First Results from a Test Bench for Very High Resolution Small Animal PET Using Solid-State Detectors

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for

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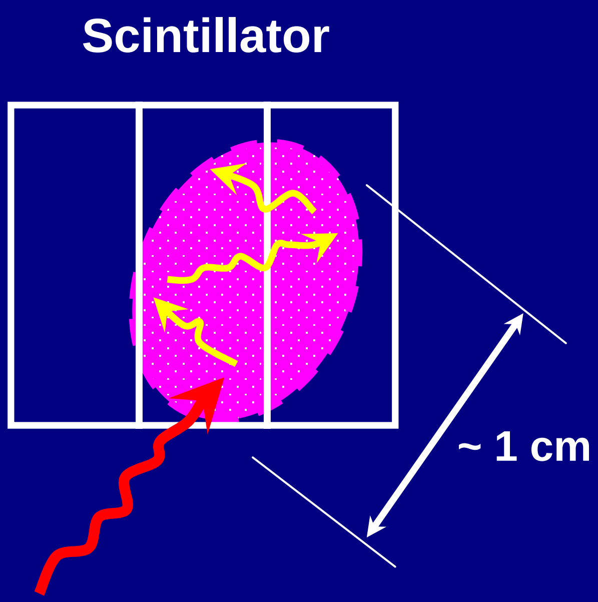
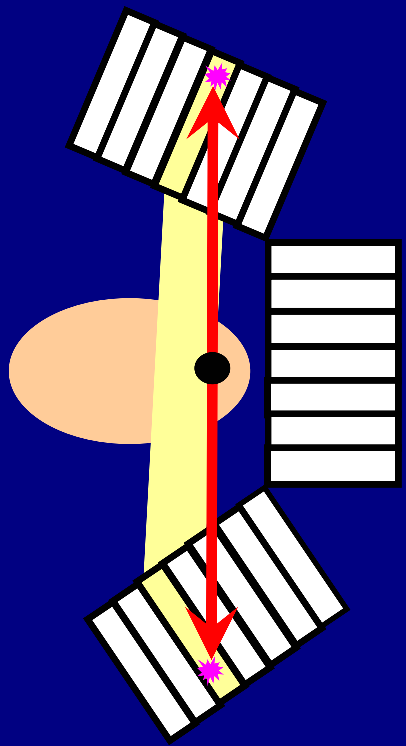
Resolution Limitations for Conventional PET

