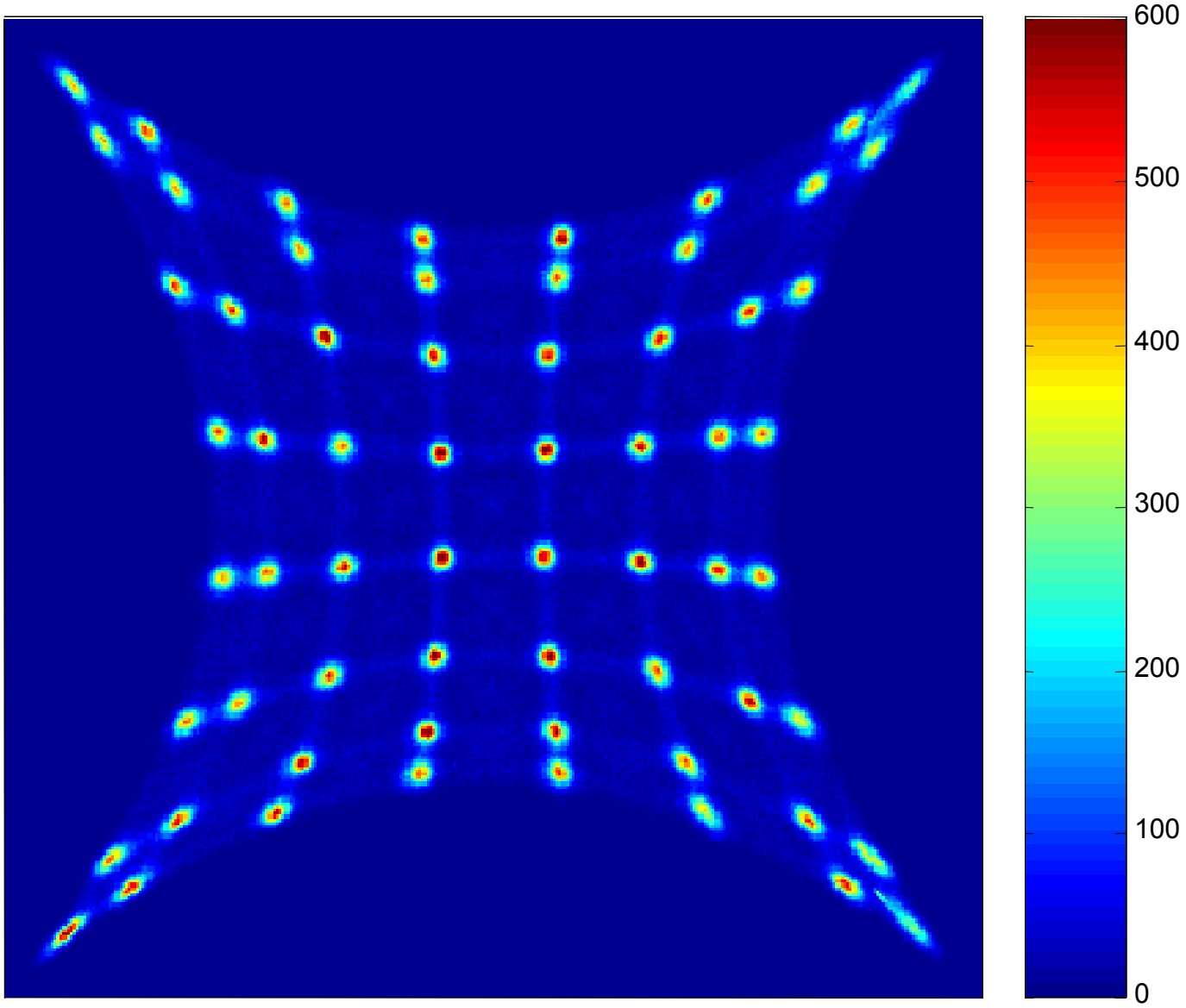
- 8x8 MLS
- 1.65 mm x 1.65 mm x 22.00 mm
- 1.75 mm pitch
- 3M VM2000 reflective film
- rough side surfaces, polished ends
- coupled to PSAPD using Cargille Meltmount

Electronics

- corner contacts: low noise JFET input wide bandwidth transimpedance amplifier with a 100 kohm transimpedance gain
- trigger and energy signal from analog sum of corner contacts

