A High Resolution PET Demonstrator Using a Silicon “Magnifying Glass”

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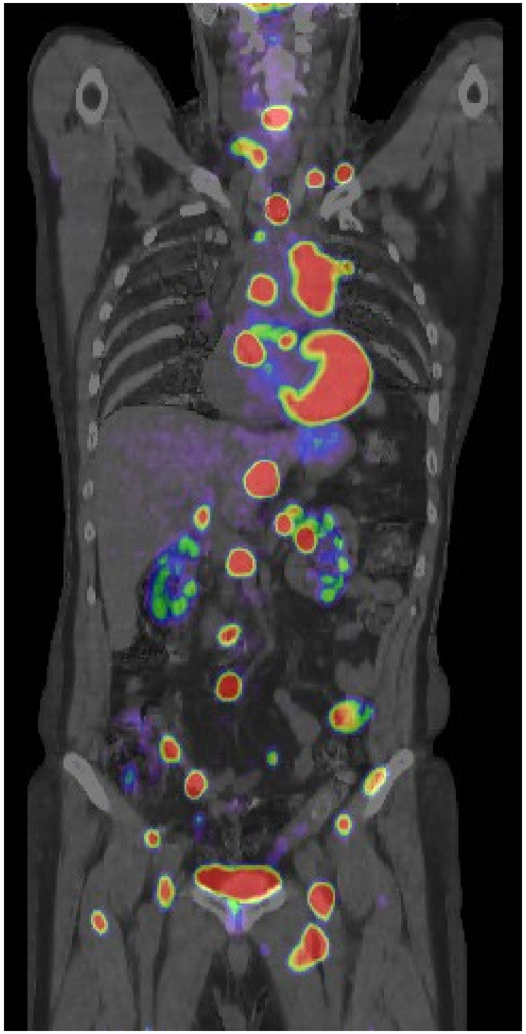
Positron Emission Tomography



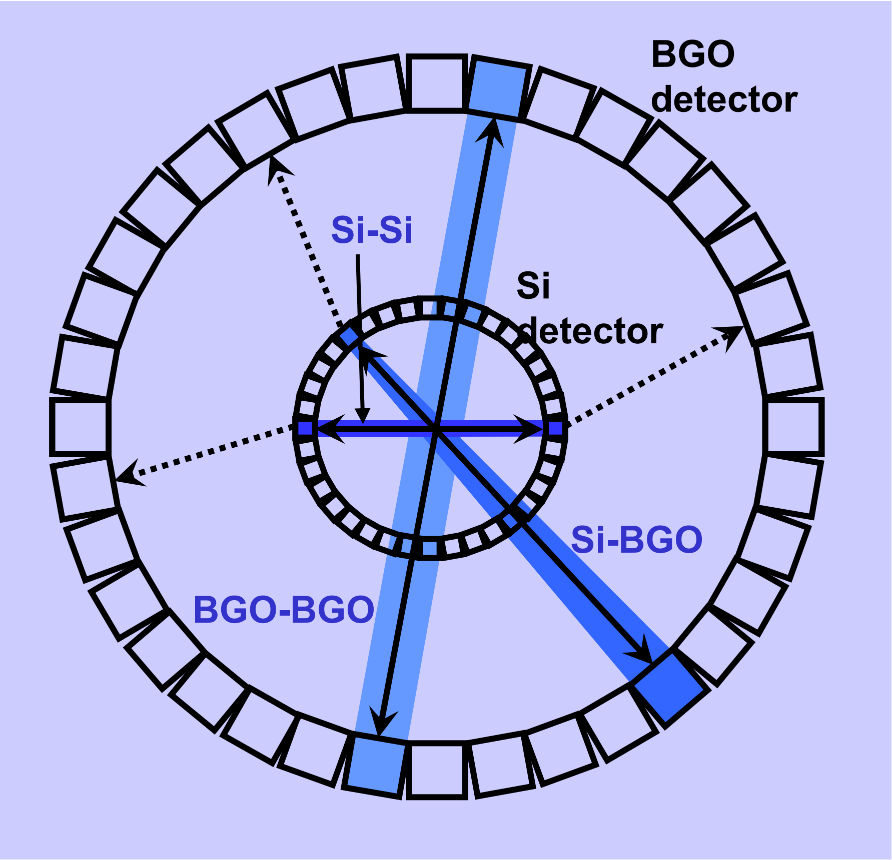
- Patient injected with tracer labeled with positron-emitting nuclide (e.g. 18-F-FDG)
- Emitted positrons annihilate creating two 511 keV photons
- Ring of radiation detectors detect photons in time-coincidence localizing decay to a line
- From collection of coincidence events, 3D distribution of radiotracer can be reconstructed
- Also used in “pre-clinical” imaging in mice and rats for studying disease processes in humans
- Typical resolution: 1.5 – 8mm FWHM

PET / CT lung cancer case

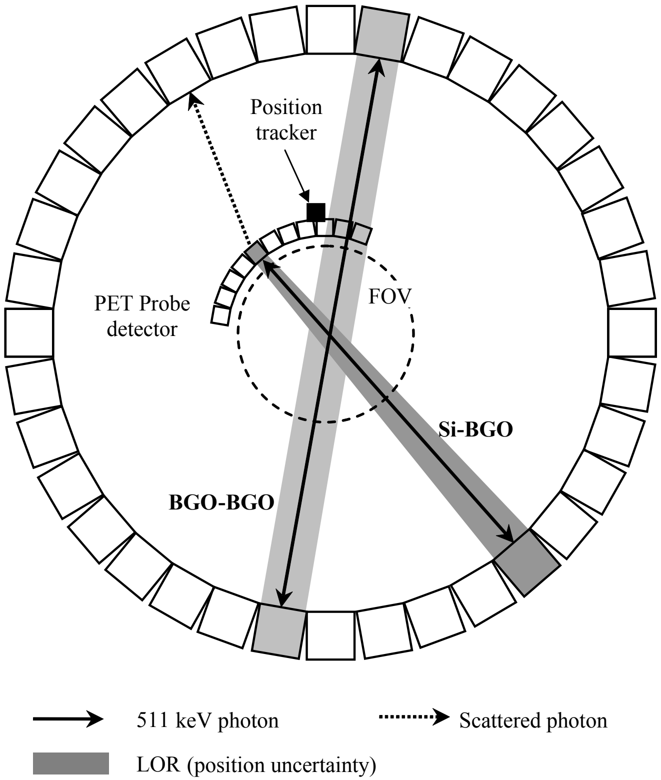
From: http://www.medical.siemens.com/siemens/en_US/gg_nm_FBAs/files/multimedia/biograph/assets/pdf/biograph_images.pdf

PET "Magnifying Glass"

- Augment conventional PET ring with high resolution insert
- Very high resolution possible in small FOV or close to detector
- Si used for initial designs because of resolution and DOI capability
- Several event possibilities: Si-Si, Si-BGO, BGO-BGO



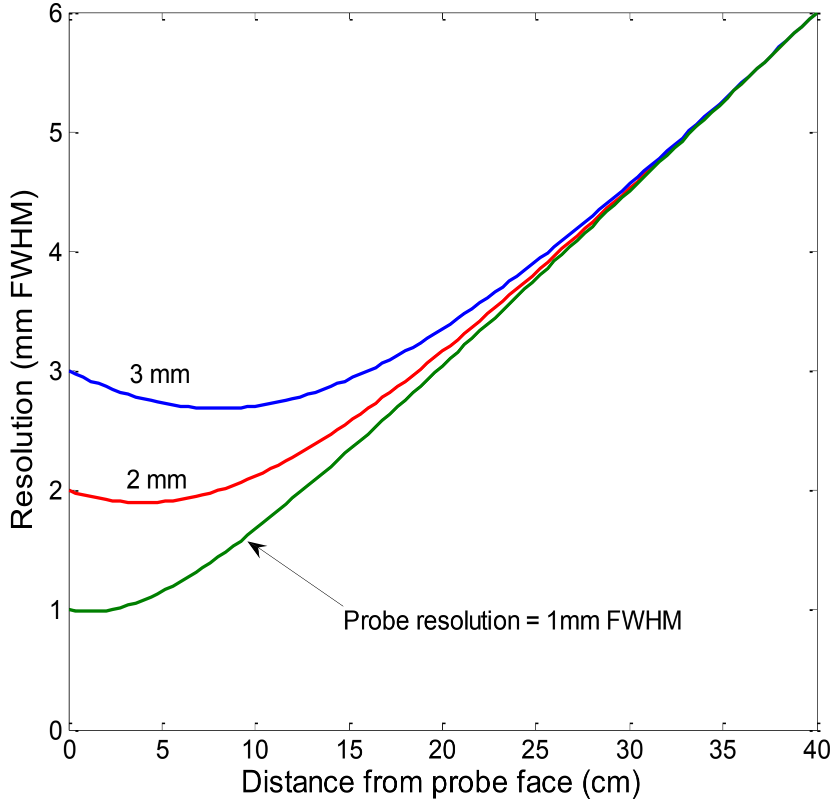
High Resolution PET Imaging Probes



- Do not need complete inner detector – partial high resolution detector sufficient in many cases
- Can potentially be used in conjunction with existing PET instruments
- Probes for head & neck cancer and prostate imaging currently under development