Inter-Crystal Scattering



- Multiple Interactions
- Energy deposited over a volume
- ~ 1 cm mean path

Depth of Interaction Uncertainty



- Penetration into crystals widens LOR

➡ Best Resolution ~ 1-2 mm

Compton PET Concept

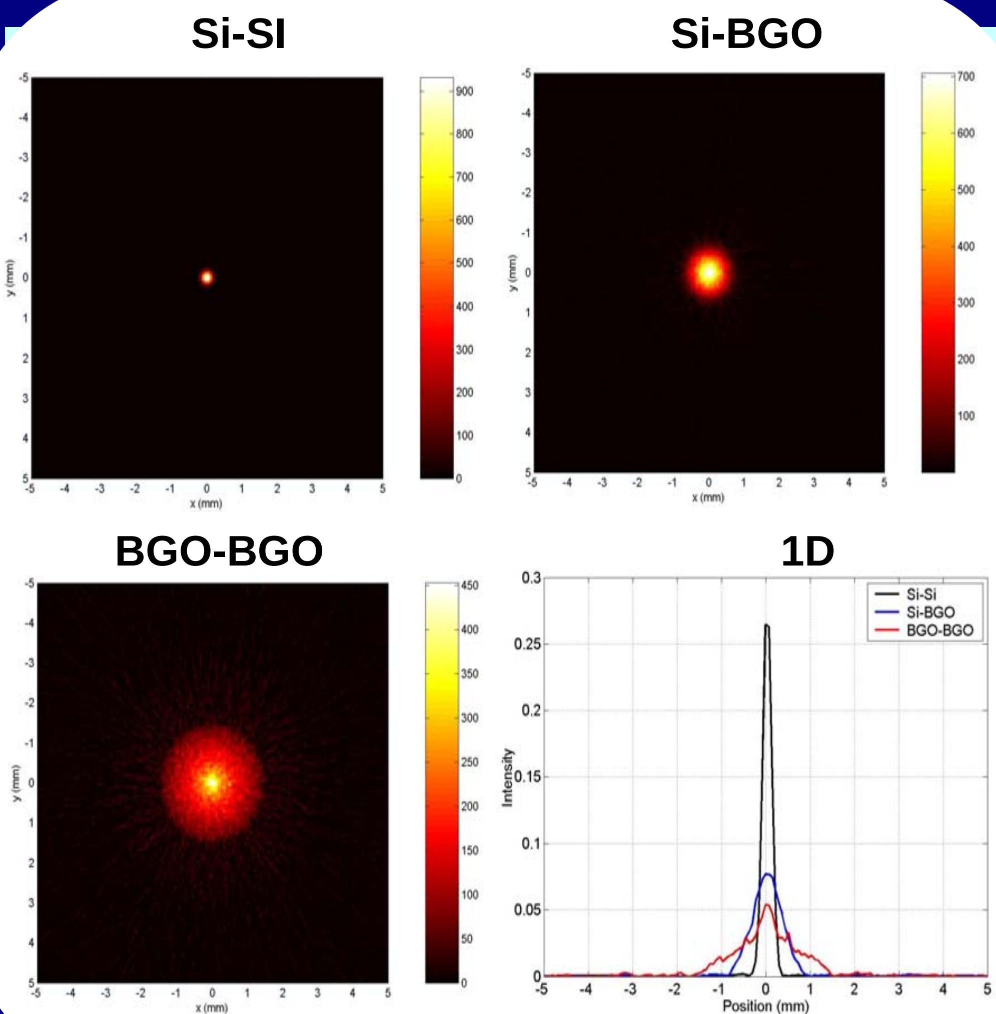


Image reconstruction: FBP

Uses two sets of detectors: low resolution and high

Low resolution detectors can be conventional PET or small animal PET scanner

High resolution detectors: 3D stack of position-sensitive solid-state detectors

Resolution to challenge positron range

Si-Si

Sensitivity: 1.0 %

***FWHM = 230 μm**

Si-BGO

Sensitivity: 9.0%

***FWHM = 790 μm**

BGO-BGO

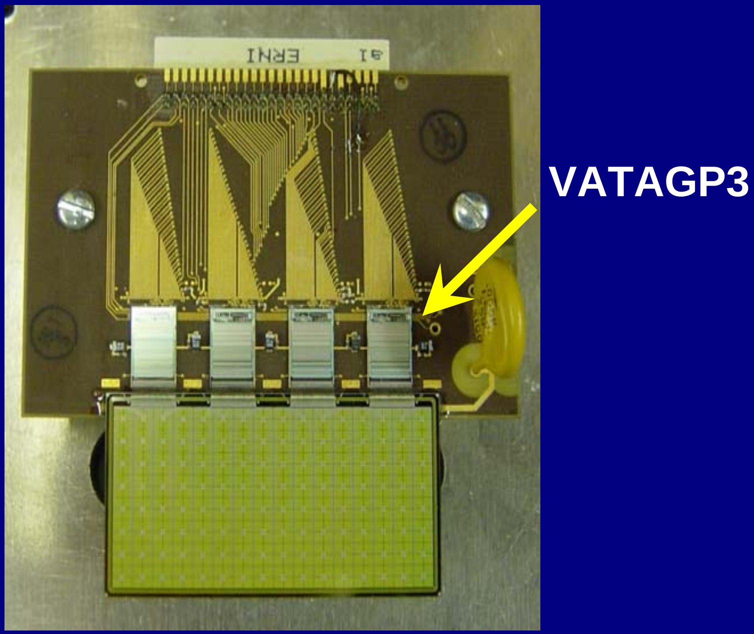
Sensitivity: 21.0 %

***FWHM = 1.45 mm**

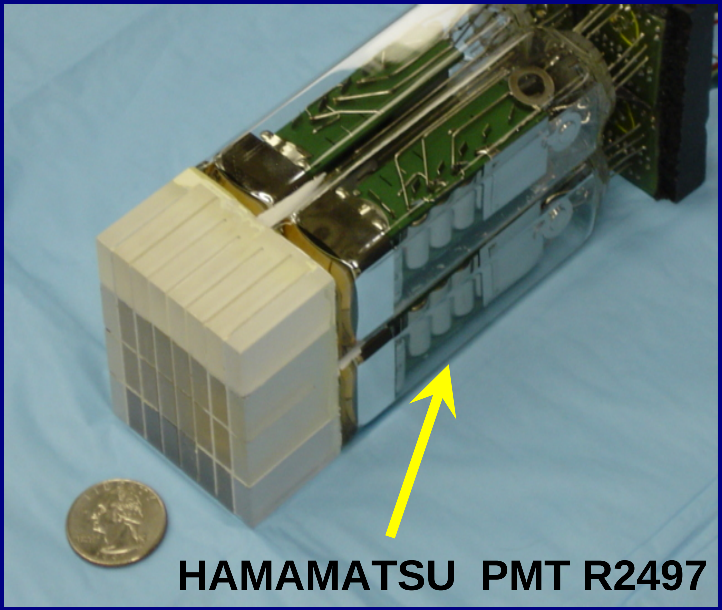
*** Not including effects of annihilation photon acolinearity and positron range**