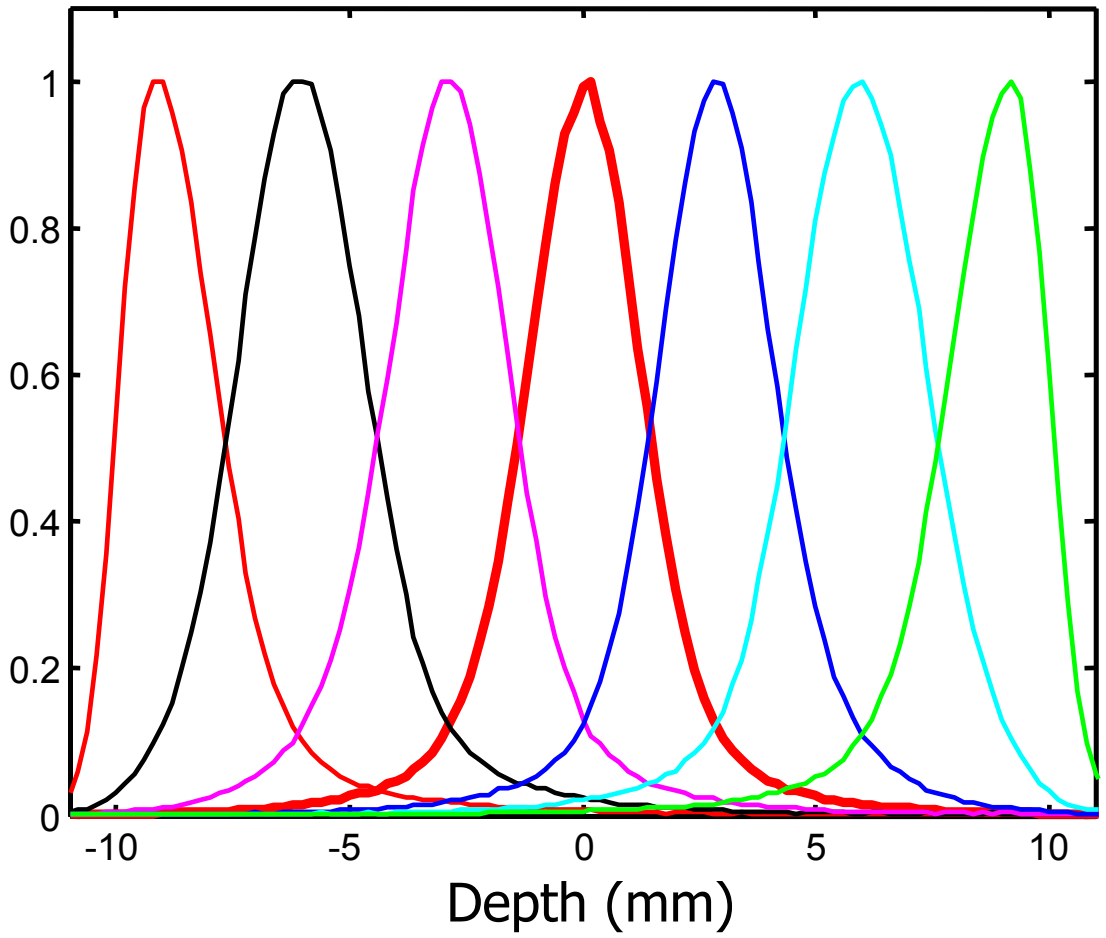


Flood Histogram – ^{22}Na



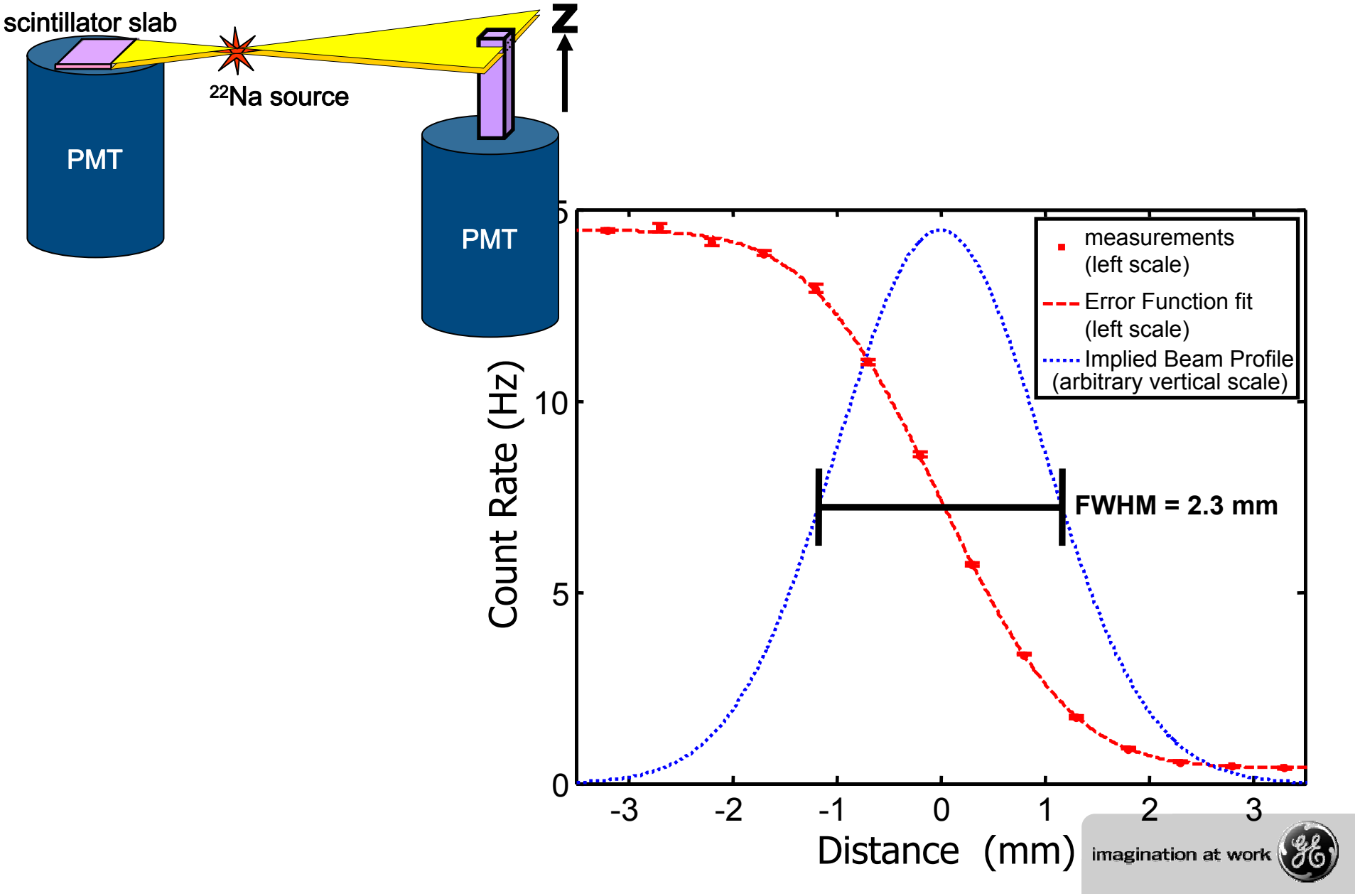
Energy Window: 250-650 keV