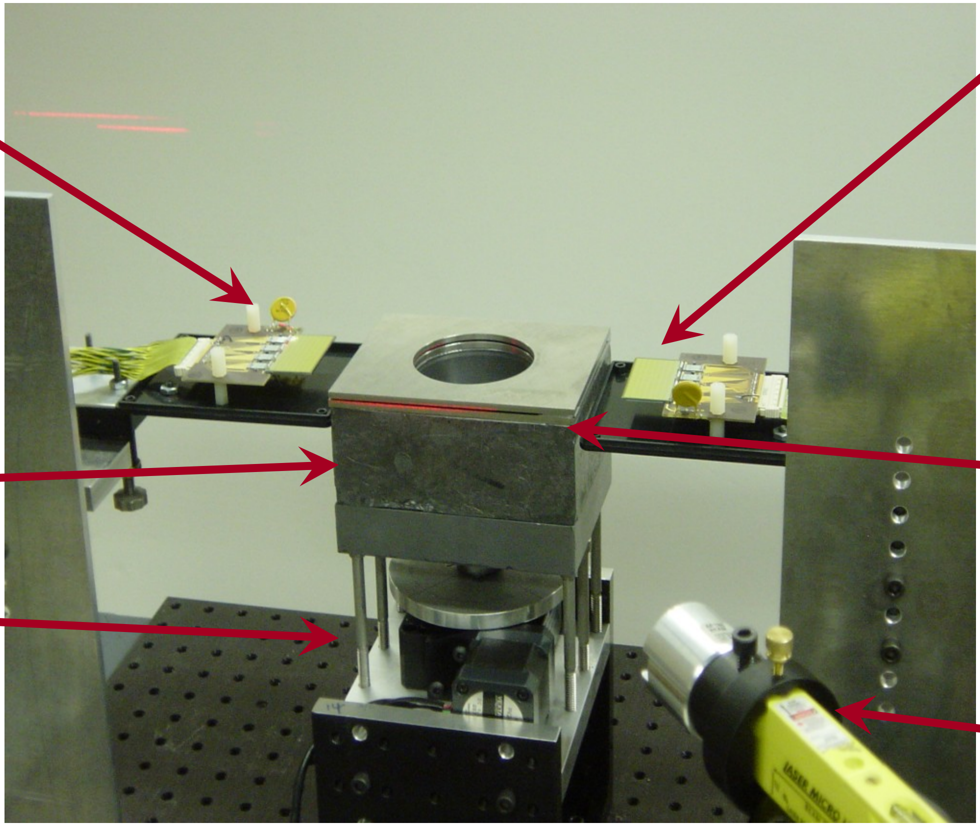
Spatial Resolution Between Detectors

- Detectors of 1mm, 2mm, and 3mm FWHM in coincidence with 6mm FWHM detector

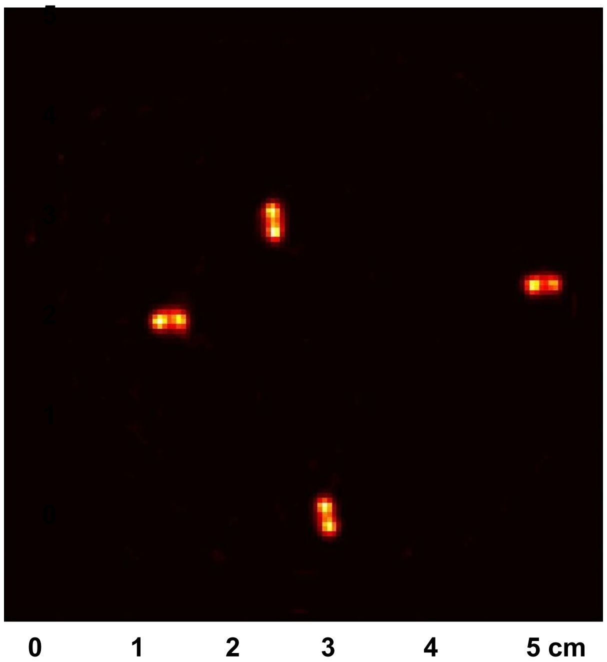


Spatial resolution improves close to detector with good resolution

Si-Si PET Demonstration



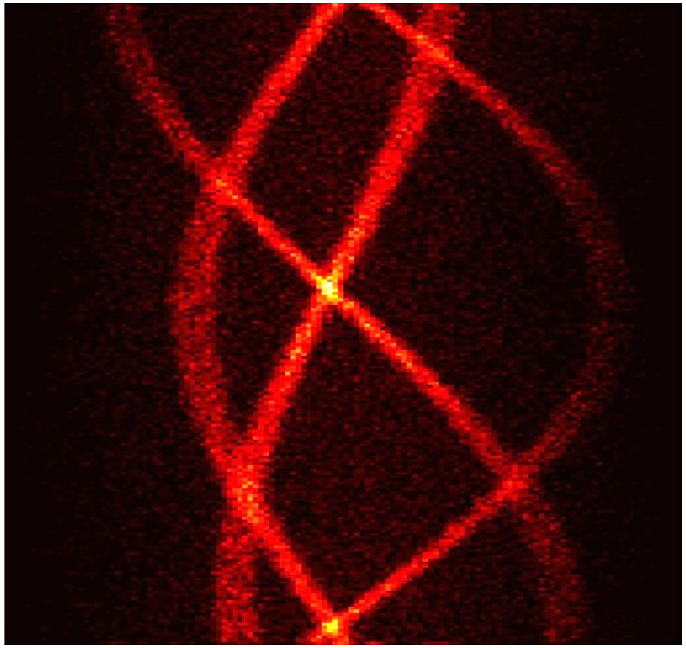
Resolution Uniformity



Source pairs at 5, 10, 15, & 20mm off-axis

Source

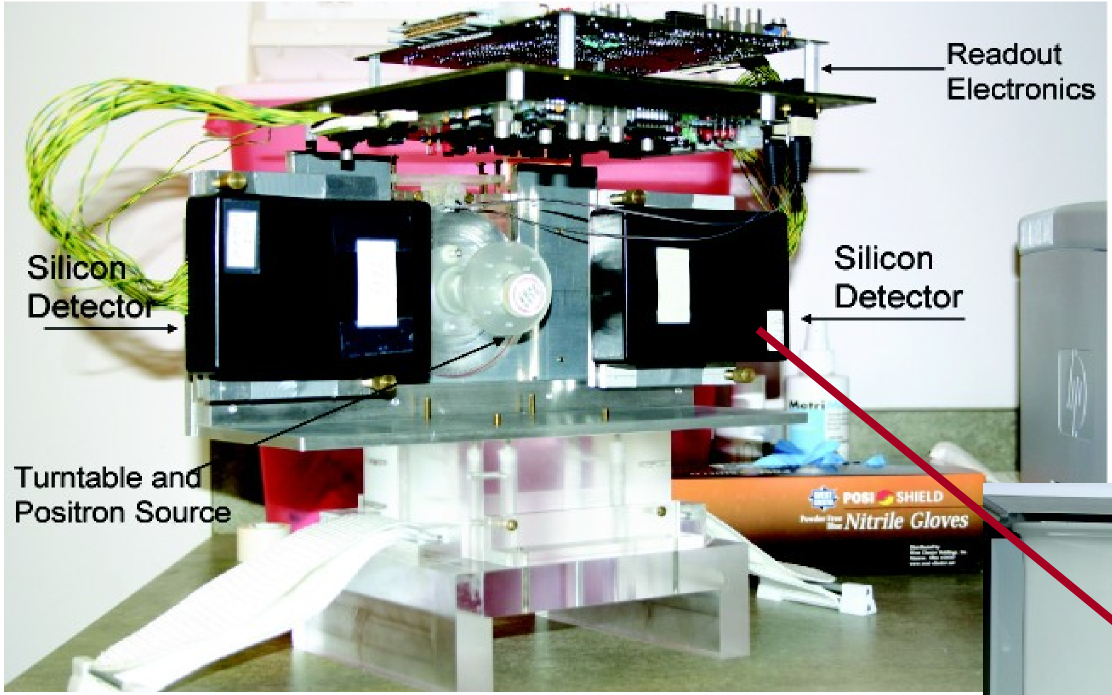
F-18 in 1.1mm glass capillary tubes



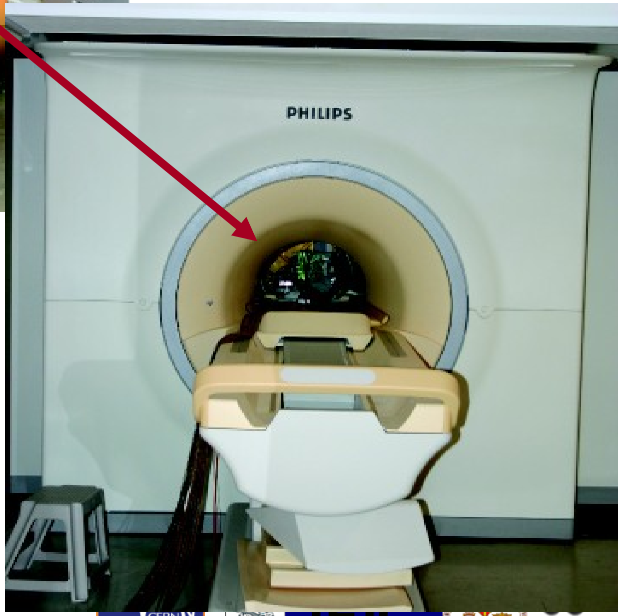
Sinogram

The sources in each pair are clearly separated at appropriate sinogram angles

MRI Compatible Silicon PET Imager

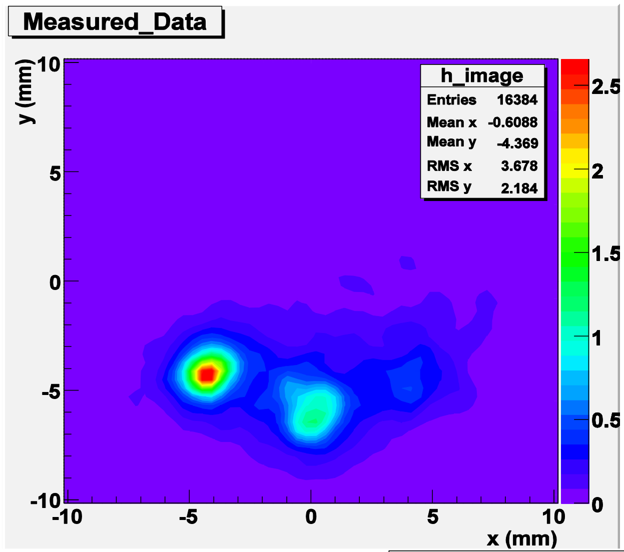


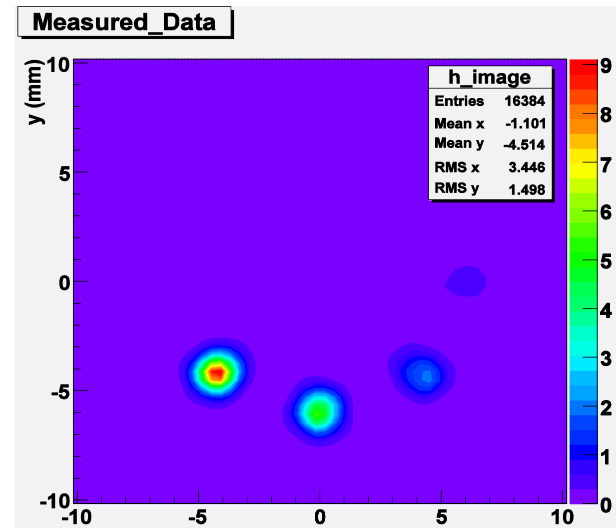
…and inserted into bore of 7T MRI magnet at OSU

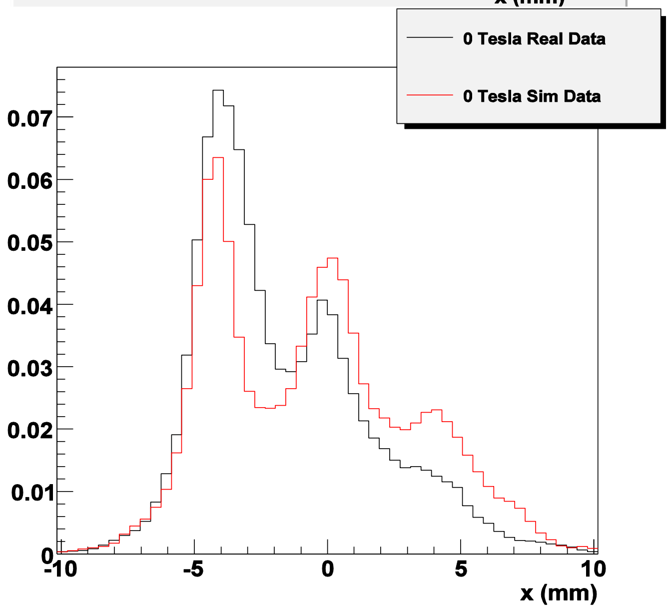


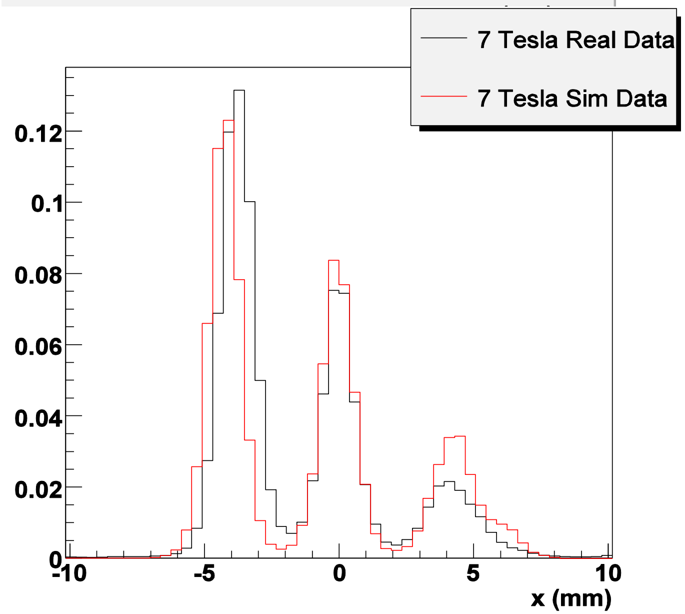
System rebuilt using no ferromagnetic materials…