Compton Pet Test Bench

Silicon detector



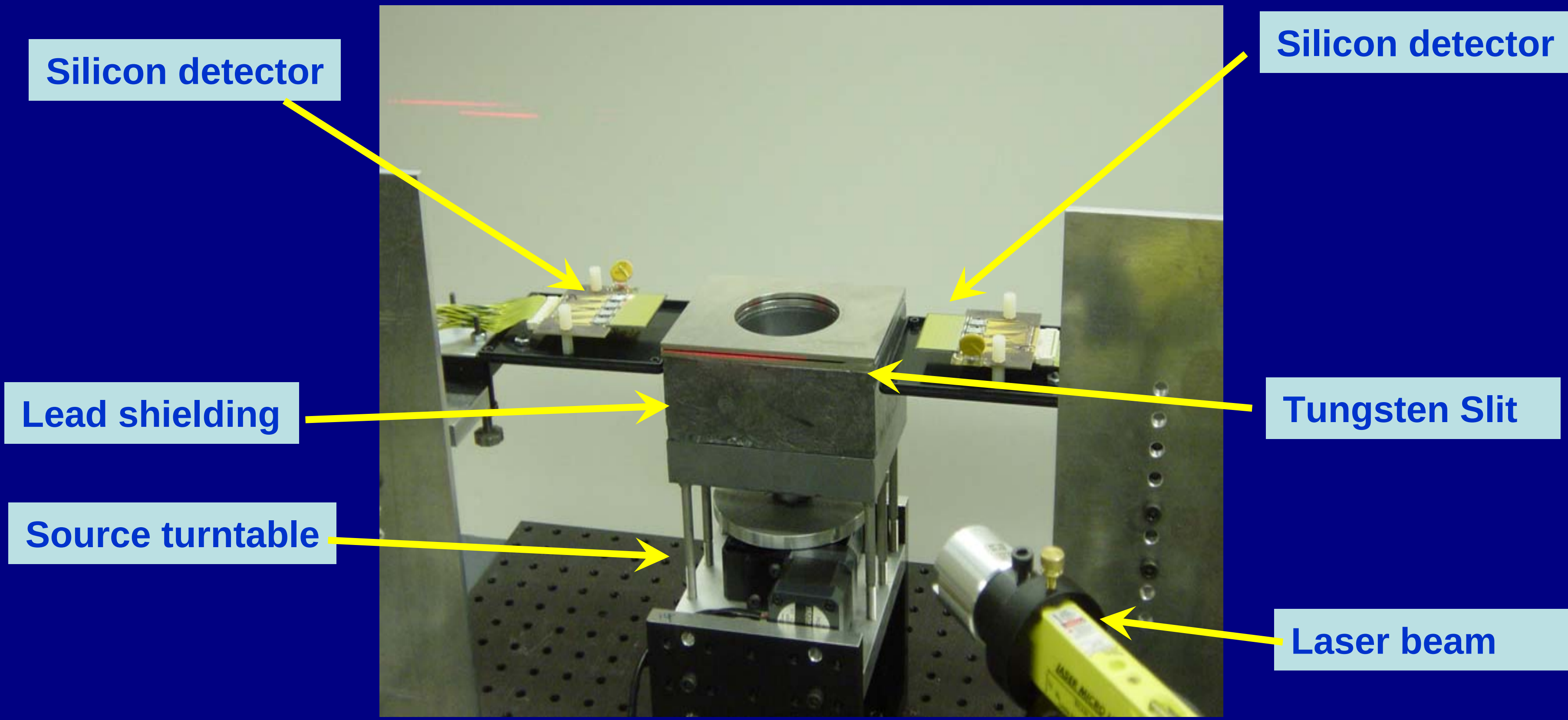
BGO detector



4.5 cm × 2.2 cm and 1 mm thick
32×16 (512) pads, 1.4 mm × 1.4 mm pixel size
Energy Resolution 1.39 keV FWHM for Tc 99m

5.3 cm × 5 cm and 3 cm thick
8×4 array, 12.5 mm × 5.25 mm crystal size
Energy Resolution 22% FWHM for Na-22