DOI Resolution

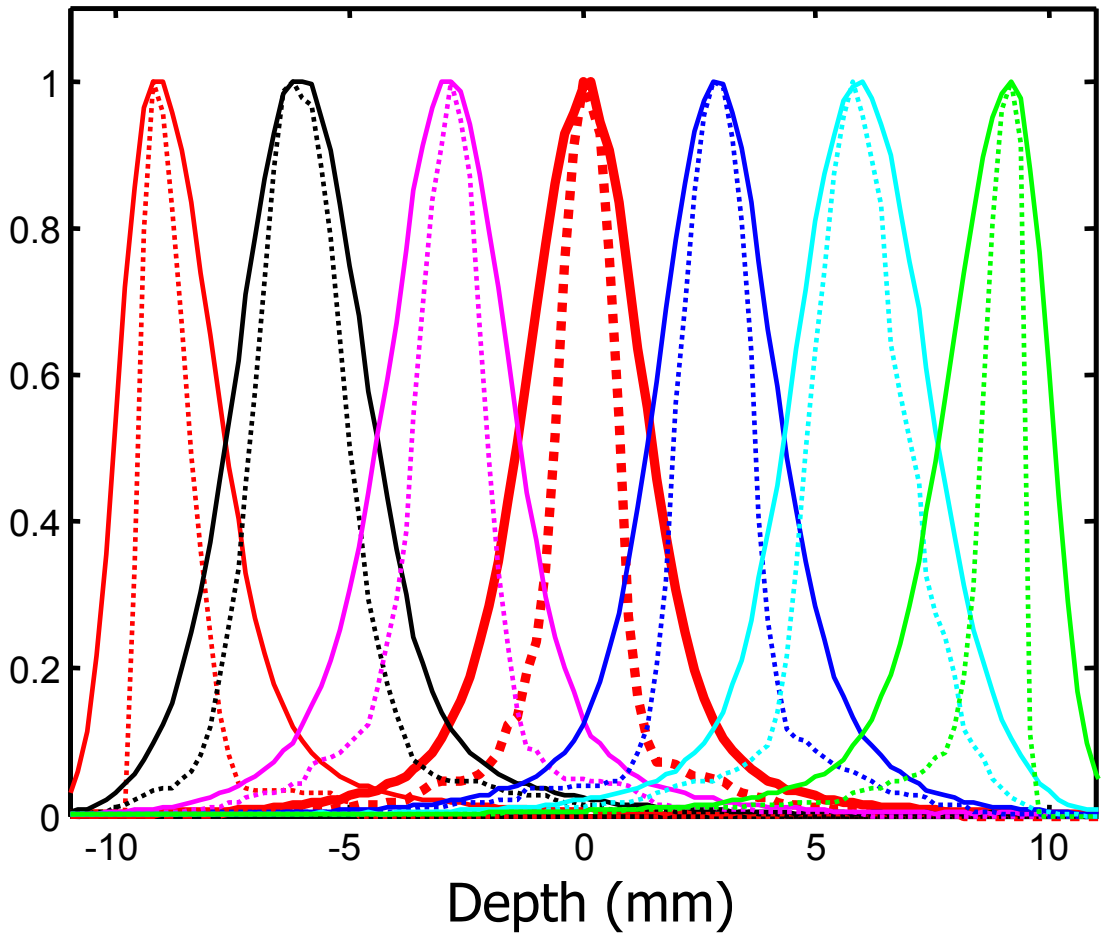


Energy Window: 250-650 keV
Integrated counts from all crystals.