Ga-68 Resolution Improvement at 7T



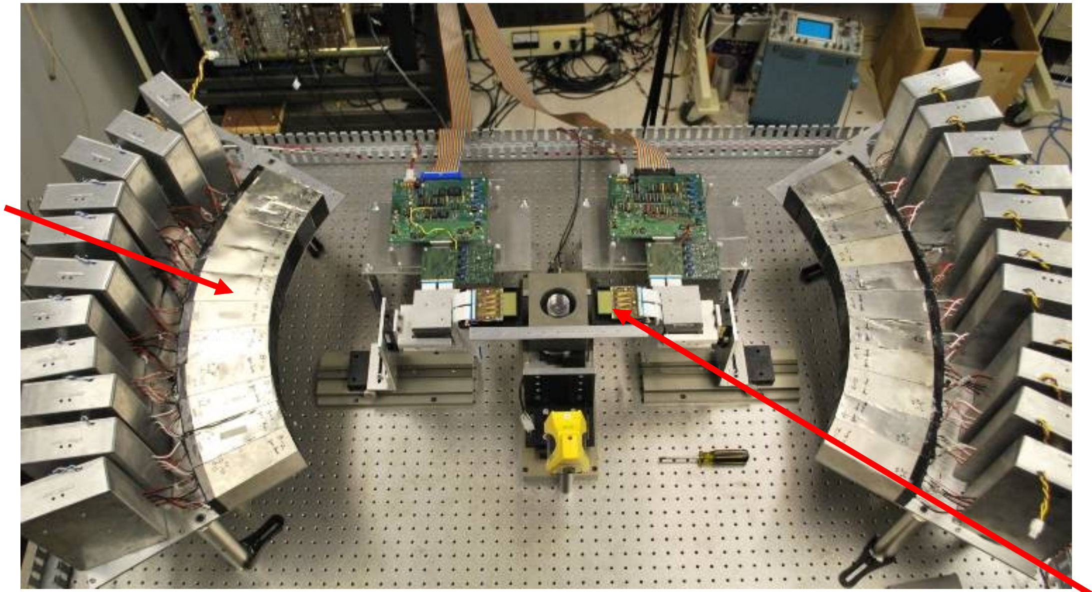




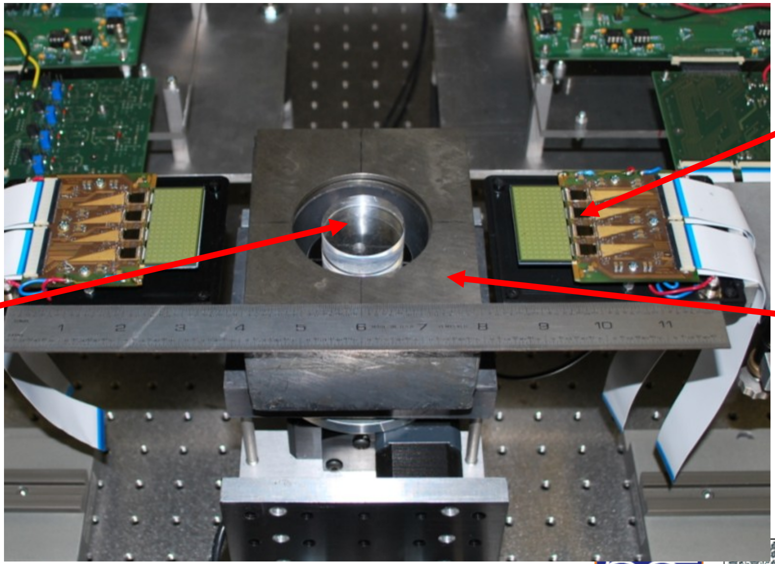


Hardware Demonstrator

BGO Detector
500mm Radius



Silicon Detector
70mm Radius

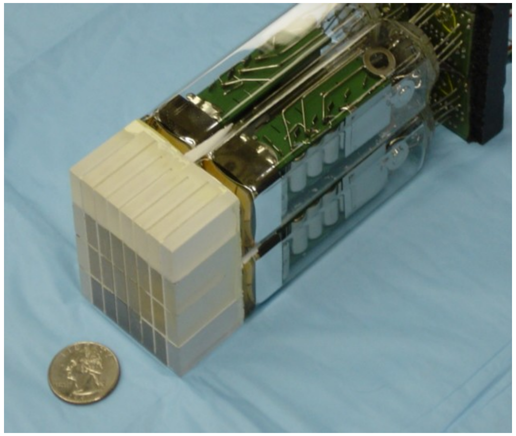


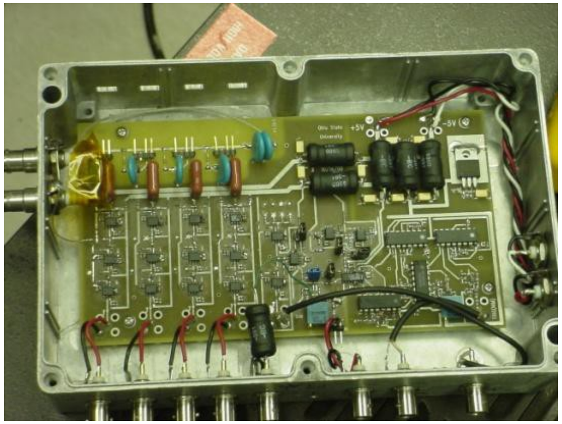
Object Turntable
45mm FOV

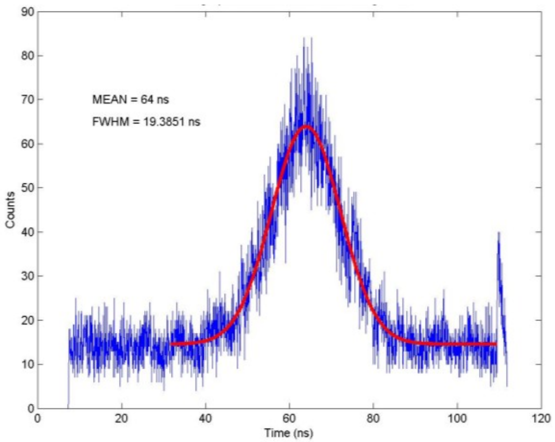
Tungsten Slice
Collimator

BGO Detectors

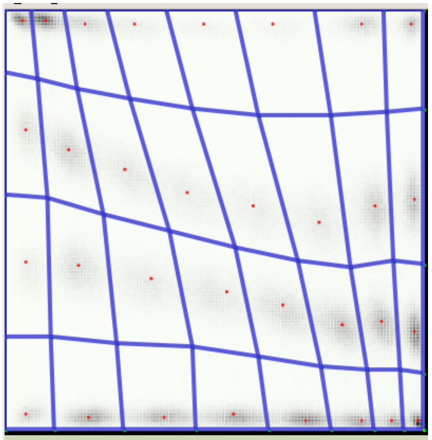
- Scavenged from CTI 931 (ca. 1986) PET scanner
  - 8 x 4 array of ~6mm x 12mm x 30mm BGO elements
- Coupled to simple analog shaping and CF disc electronics





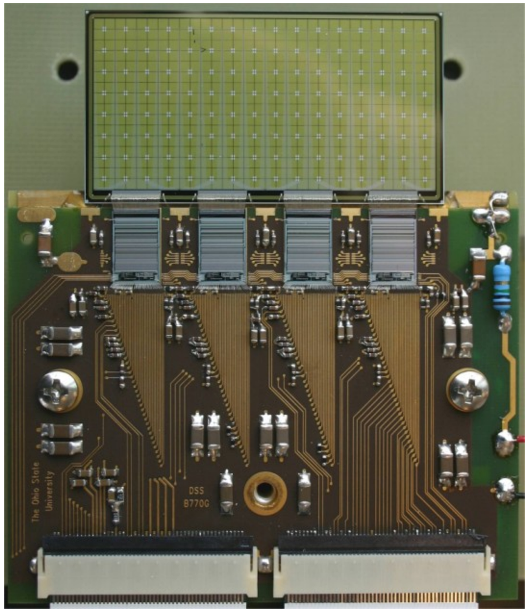


Timing performance

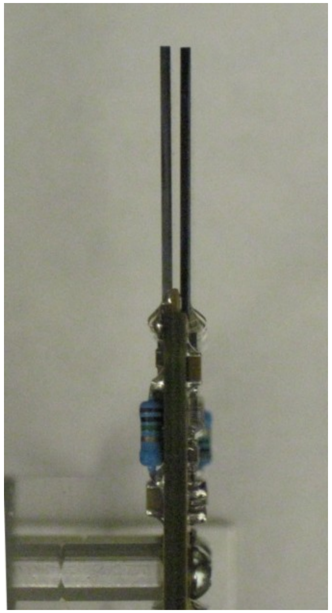


Positioning performance

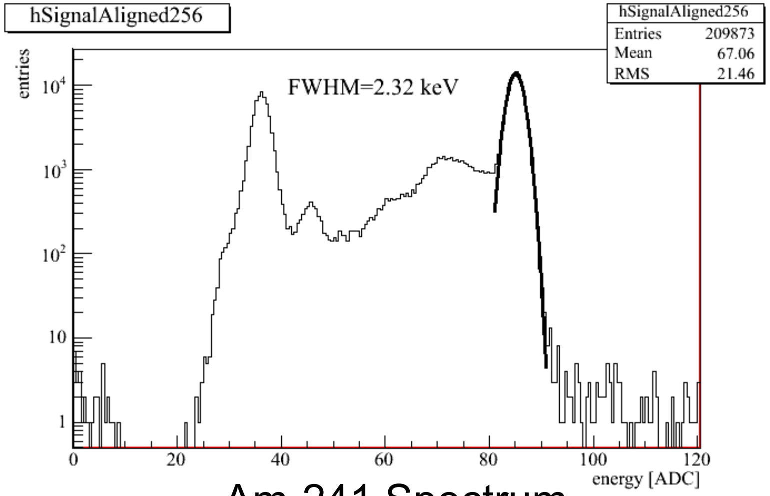
Silicon Detectors



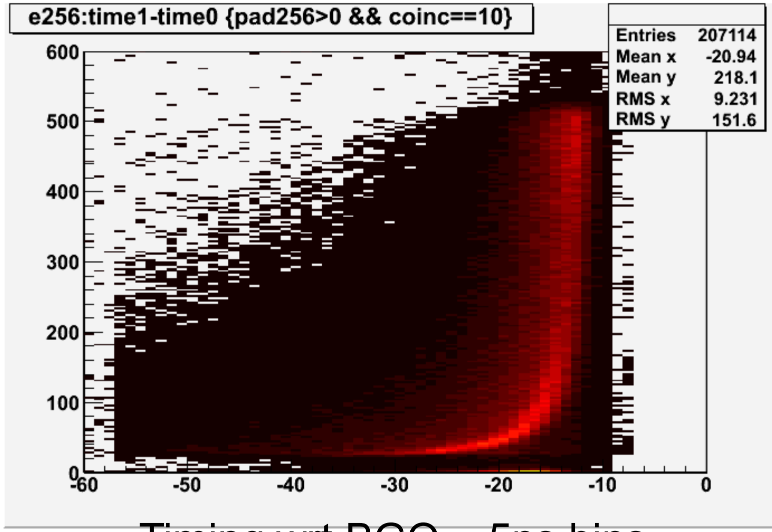
Top View



Side View



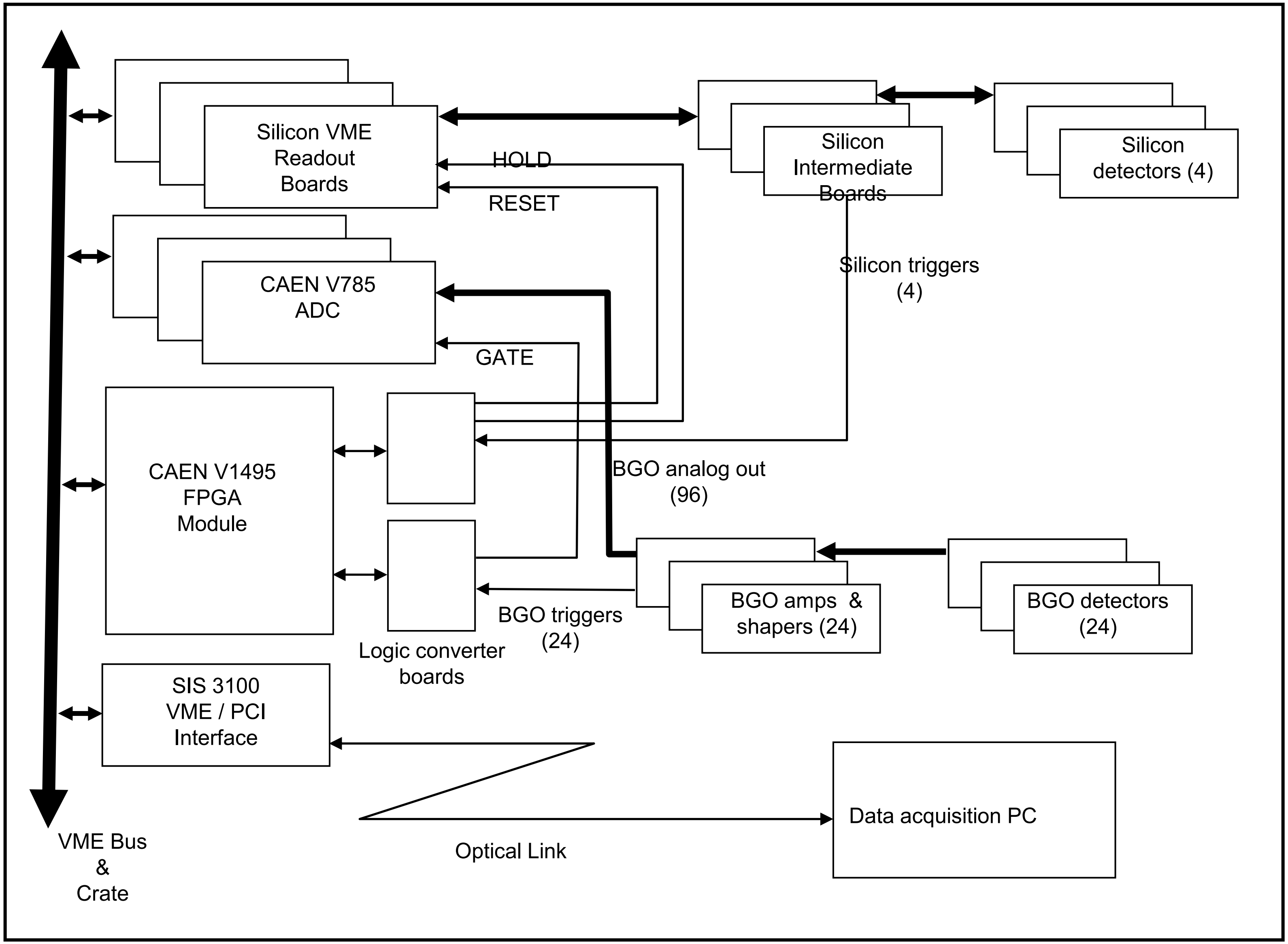
Am-241 Spectrum



Timing wrt BGO – 5ns bins

- 16 x 32 arrays of 1.4mm square elements x 1mm thick
- Read out using VATA GP7 ASICs (500ns slow, 150ns fast channel shaping time
- Excellent spatial and energy resolution. Timing resolution? Not so much.