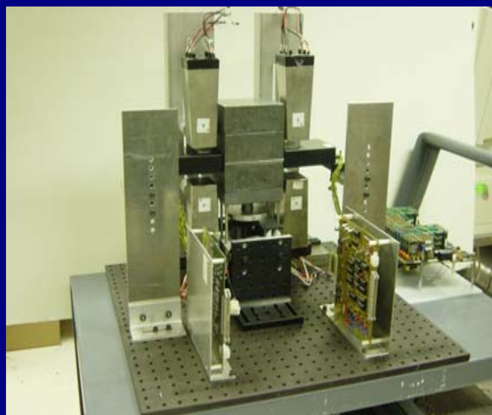
Setup and Alignment

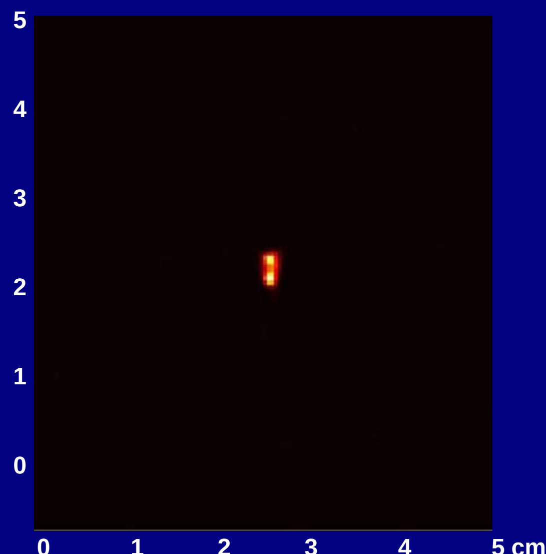


BGO detectors, electronics not shown

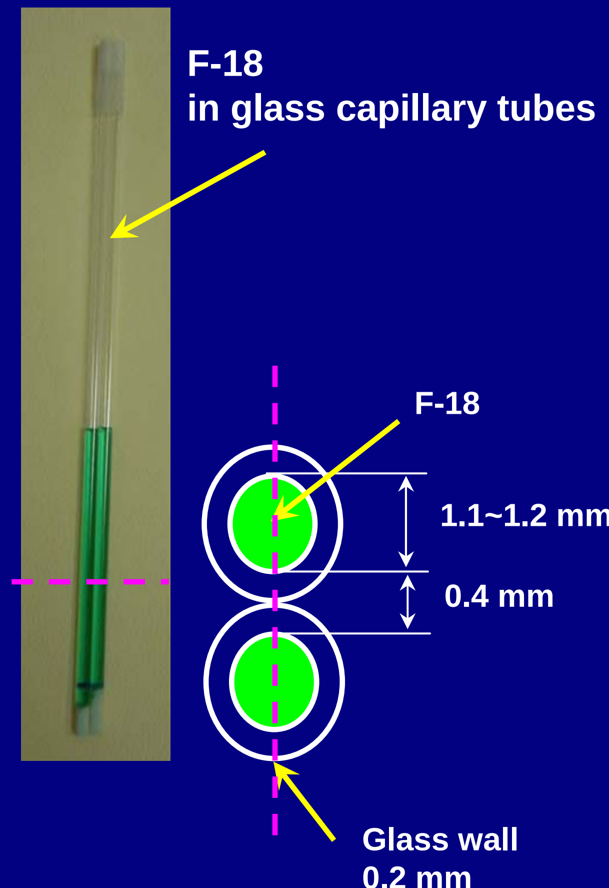
Images of Two Point Sources

Compton PET

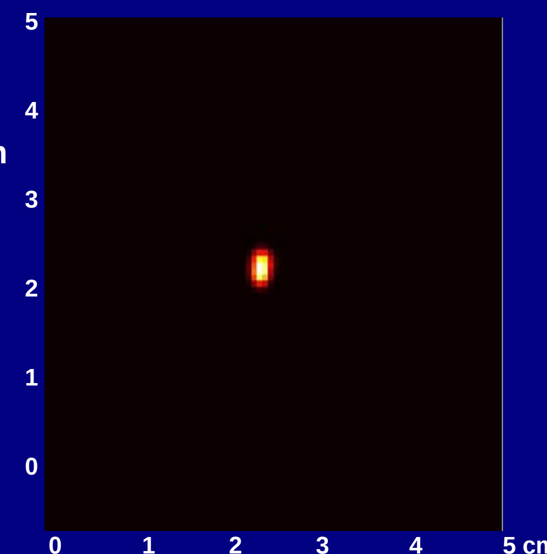




Source

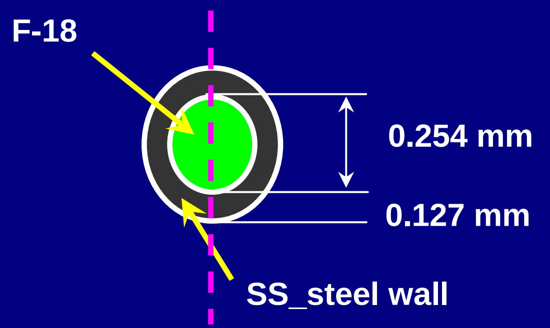


MicroPET R4

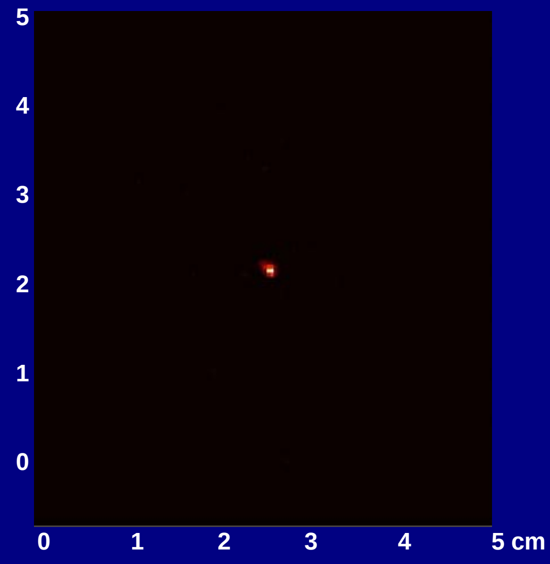


ML-EM Image reconstruction with Si-Si coincidence events only

Compton PET: Intrinsic Resolution



Needle 25G (ID = 0.254 mm, OD = 0.5mm, SS_steel wall = 0.127 mm)



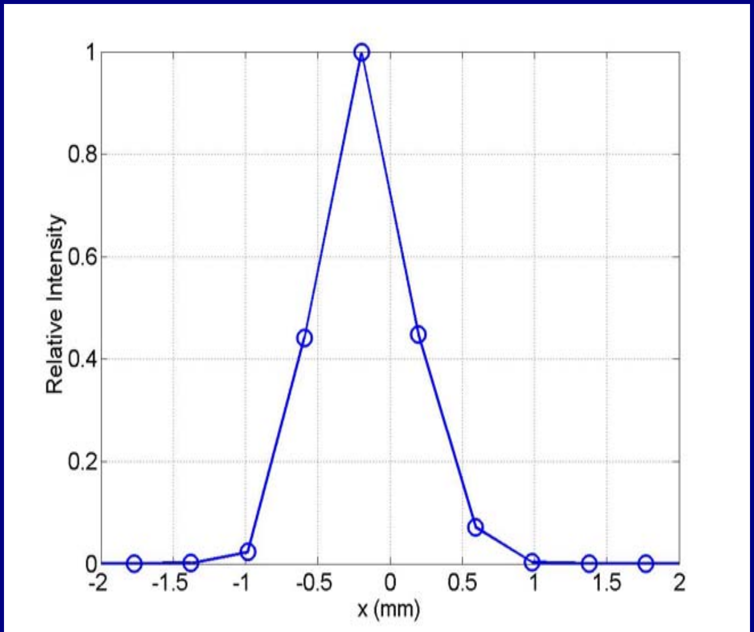
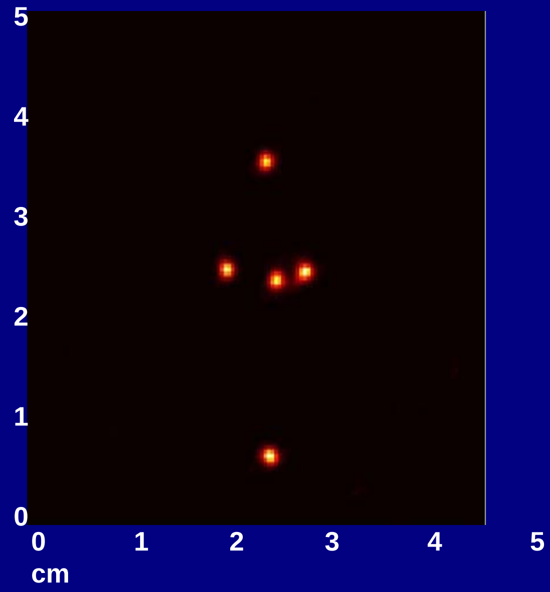
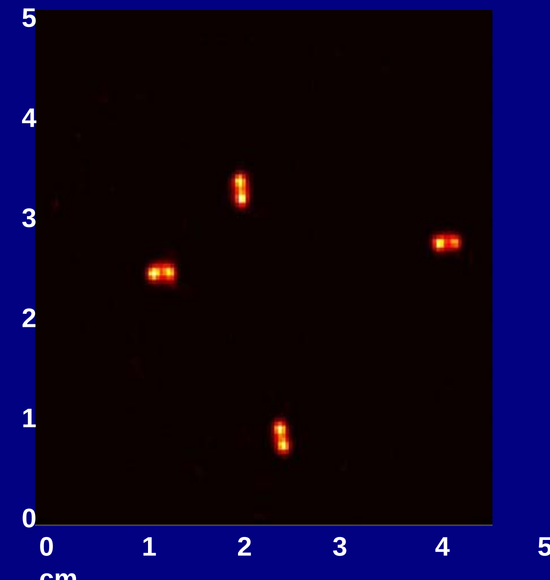


Image Resolution = 700 μm FWHM

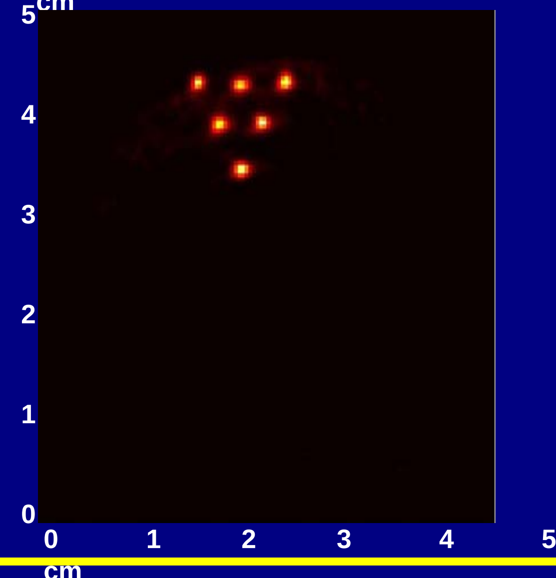
Compton PET: Resolution Uniformity





F-18 in capillary tubes
(I.D. 1.1 ~ 1.2 mm)