Width of Electronically Collimated Beam

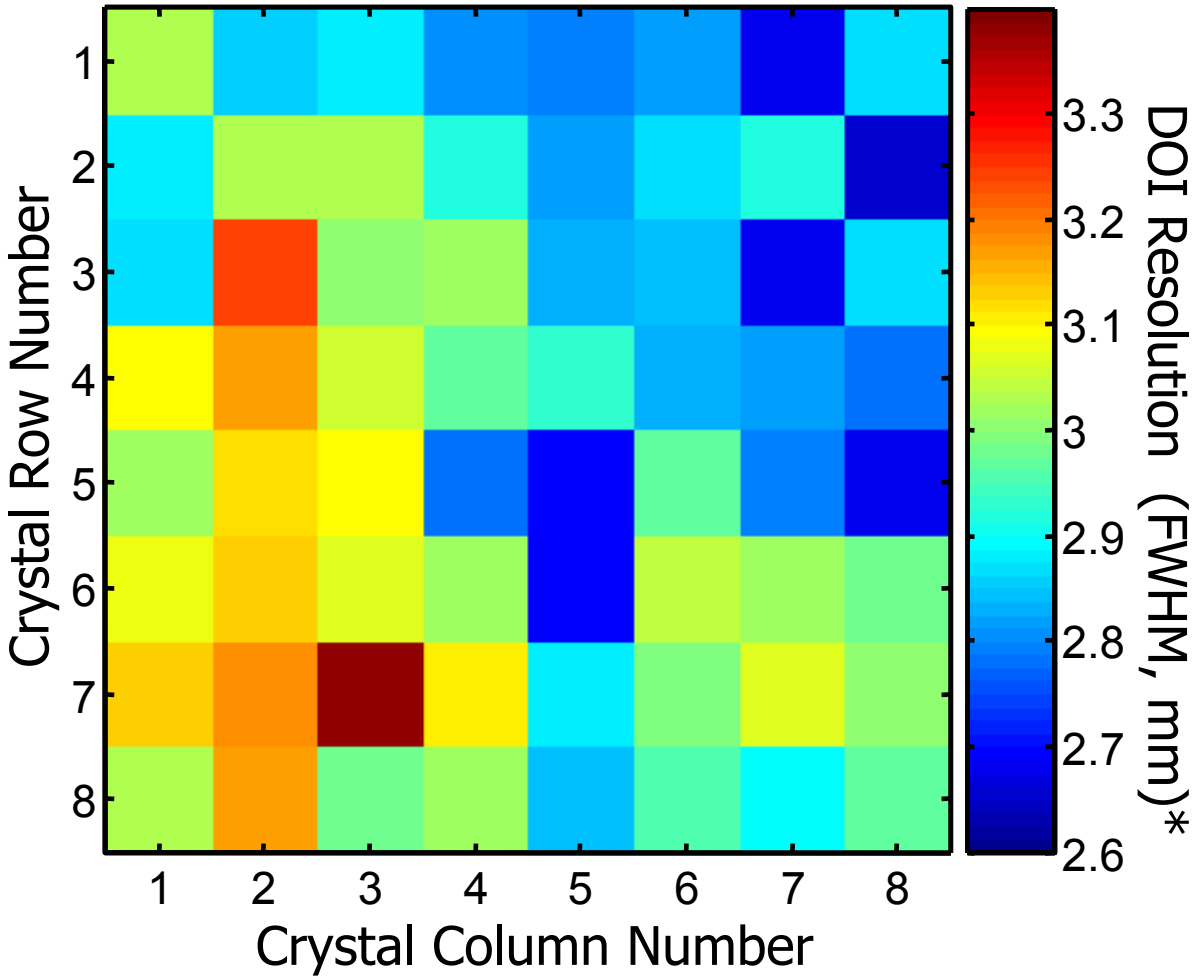


DOI Resolution (deconvolved)



Energy Window: 250-650 keV
Integrated counts from all crystals.