Data Acquisition System

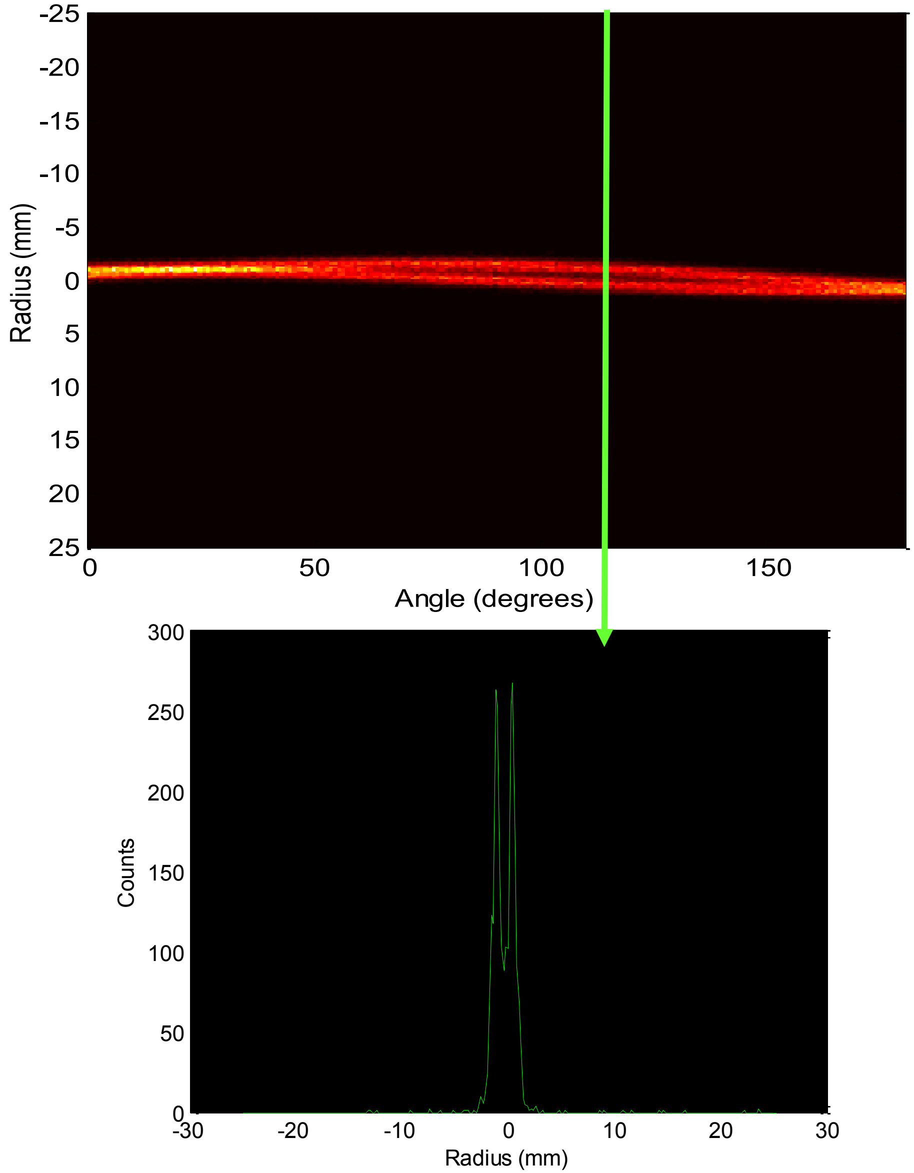


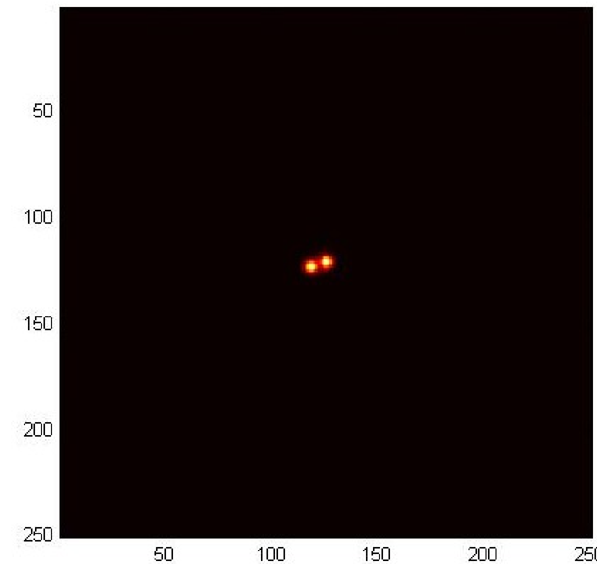
Data Acquisition

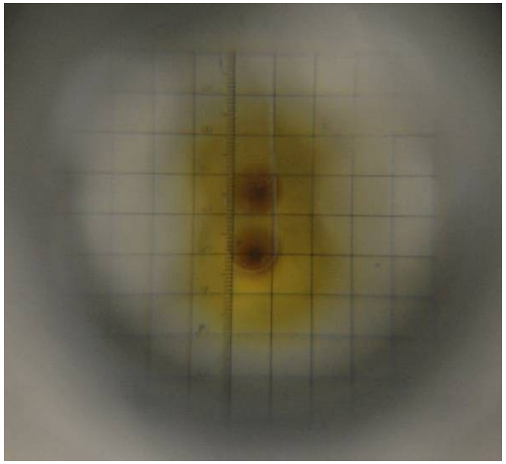
- Na-22 and F-18 filled sources.
  - Na-22 long half-life but restricted configurations
  - F-18 110m half-life but flexible phantoms
- Objects rotated in 6° increments
- Si-Si, Si-BGO, and BGO-BGO events can be collected individually or in groups (deadtime)
- Typical acquisition time: 5 hours
- All data stored in list (time-mark, position, energy, etc.) and subsequently processed into sinograms (0.2mm x 0.9° bins)

Results

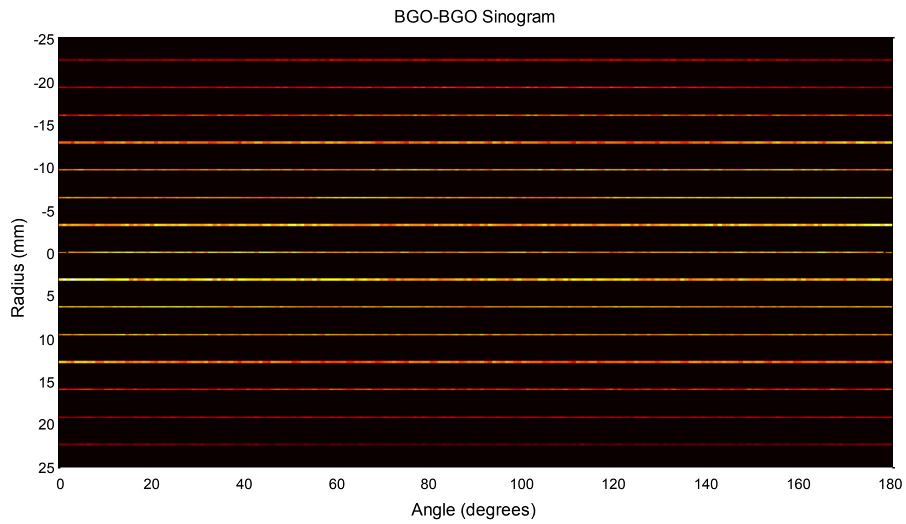
Na-22 Points 1.5mm center-to center (Si-Si events)

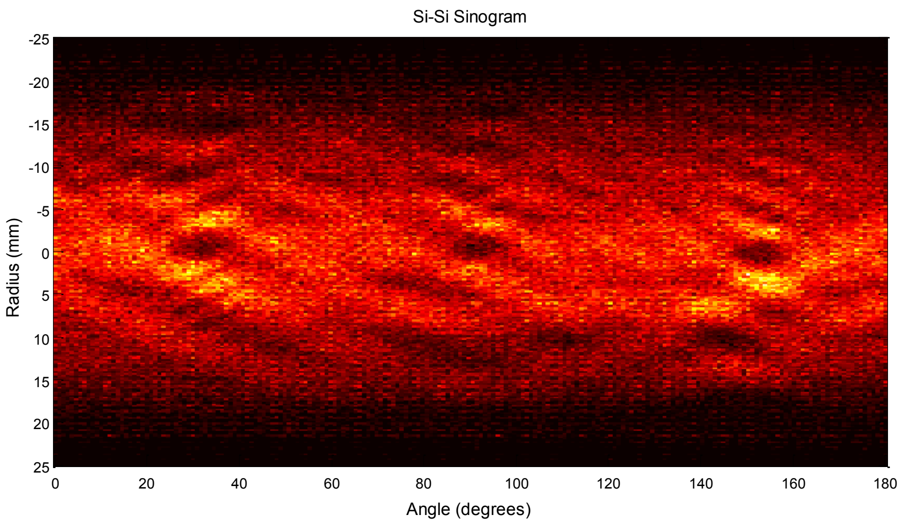


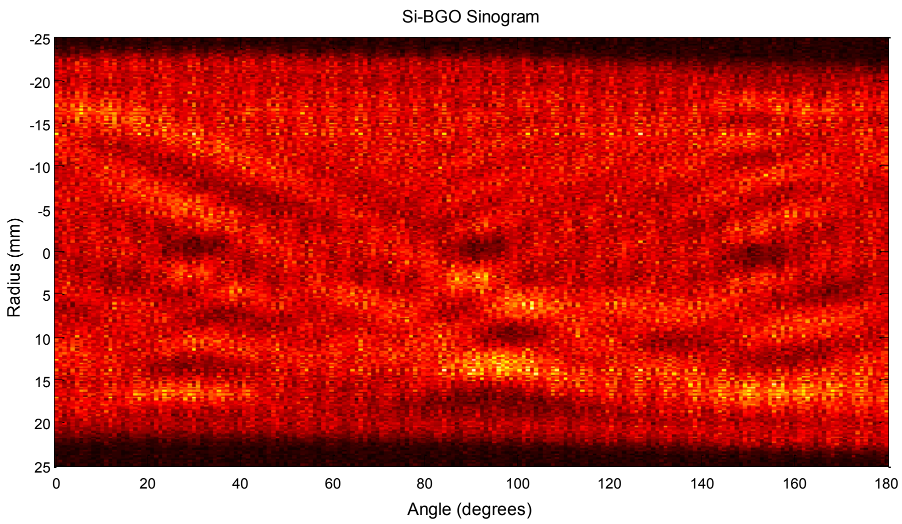




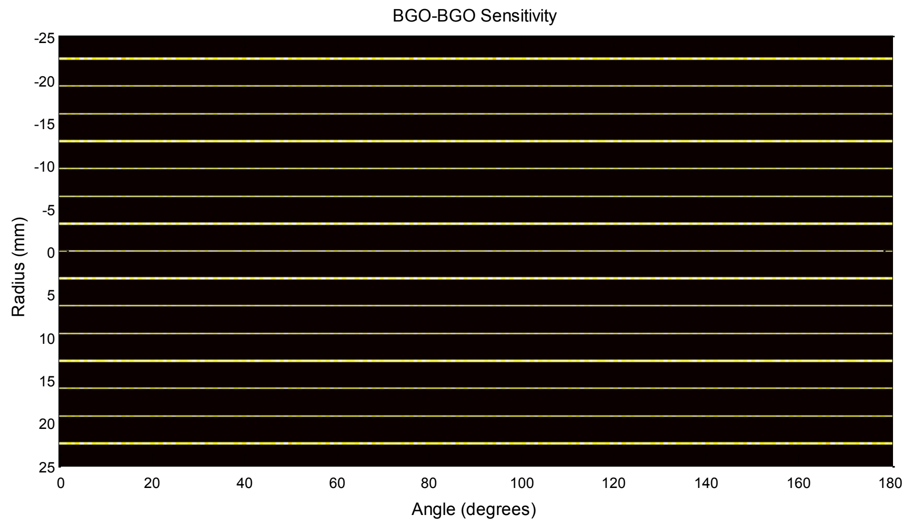
Micro Jaszczak Sinograms

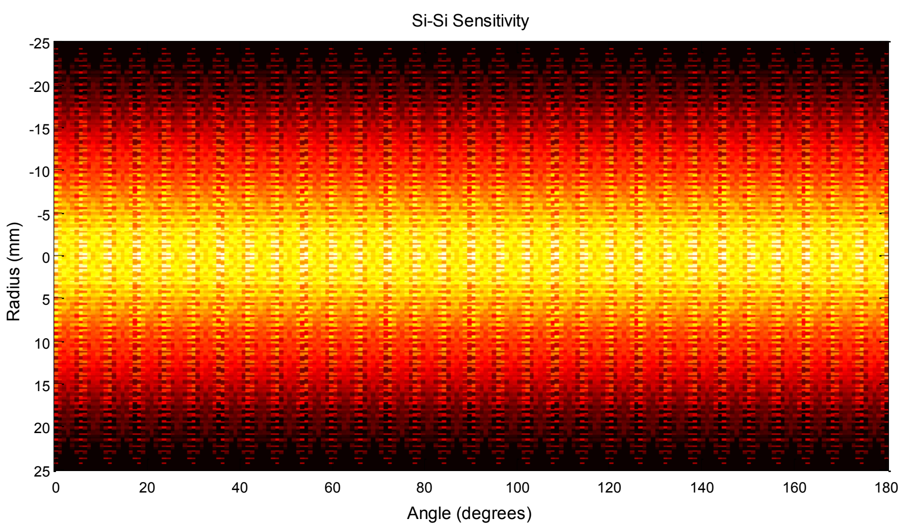


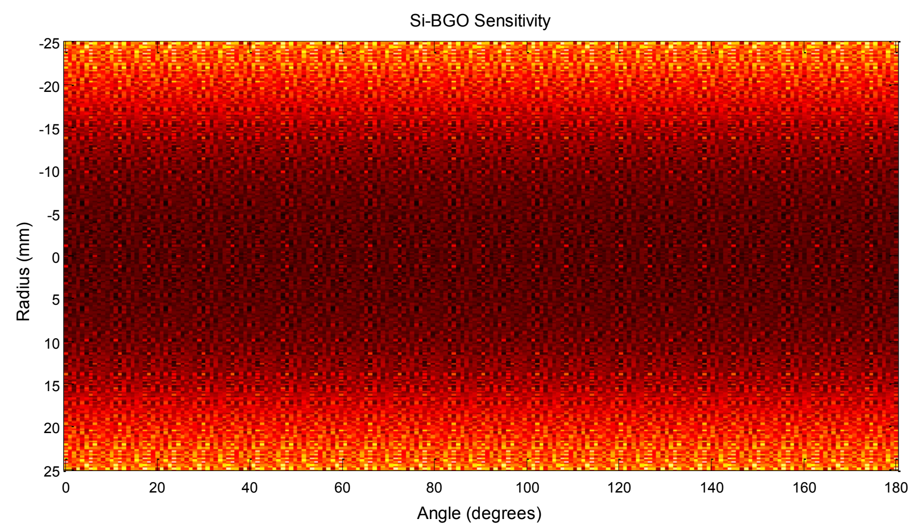




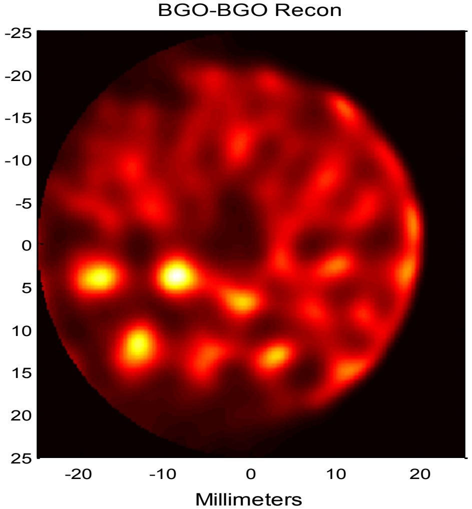
Sensitivity

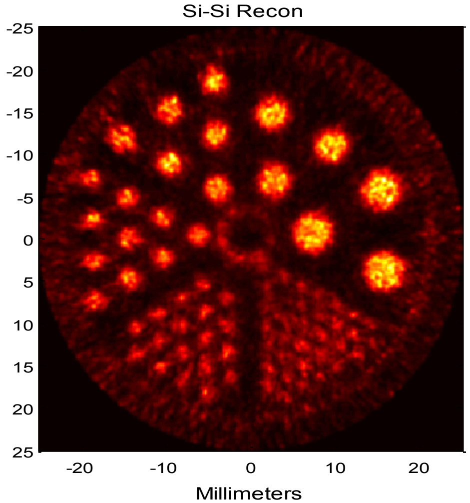


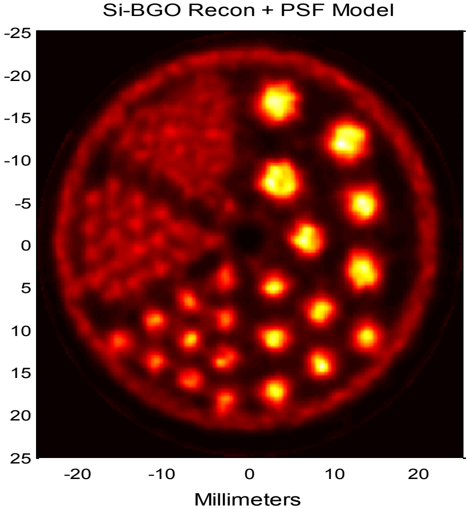




Reconstructions







1.4M Events

700K Events

2.4M Events

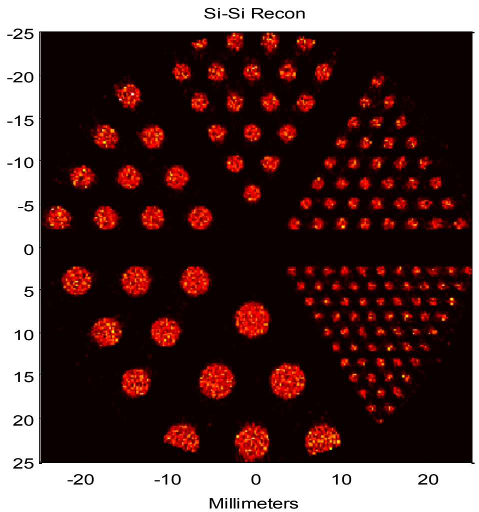
Regularized maximum likelihood reconstruction