Resolution:
~ 700 µm FWHM across FOV

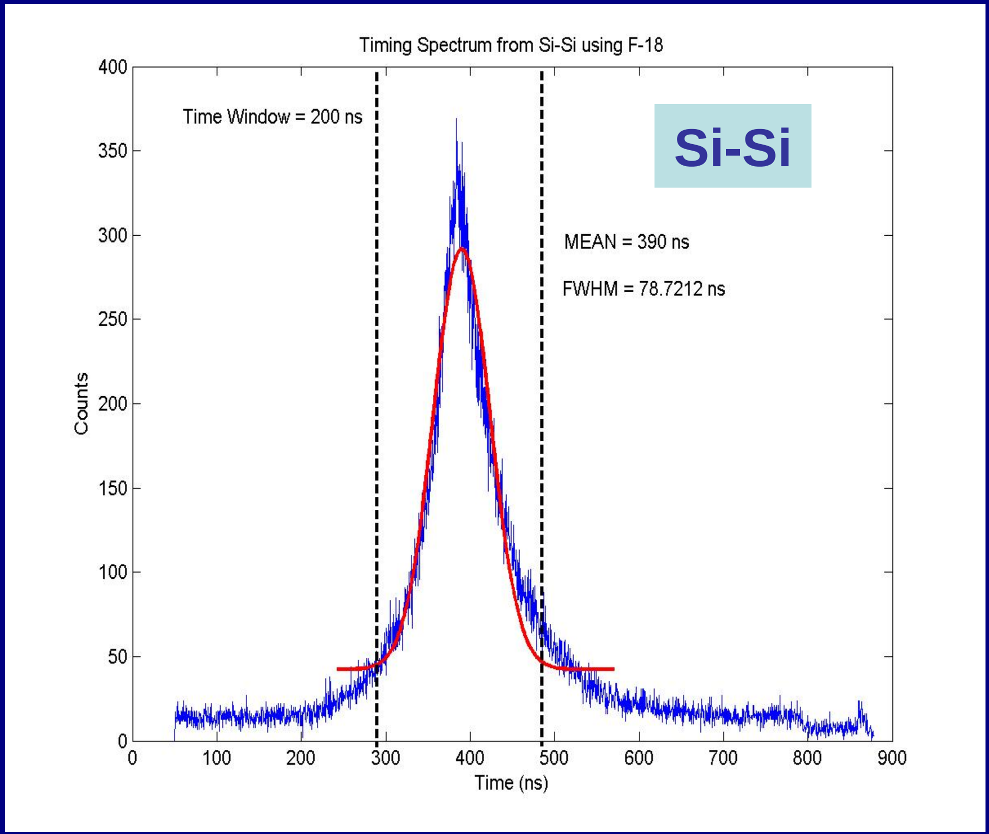


Summary of Current Situation

- Both simulation as well as experimental results confirm Compton (or Silicon) PET concept.
- Testbench resolution 700 μm FWHM – better than the resolution we were able to achieve with a commercial mircoPET R4 system using the same test object and even better reconstruction software.
- Uniform resolution over the entire Field of View.

Next Steps: Use the test setup to study some of the limitations of this concept.