DOI Resolution Map*



*without deconvolution of beam width

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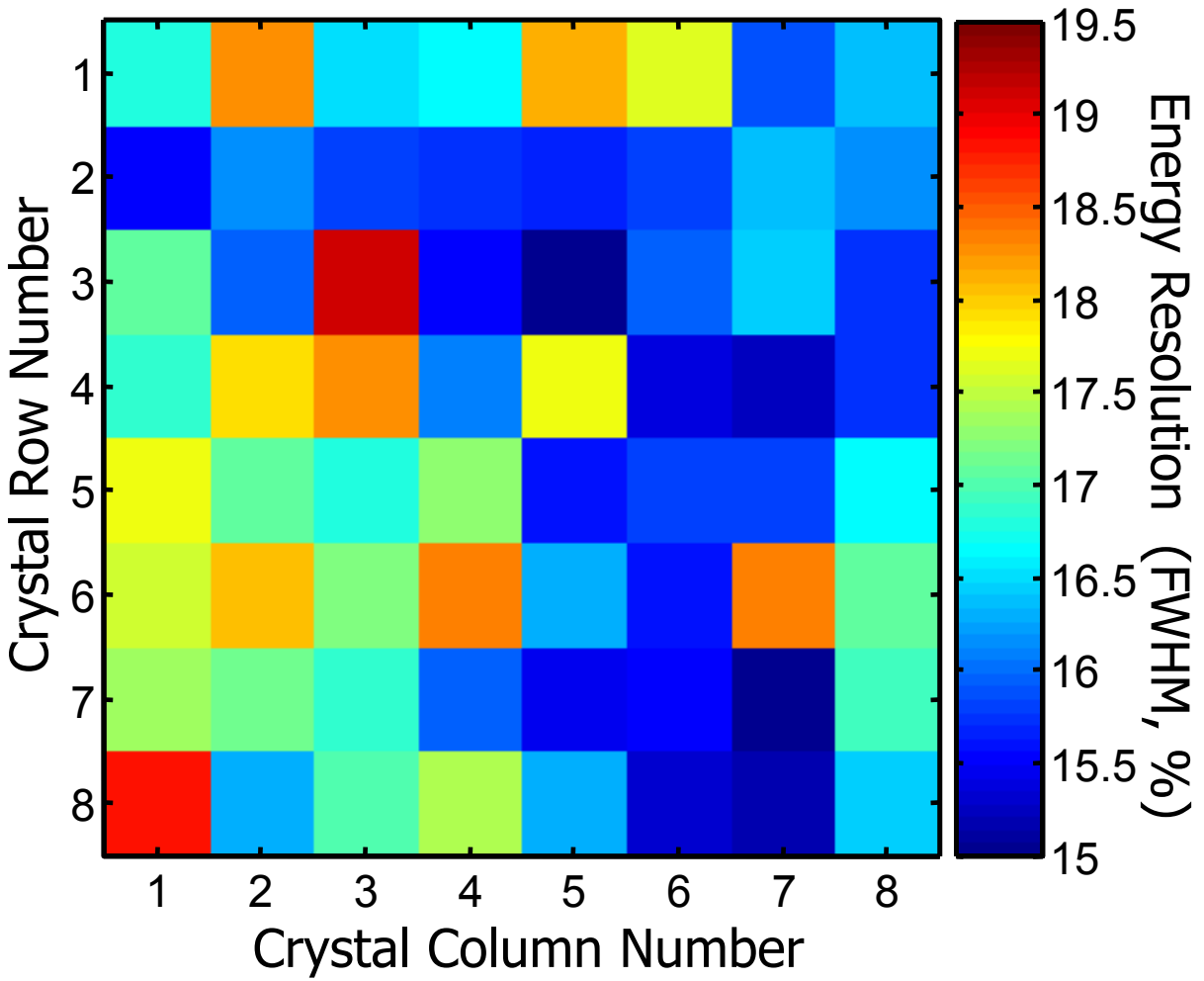
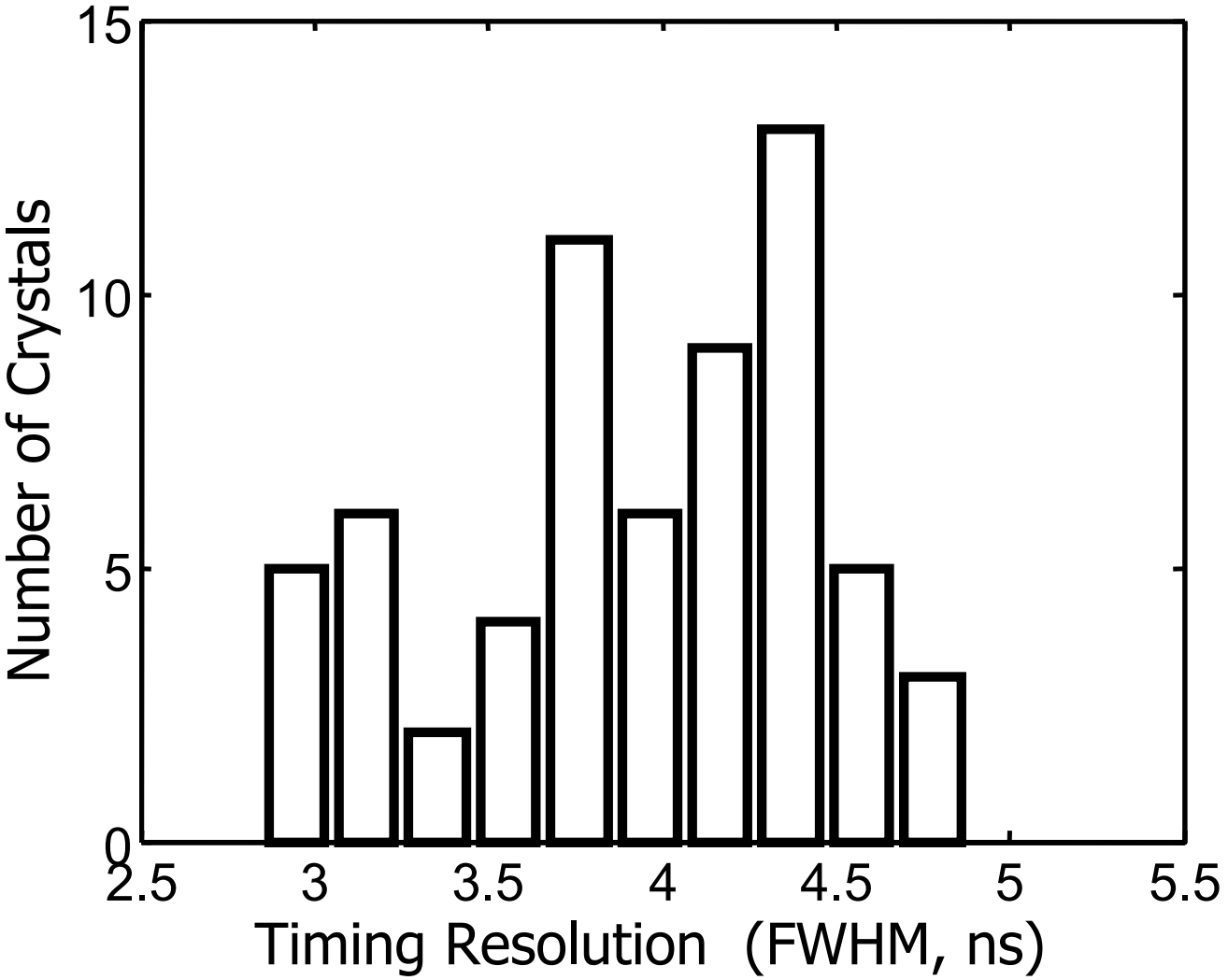
Energy Resolution Map