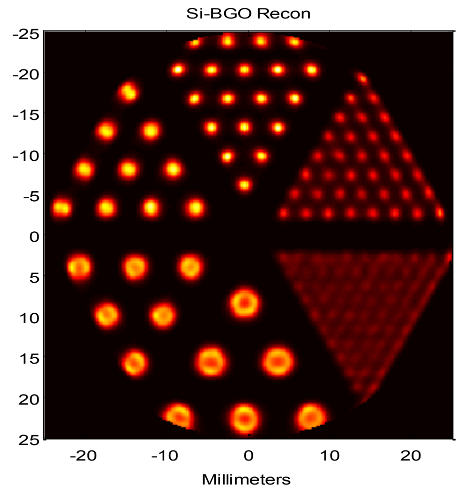
Rod diameters: 4.8mm, 4.0mm, 3.2mm, 2.4mm, 1.6mm & 1.2mm

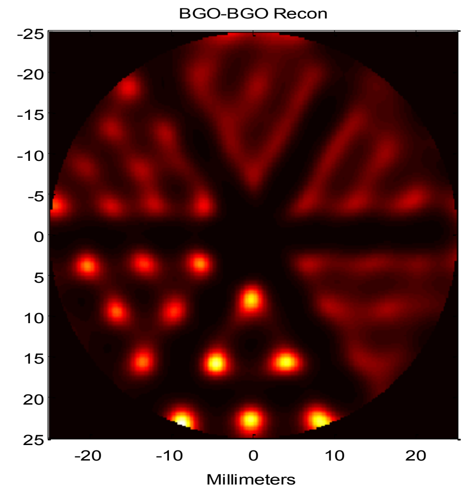
Expected Composite Performance

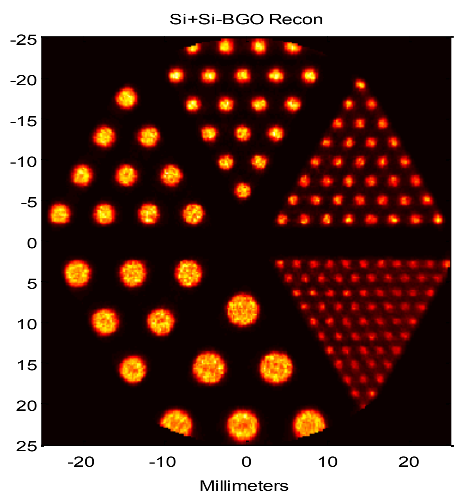
- Even a small fraction of high-resolution data can significantly improve performance (better resolution at same variance or vice-versa)
- When desired resolution operating point is better than the lowest resolution events, they will have little influence on performance
- Post-smoothed, penalized ML reconstruction must correctly model LOR widths and sensitivities

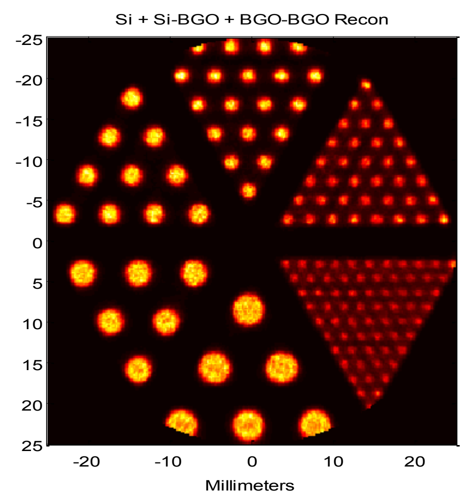
Composite Reconstructions





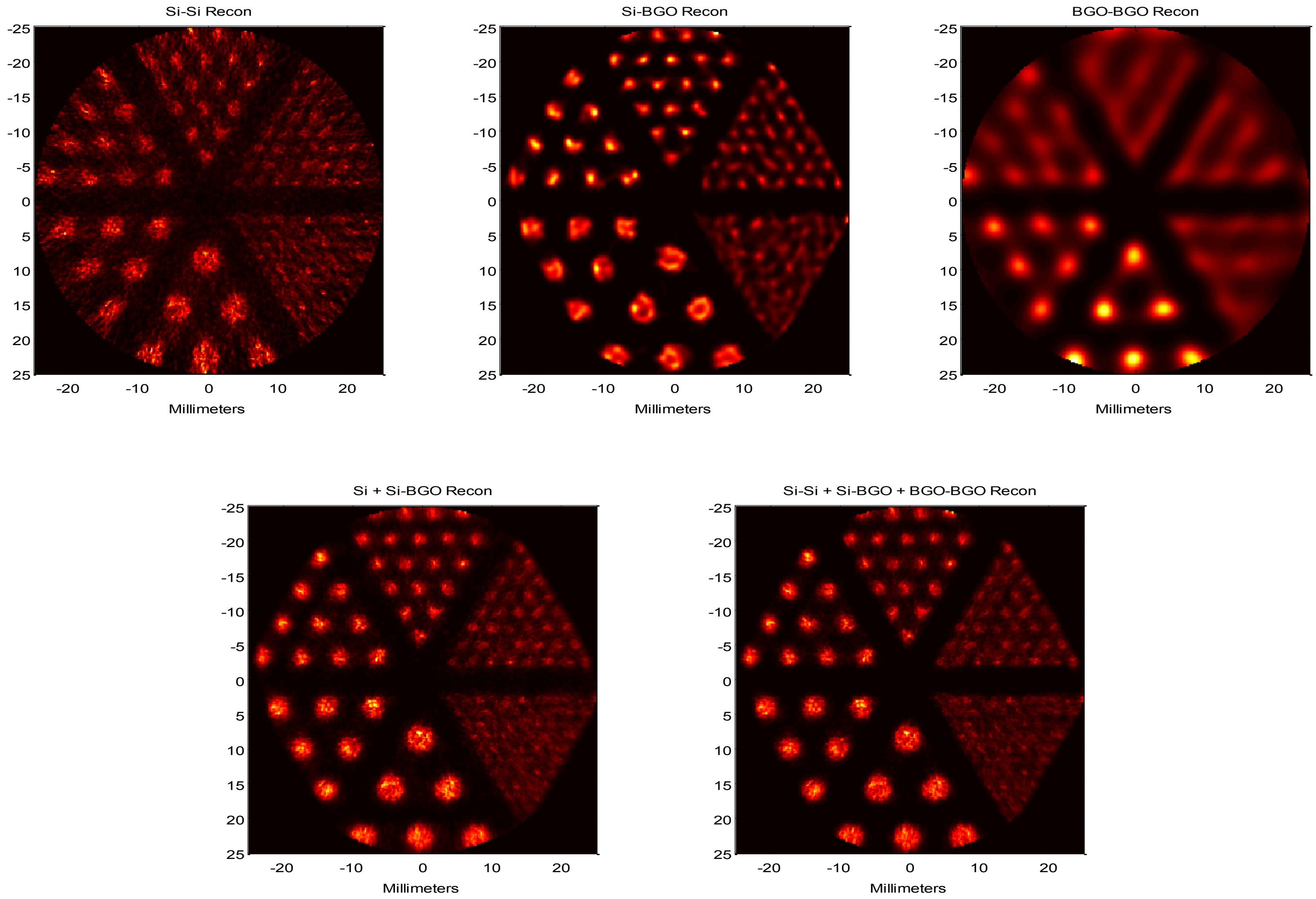






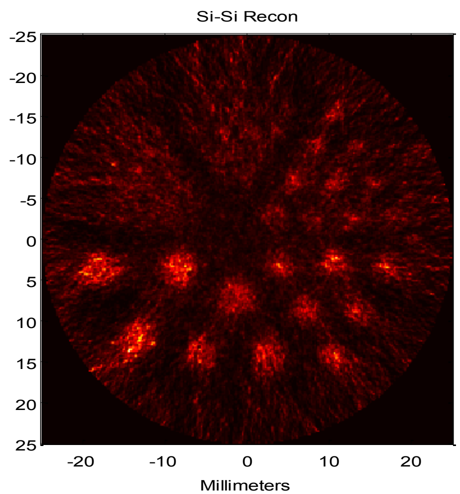
50M total count simulations (Si-Si 3%, Si-BGO 14%, BGO-BGO 86%)

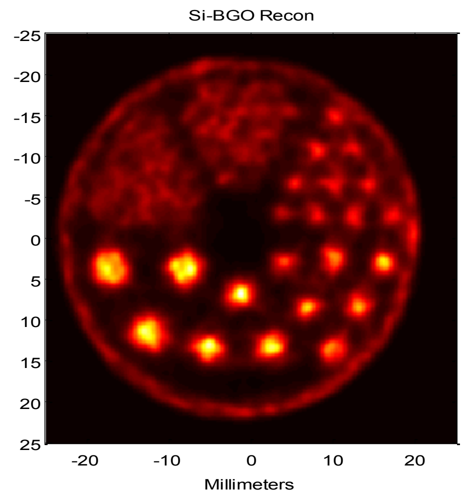
Composite Reconstructions

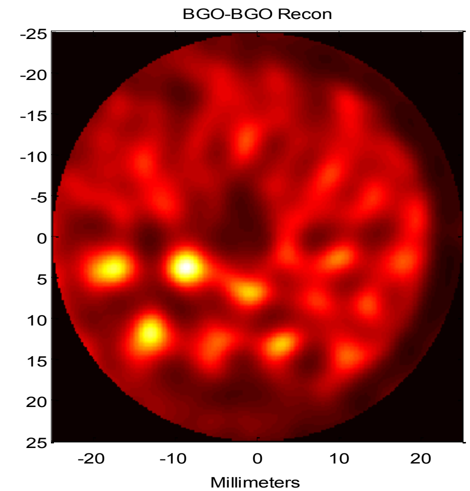


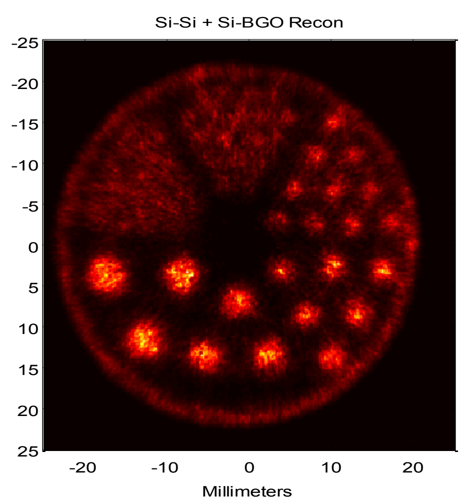
1.7M total count simulations (Si-Si 46K Si-BGO 235K, BGO-BGO 1.42M)

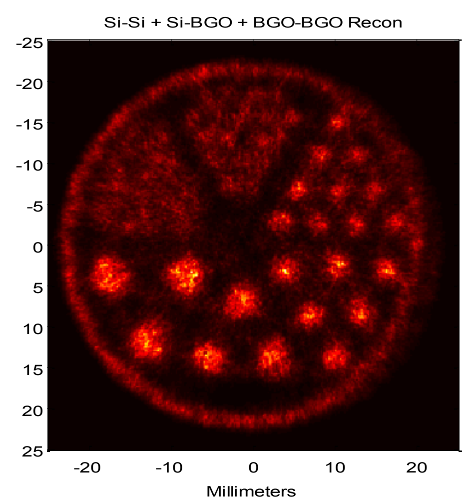
Composite Reconstructions











1.7M total count actual (Si-Si 46K Si-BGO 235K, BGO-BGO 1.42M)

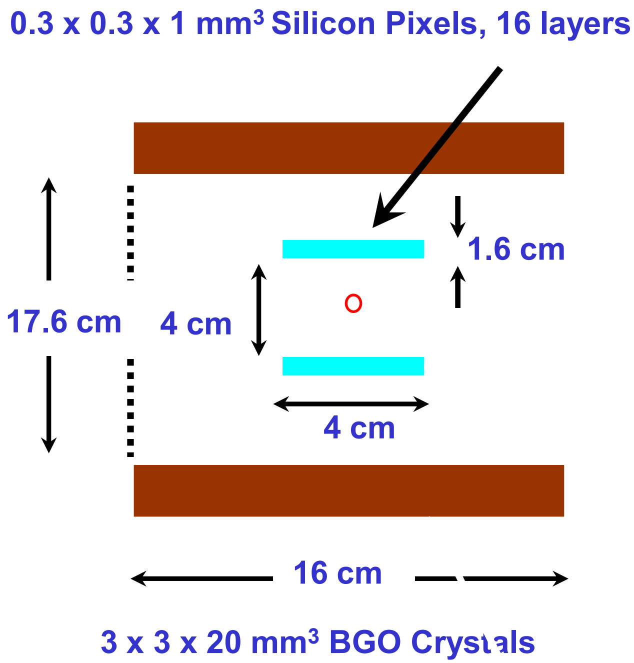
Summary

- Dual-ring PET hardware demonstrator
  - Shows high resolution capabilities
  - Shows advantage of magnifying geometries
  - Allows validation of methods for combining multires info
- Flexibility allows exploration of alternate geometries
  - Higher res inner detectors (1mm x 1mm Si)
  - External high resolution probes
- BGO will be replaced by LSYO arrays + PSPMT
- Will upgrade DAQ to reduce deadtime

Challenges

- Packaging and packing density of active detector
  - Useful system for rodent imaging would need ~150 cm^3 Si
  - Hi-res probe systems, similar
- Large number of channels of electronics
  - 150 cm^3 with 1mm^3 elements = 150K channels
  - Readout speed
- Sorting out event possibilities
  - Many more types of good and bad events than conventional PET
- Time resolution
  - 100 ns FWHM unacceptable except for demonstrations
  - ~5ns FWHM is almost necessary, 20ps FWHM desirable for time-of-flight
- Comparison with more conventional PET instruments??