Limitation 1: Silicon Detector Time Resolution

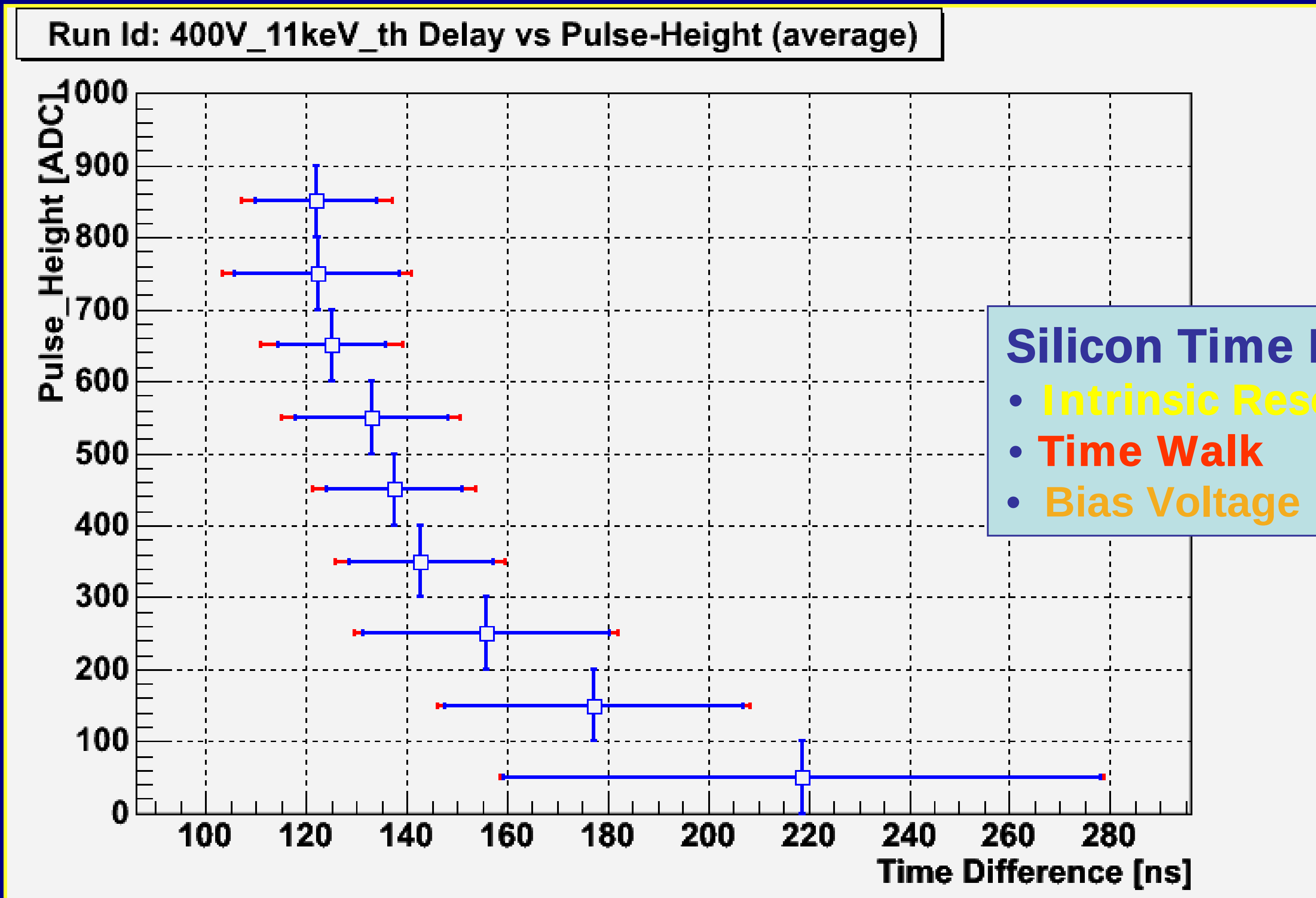


FWHM = 78.7 ns (due to Time Walk)

➡ **Timing window = 200 ns**

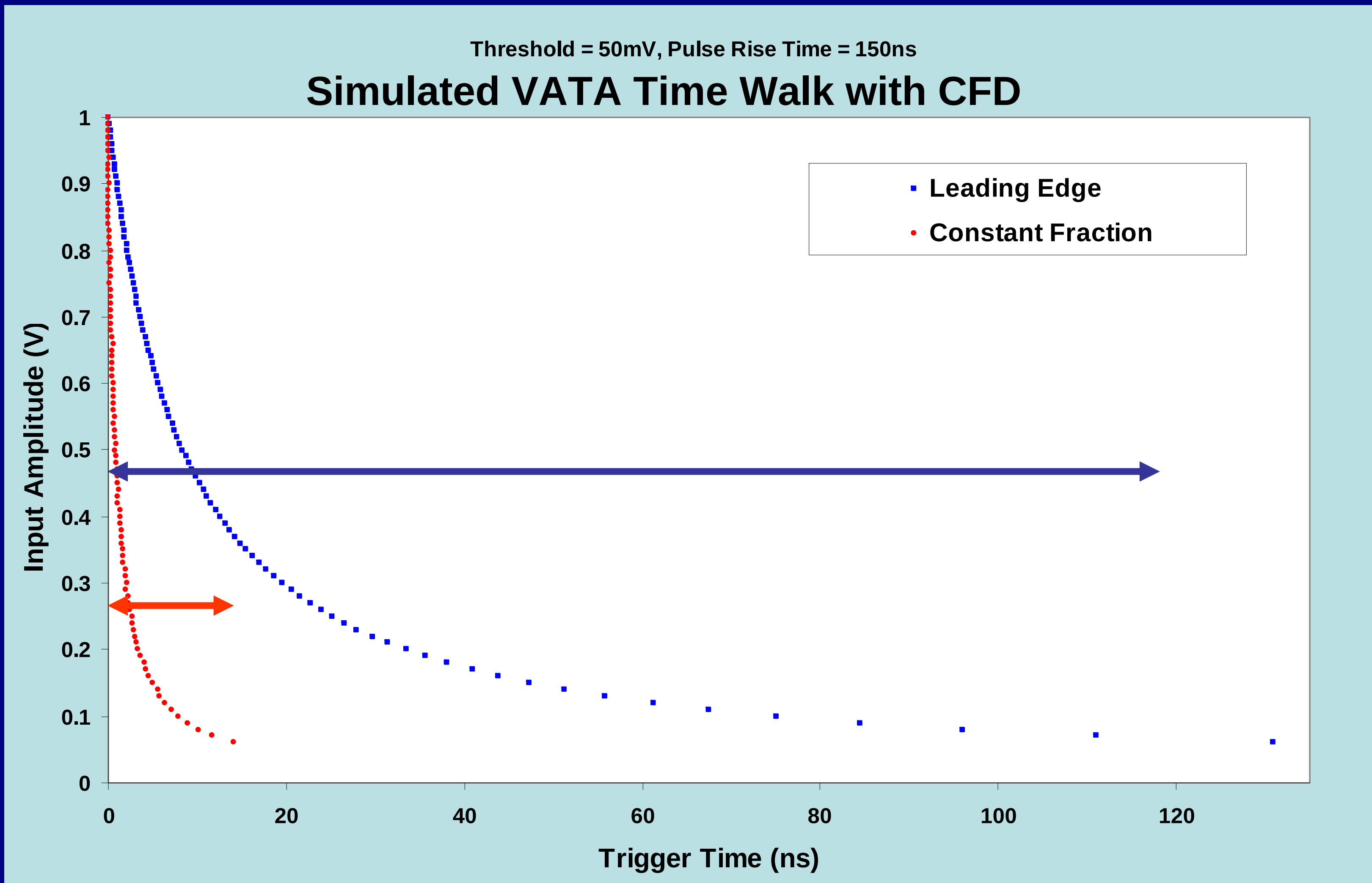
[see Poster J03-24 for more details]

Measurement of Silicon Detector Time Resolution



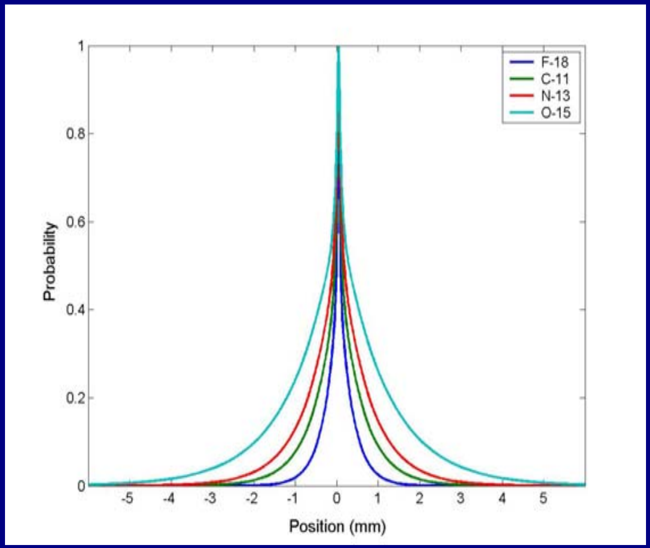
Silicon Time Resolution
- Intrinsic Resolution
- Time Walk
- Bias Voltage