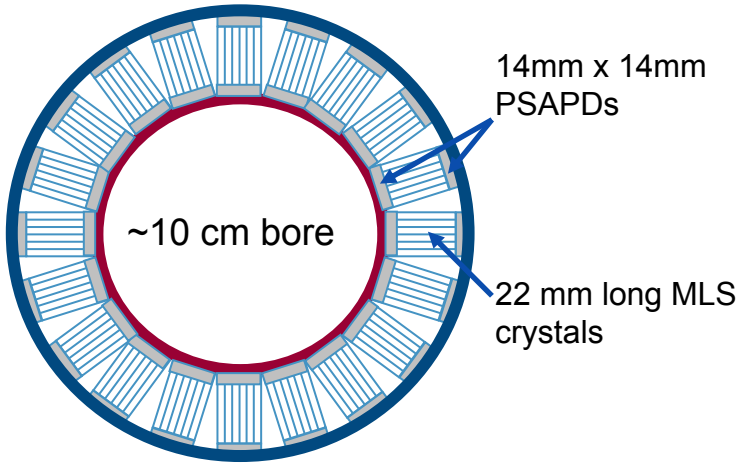


Timing Resolution Distribution

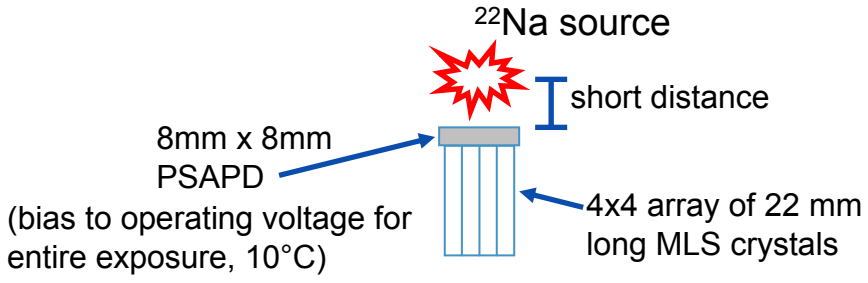


Radiation Damage? (preliminary measurements)

Small-animal PET is *not* a “high radiation” environment.