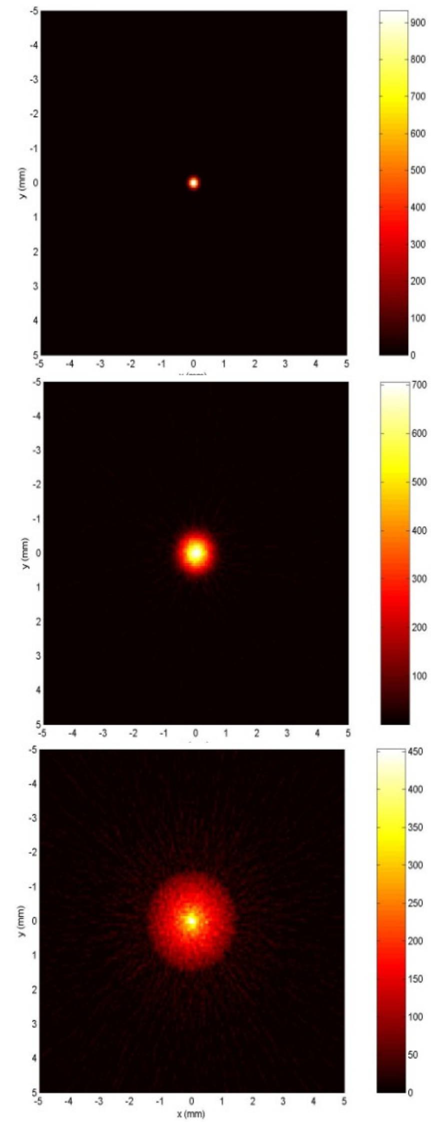
Simulated System and Results



Lower E Threshold: 350 keV

Interaction Selection Method:

BGO crystal with Maximum E



Si-Si
- Sensitivity: 1.0 %
- *FWHM = 230 μm

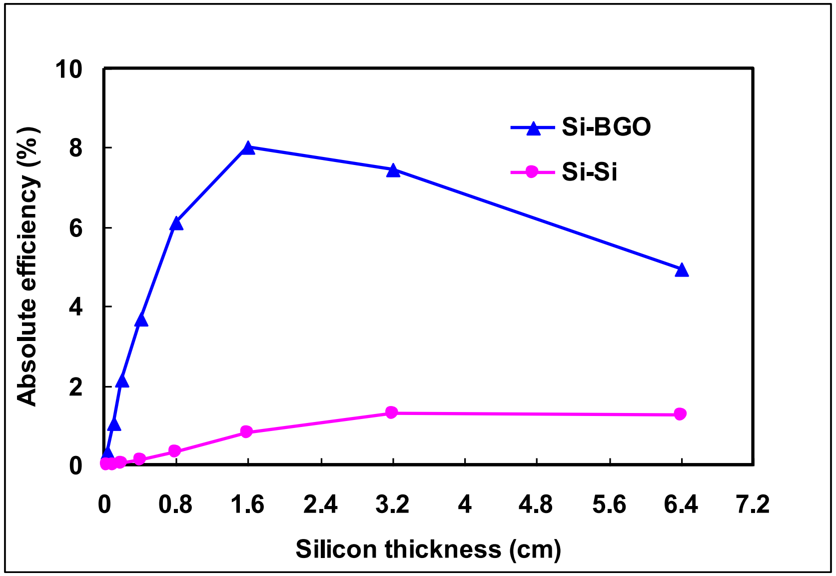
Si-BGO
- Sensitivity : 9.0%
- *FWHM = 790 μm

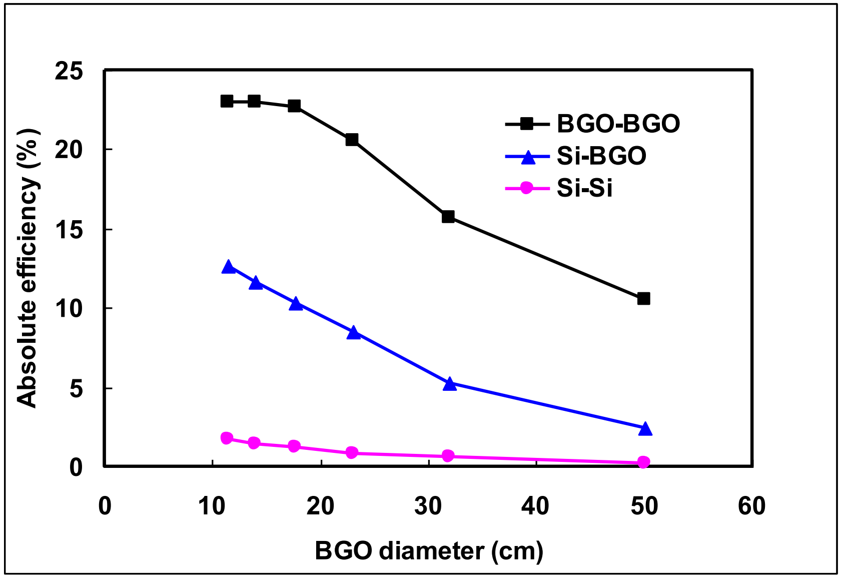
BGO-BGO
- Sensitivity: 21.0 %
- *FWHM = 1.45 mm

Image reconstruction: FBP

* Does not include acolinearity and positron range

Can It Have Enough Efficiency?



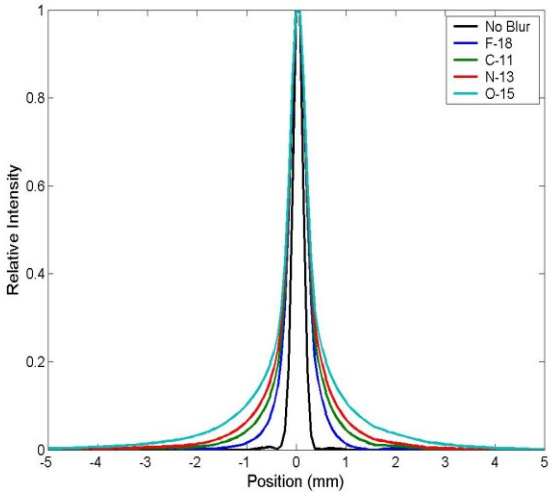


Further evaluate a system having the following characteristics

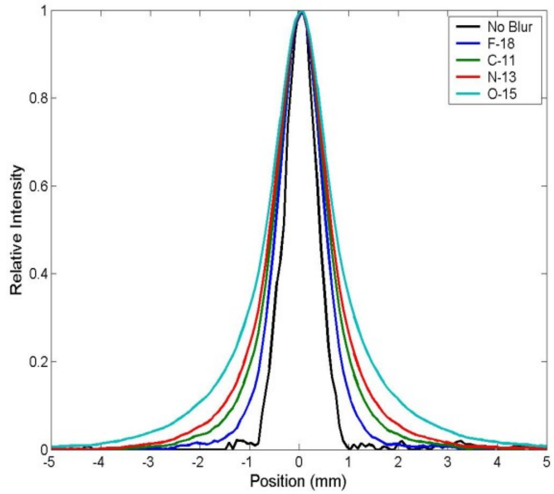
- Silicon 4cm ID, 7.2cm OD (16 layers of 0.3 mm × 0.3 mm × 1 mm elements)
- BGO detector 17.6 cm diameter, 16 cm length, and 2 cm thickness segmented into 3 mm × 3 mm × 20 mm crystals

Overall Spatial Resolution

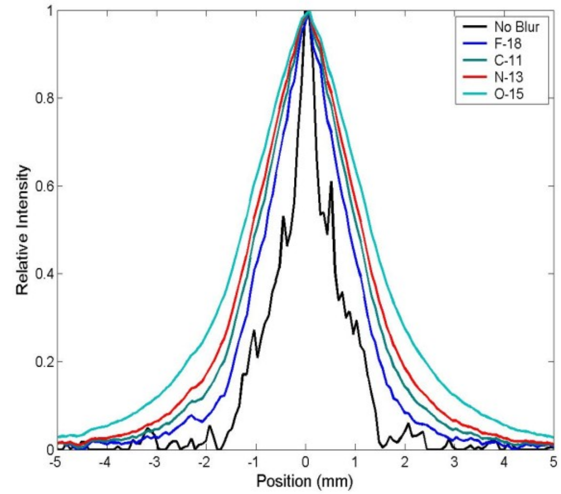
Si-Si



Si-BGO

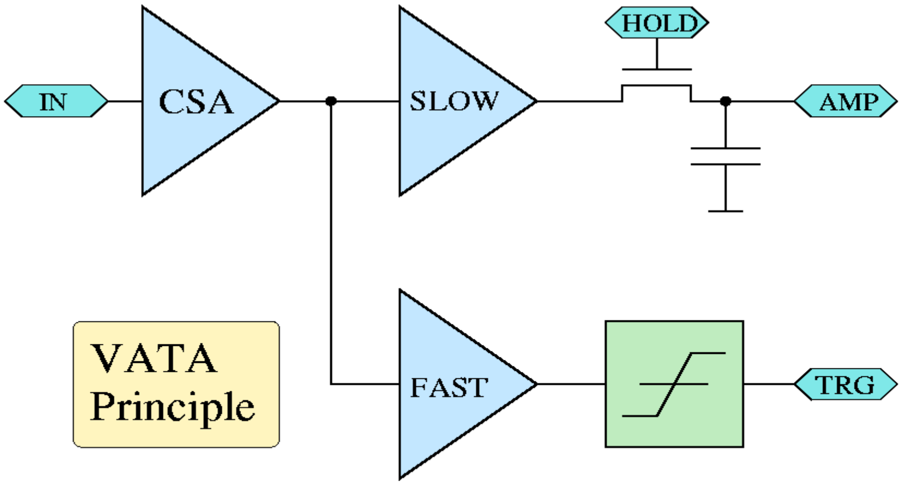


BGO-BGO



Event	Spatial Resolution (mm FWHM)					
	Geometric	Geometric + Acolinearity	Overall F-18	Overall C-11	Overall N-13	Overall O-15
Si-Si	0.234	0.241	0.393	0.443	0.492	0.553
Si-BGO	0.788	0.816	1.062	1.261	1.419	1.742
BGO-BGO	1.452	1.458	1.977	2.270	2.490	3.069

VATA Readout ASICs

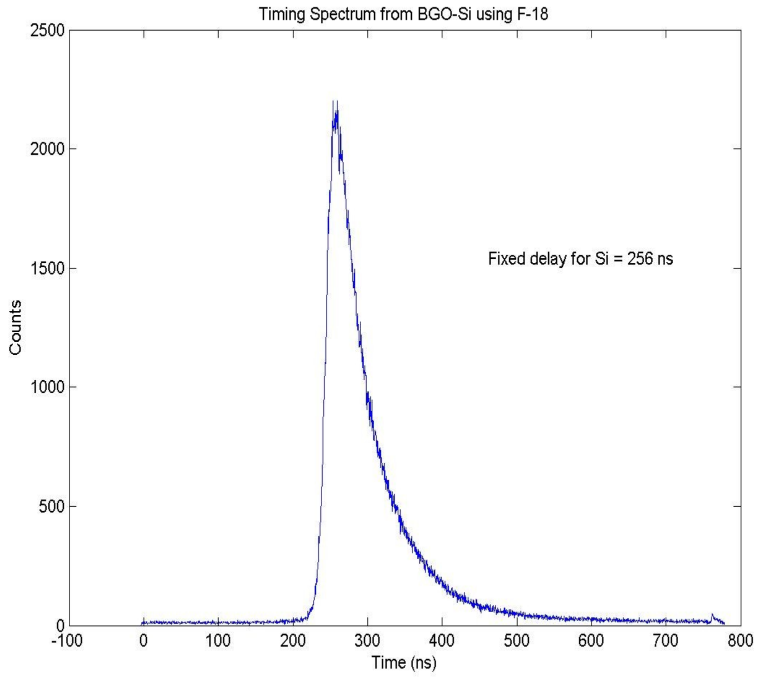


GP-3: 2.5-3 μs shaping in slow channel
200 ns peaking time in fast channel

Serial, sparse, sparse + adjacent channel readout

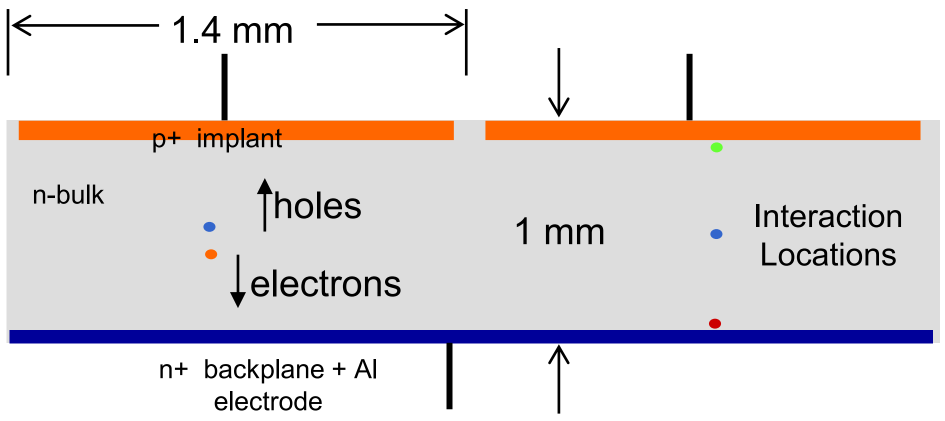
Timing

- Desired time resolution <10ns FWHM
- Marginal timing is evident
- Slower signal generation from events near backplane
- Large range of pulse-height coupled with leading-edge trigger is biggest issue
- Large time-walk is the result