Time Walk: LE versus CFD



Limitation 2: Positron Range Distribution

Distribution of Positron Range



[by Levin and Hoffman]

Positron Annihilation Point Distribution

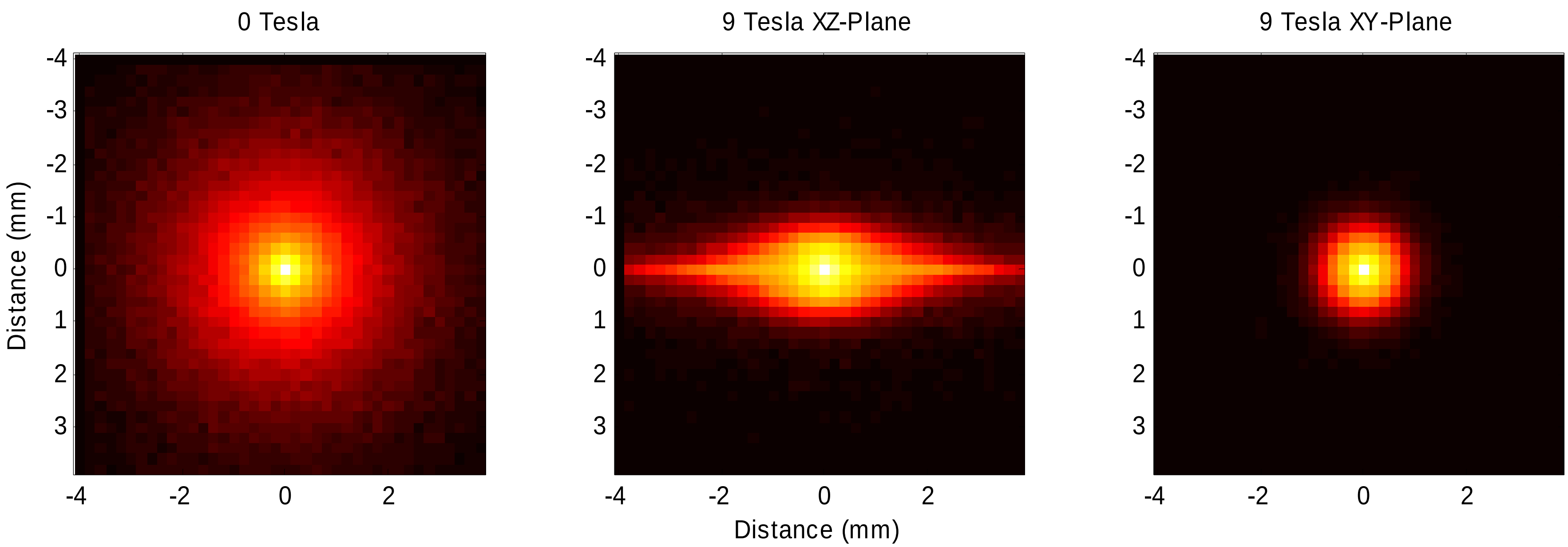
	F-18	C-11	N-13	O-15
Max energy (MeV)	0.64	0.97	1.19	1.72
Mean energy (MeV)	0.25	0.39	0.49	0.74
FWHM (mm)	0.10	0.19	0.28	0.50
FWTM (mm)	1.03	1.86	2.53	4.14

Spatial resolution (FWHM [mm])

Event	Geometric + Acolinearity	Overall F-18	Overall C-11	Overall N-13	Overall O-15
Si-Si	0.241	0.393	0.443	0.492	0.553
Si-BGO	0.816	1.062	1.261	1.419	1.742
BGO-BGO	1.458	1.977	2.270	2.490	3.069

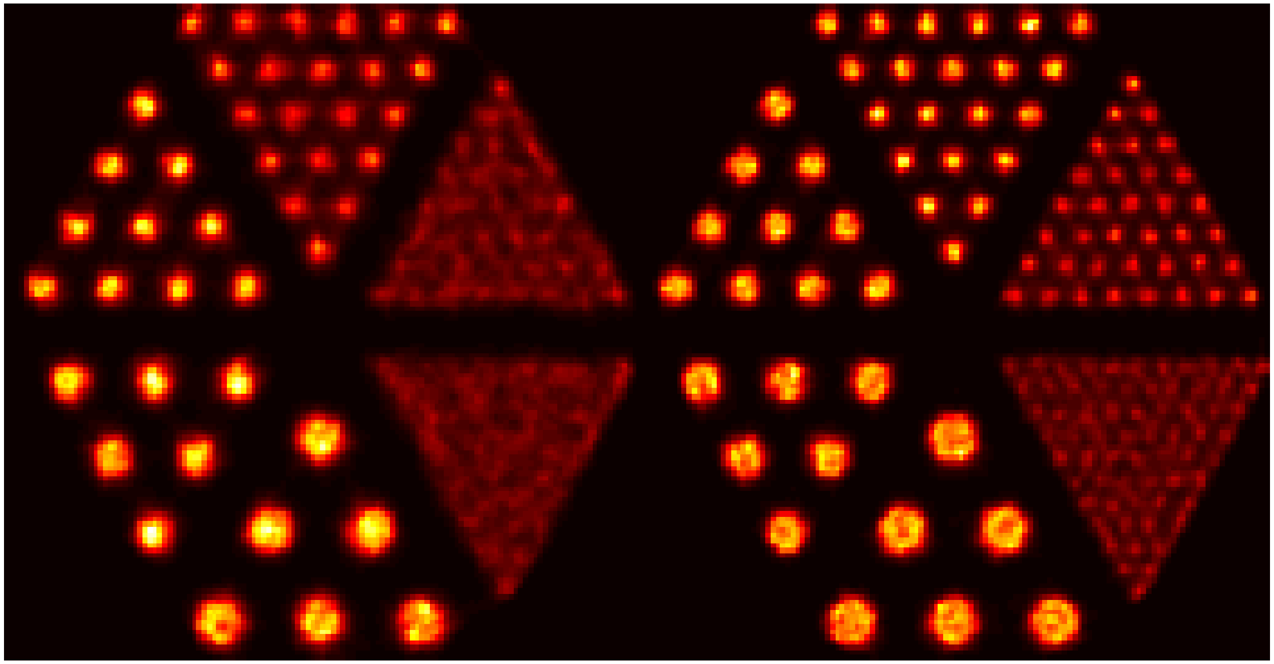
Revisiting an Old Idea

- Embed PET FOV in strong magnetic field (Raylman, Hammer, etc.)
- Positrons spiral and range is reduced transverse to B-field vector
- Not very effective for F-18 positrons
- Potentially useful for emitters with higher endpoint energies (I-124, Tc-94m, etc.) Increasingly being used in small animal imaging