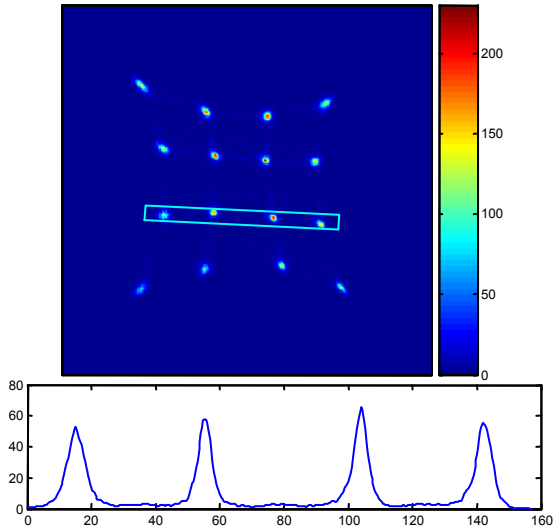
small-animal scanner



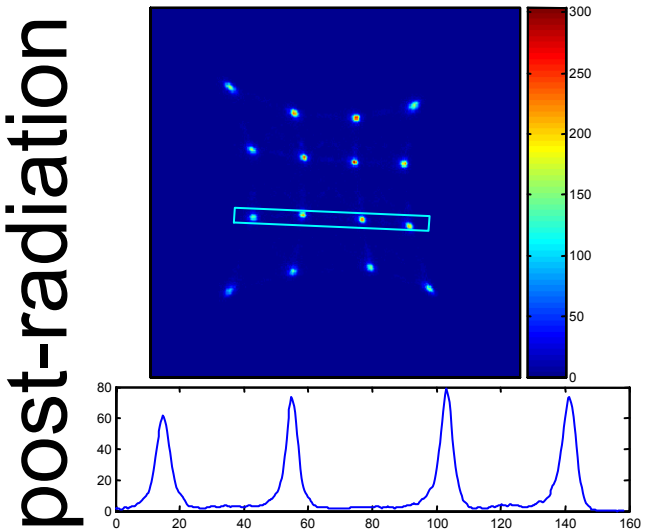
test setup

Exposed PSAPD to 2 - 10 years*
equivalent accumulated 511 keV flux

pre-radiation



post-radiation



No Negative Impact on Performance Observed

*depending on scanner utilization assumptions

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Conclusion

Demonstrated High-Res DOI PET detector with:

- 8x8 array of 1.65 mm x 1.65 mm x 22.00 mm crystals, with surface treatments chosen to optimize DOI resolution
- Minimal dead-space within array
- Compact front-end electronics
- No radiation damage effects observed
- Tileable design
- Excellent performance
  - DOI resolution of <3 mm FWHM
  - Energy resolution of ~16% FWHM
  - Timing resolution of ~4 ns FWHM (vs. plastic)

References

- DOI in PET

  L. R. MacDonald and M. Dahlbom, "Parallax Correction in PET Using Depth of Interaction Information," *IEEE Trans. Nucl. Sci.*, vol. 45, no. 4, pp. 2232 – 2237, Aug. 1998.

  Y. Shao, R. M. Manjeshwar, F. P. Jansen, P. N. Kumar, A. F. Chatziioannou, “Simulation Studies for a High Resolution and High Sensitivity Small Animal PET with DOI Detection Capability,” presented at *IEEE Medical Imaging Conference*, M6-11, Portland, OR, Oct. 2003.

- dual-end readout

  W. W. Moses, S. E. Derenzo, "Design Studies for a PET Detector Module Using a PIN Photodiode to Measure Depth of Interaction," *IEEE Trans. Nucl. Sci.*, vol. 41, pp. 1441 – 1445, Aug. 1994.

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- PSAPDs

  K. S. Shah, R. Farrell, R. Grazioso, E. S. Harmon, E. Karplus, "Position-Sensitive Avalanche Photodiodes for Gamma-Ray Imaging," *IEEE Trans. Nucl. Sci.*, vol. 49, no. 4, pp. 1687 – 1692, Aug. 2002.

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  C. M. Pepin, P. Berard, R. Lecomte, "Comparison of LSO, LGSO and MLS Scintillators," in *Proc. IEEE Nuclear Science Symposium*, vol. 1, San Diego, CA, Nov. 2001, pp. 124 – 128.

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  R. S. Miyaoka, S. G. Kohlmyer, T. K. Lewellen, "Performance Characteristics of Micro Crystal Element (MiCE) Detectors," *IEEE Trans. Nucl. Sci.*, vol. 48, no. 4, pp. 1403 – 1407, Aug. 2001.

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