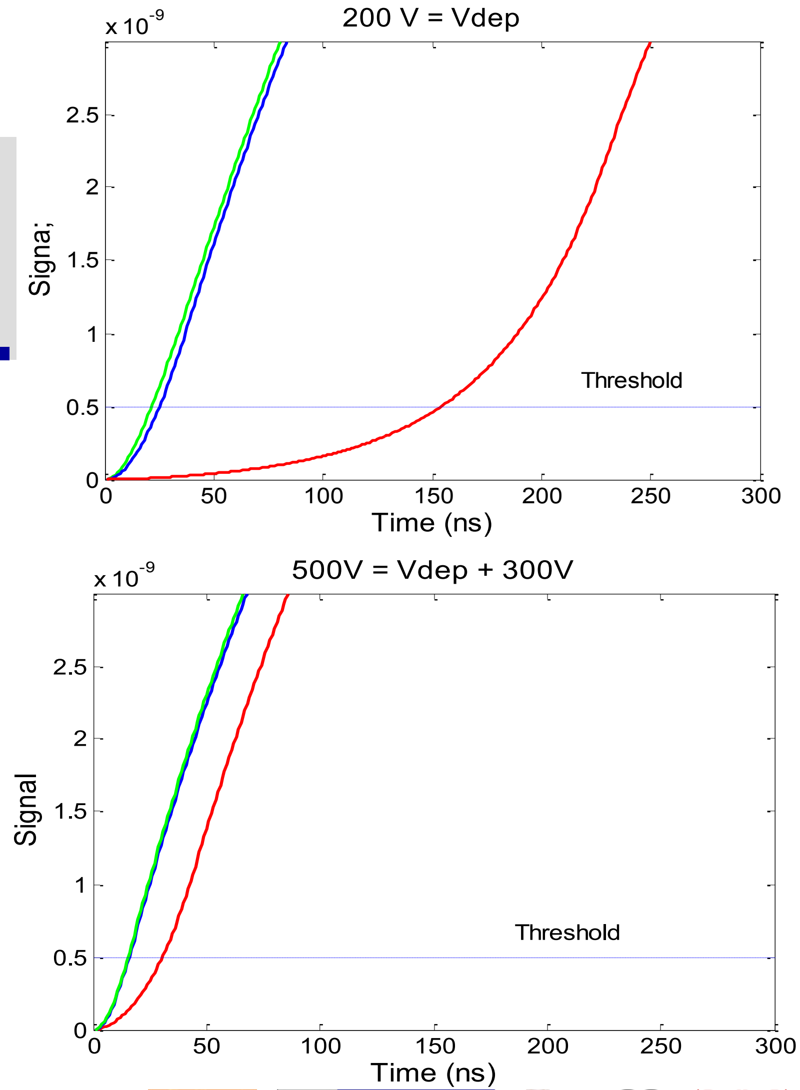


BGO-Silicon timing spectrum for 511 keV source

Simple Signal Generation Model

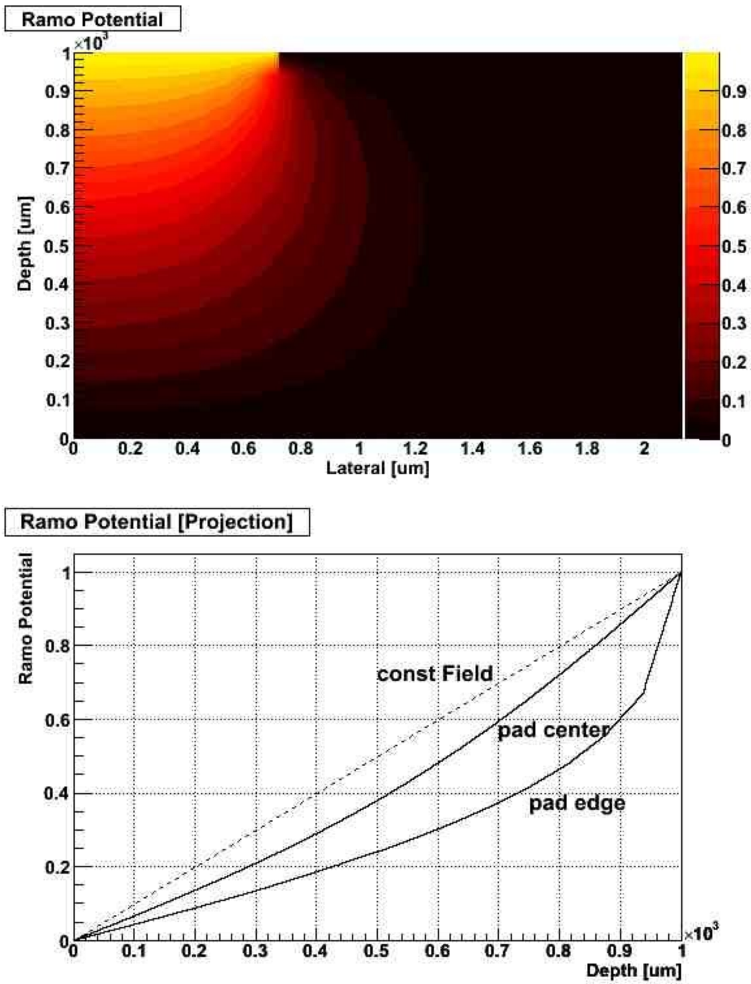


Simplified Pad Detector



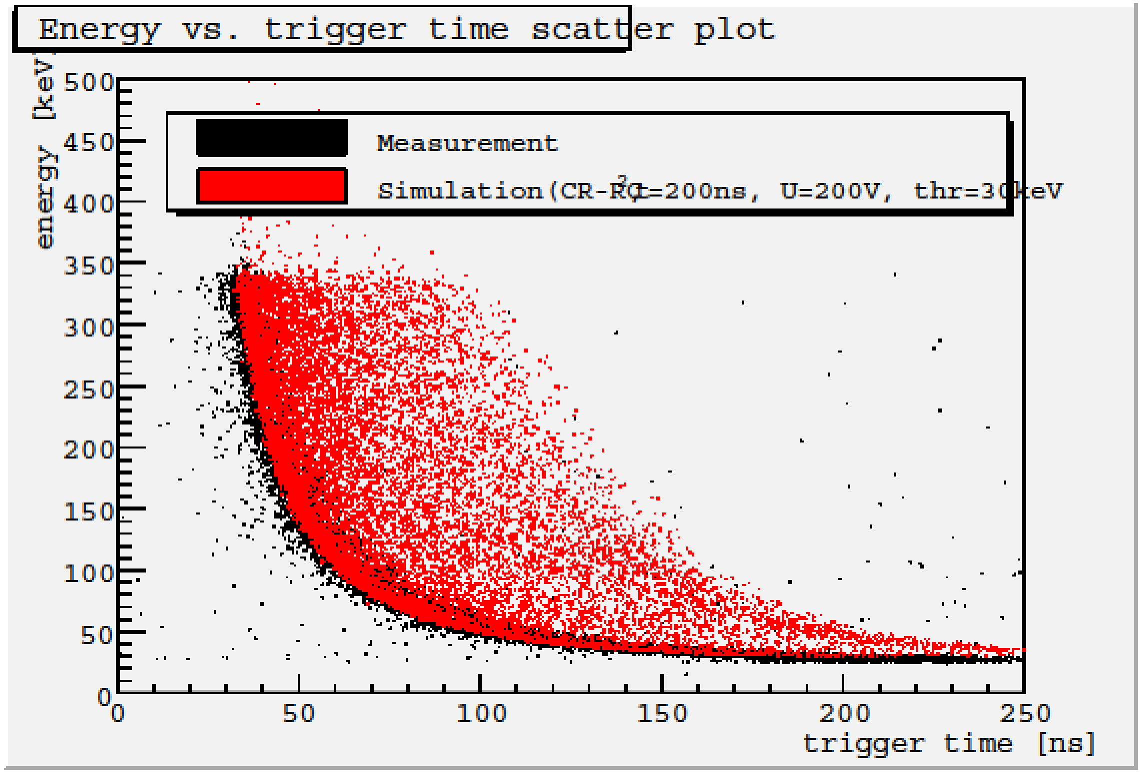
- Depth dependence of signal evident
- Non-linear effect with depth
- Higher bias helps

But…*It gets worse!*



- Pad size is nearly same as detector thickness
- Weighting potential depends on x & y in addition to z
- Result is additional jitter due to unknown 3D interaction location

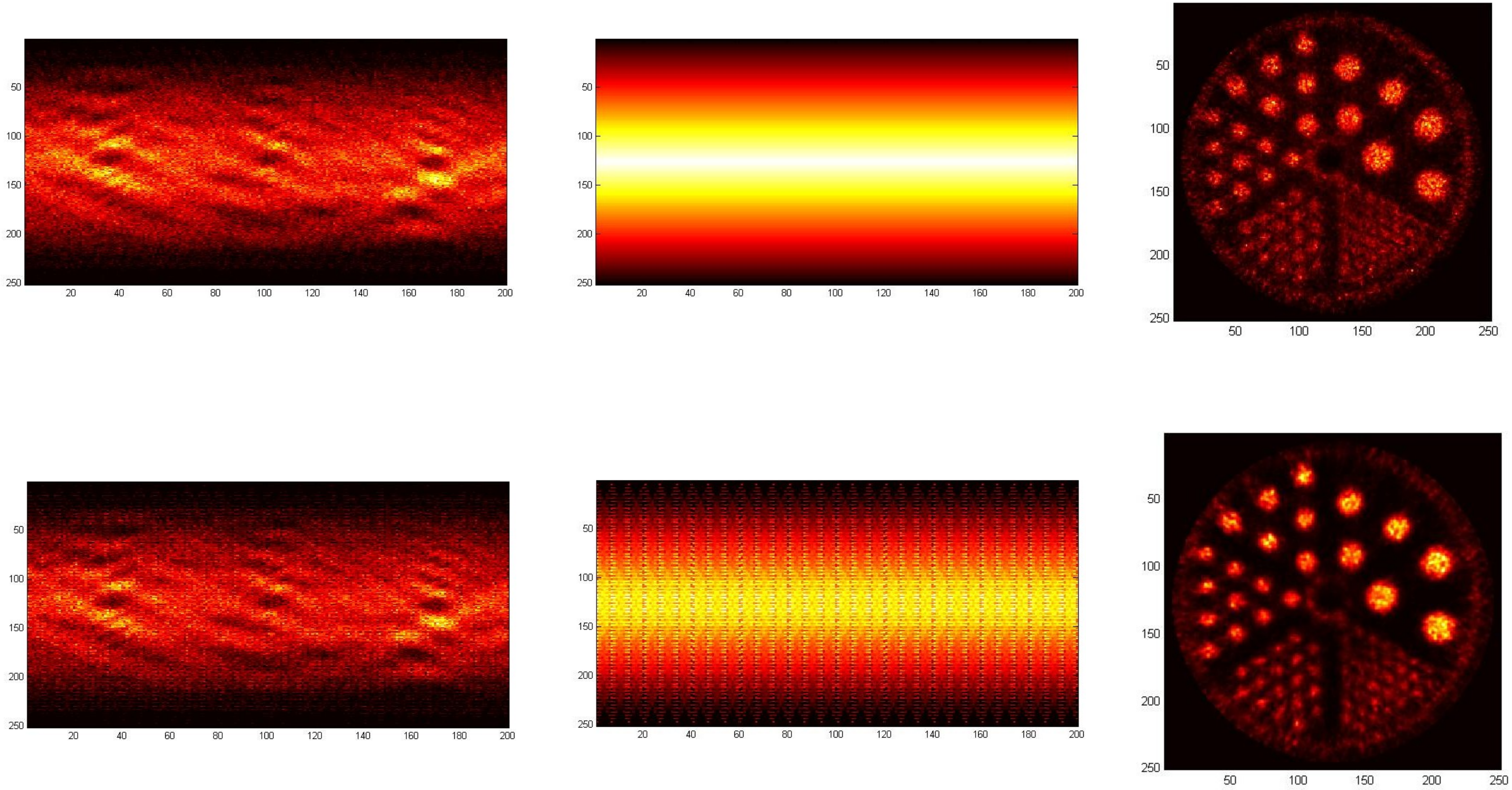
T-CAD Simulation / Measurements



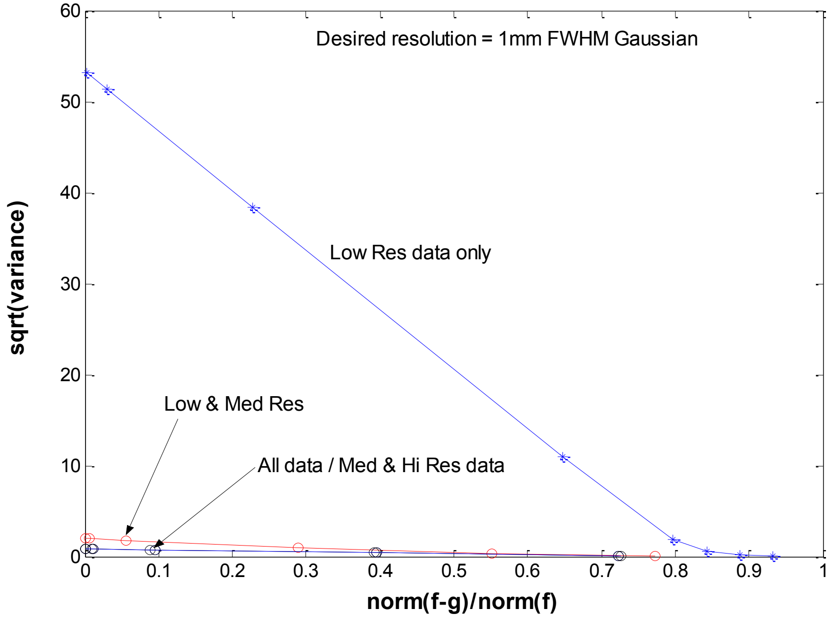
Energy deposited in Si detector vs. triggering time

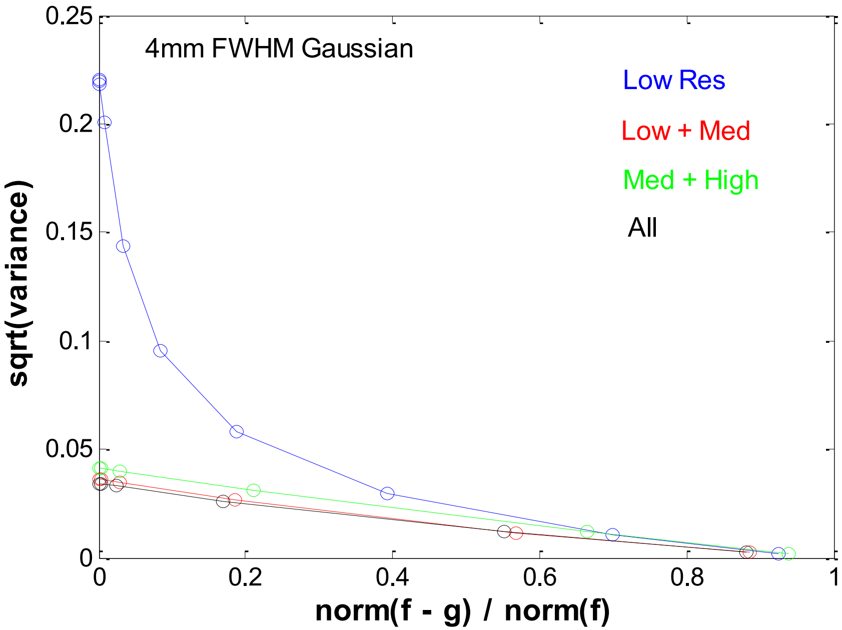
“Randomization”

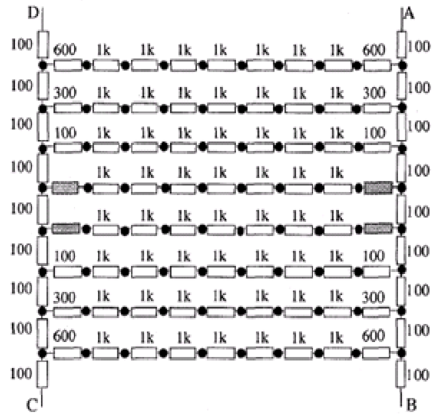
Don’t do it!

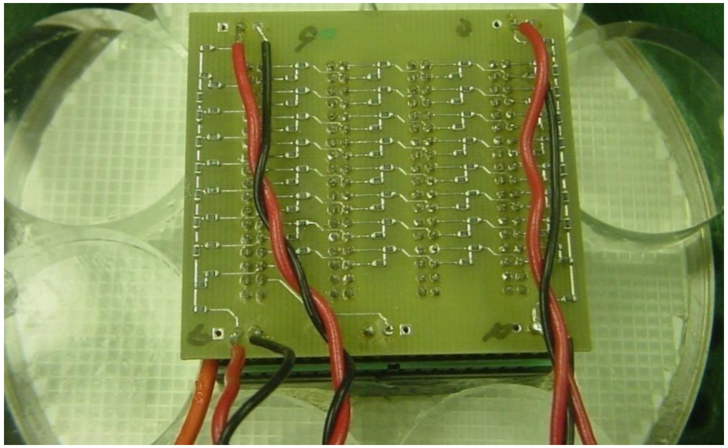


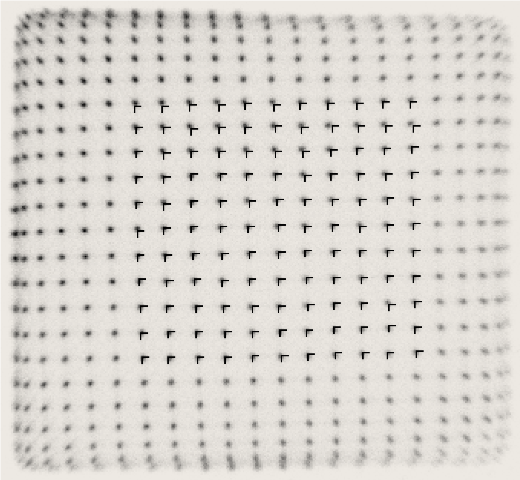
Can a Small Amount of Hi Res Data Have an Effect on Performance?

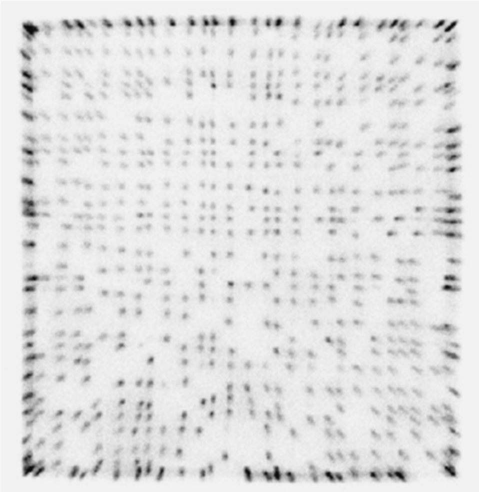




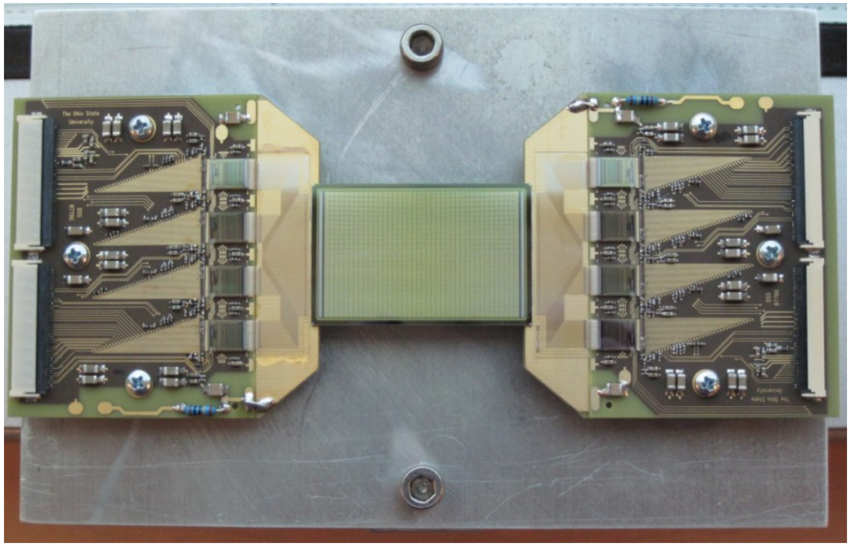

D
A
100 600 1k 1k 1k 1k 1k 1k 1k 600 100
100 300 1k 1k 1k 1k 1k 1k 1k 300 100
100 100 1k 1k 1k 1k 1k 1k 1k 100 100
100 1k 1k 1k 1k 1k 1k 1k 100
100 1k 1k 1k 1k 1k 1k 1k 100
100 100 1k 1k 1k 1k 1k 1k 1k 100 100
100 300 1k 1k 1k 1k 1k 1k 1k 300 100
100 600 1k 1k 1k 1k 1k 1k 1k 600 100
100 100
C
B

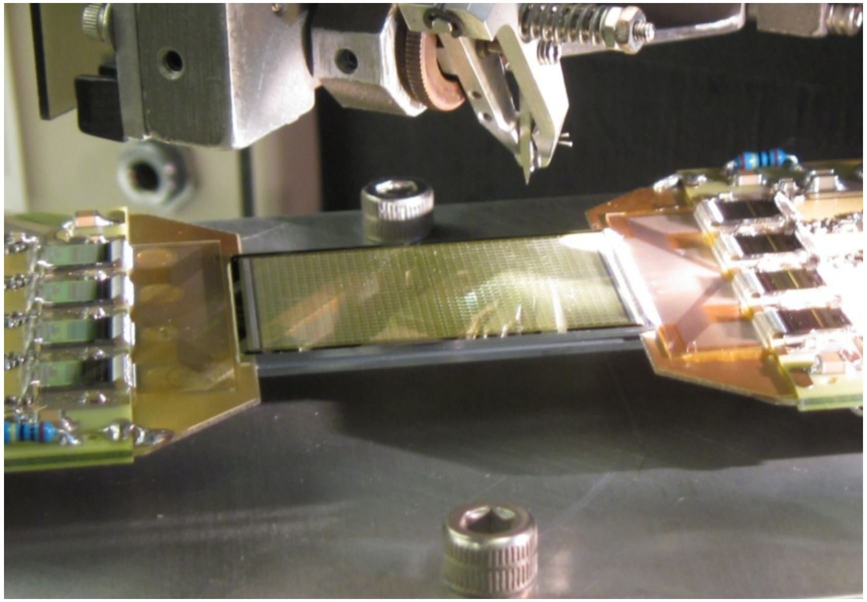




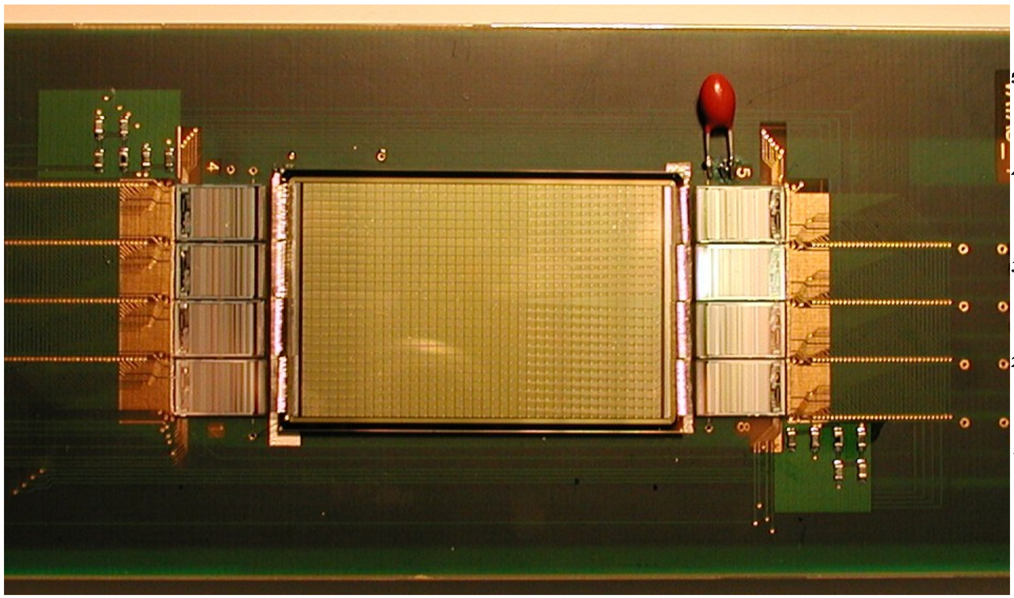


1mm Pad Detectors

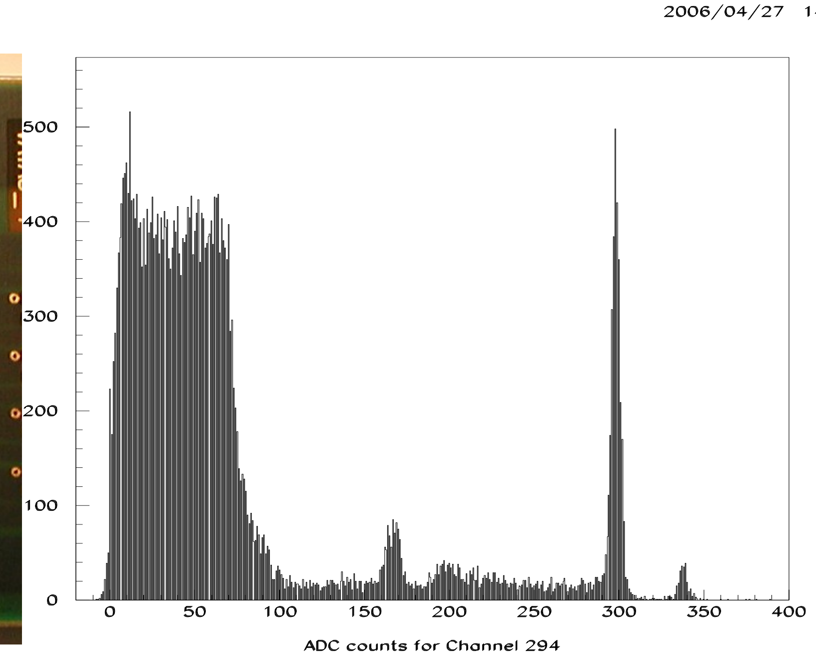




New Pad Detectors



1040 (26 x 40) 1mm x 1mm pads, 1mm thick



Co-57 Spectrum

Should allow 0.5 – 0.6mm FWHM spatial resolution

Intrinsic Resolution Between Detectors

- Already large uncertainty along path of annihilation photons (undone by tomographic reconstruction)
- Resolution determined primarily by uncertainty *transverse* to the photon paths

$$R_D \approx 2.35\sqrt{\left((1-\alpha)^2\left(\sin^2\theta_1\sigma_{D1}^2+\cos^2\theta_1\sigma_{C1}^2\right)+\alpha^2\left(\sin^2\theta_2\sigma_{D2}^2+\cos^2\theta_2\sigma_{C2}^2\right)\right)}$$