Simulated Range Reduction for I-124

Effect on Image Quality

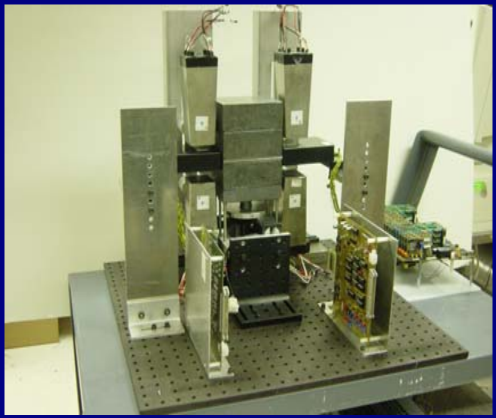


0 T

9 T

Axially constant object transverse to B-field

Experimental Verification



+

Combine Compton PET with
8 T MRI system at OSU Medical School

Compton PET Summary

- In order to achieve sub-millimeter spatial, a small animal PET based the Compton PET concept was developed.
- Simulation results demonstrated sub-millimeter spatial resolution of the Compton PET
  (0.4 mm FWHM from Si-Si and 1.0 mm FWHM from Si-BGO).
- Experimental results with a prototype setup using 1.4 mm x 1.4 mm x 1 mm silicon pads verified very high resolution (700 μm FWHM).
- Experimental results demonstrate the Si pad detector time resolution can be better than 10 ns.

and Outlook

- Test setup to operate Compton PET prototype in an 8 T MRI system in preparation.
- Development of a new ASIC with significantly reduced time walk jitter underway.

Acknowledgments

D. Burdette	E. Chesi	N. H. Clinthorne
S. S. Huh	H. Kagan	C. Lacasta
G. Llosa	M. Mikuz	S.-J. Park
W. L. Rogers	A. Studen	P. Weilhammer

(CIMA Collaboration)

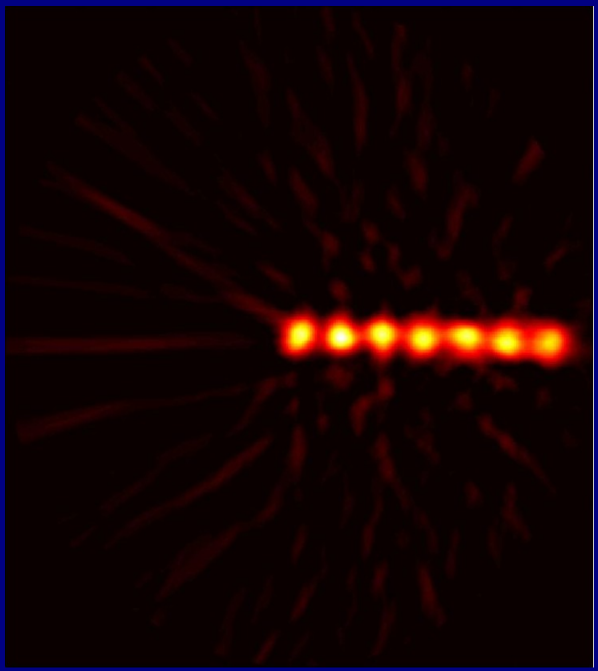
Funded in part by DOE and NIH

Additional Transparencies

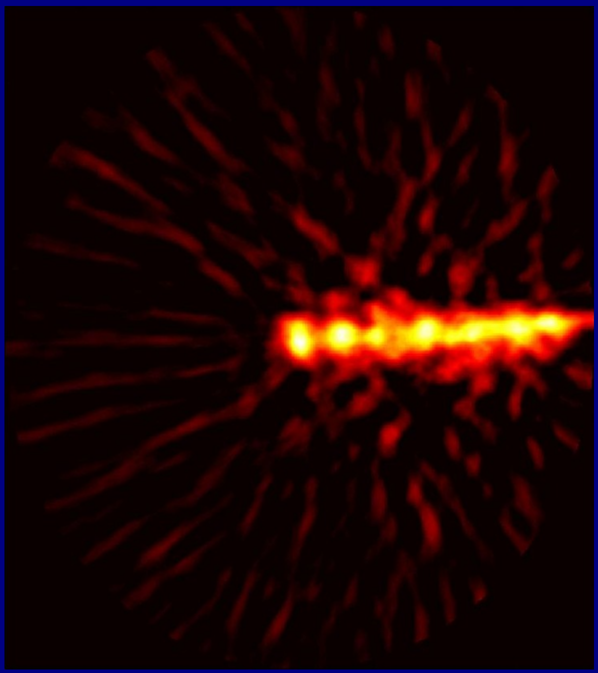
Scatters and DOI Uncertainty Problem in a BGO PET

- EGS4 Monte Carlo simulations
- BGO PET (17.6 cm I.D. 16 cm length segmented with 3 mm x 3mm x 20 mm crystals)
- Point sources at 0, 3, 6, 9, 12, 15, and 18 mm from center of FOV
- Filtered back projection reconstruction

True first interaction position

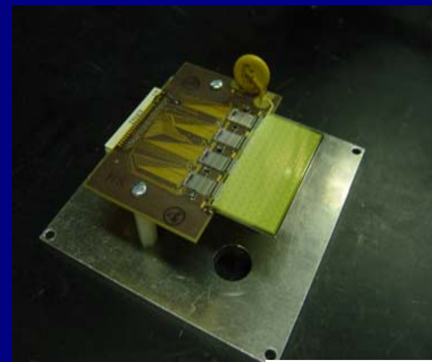


Centroid of scattered E distribution

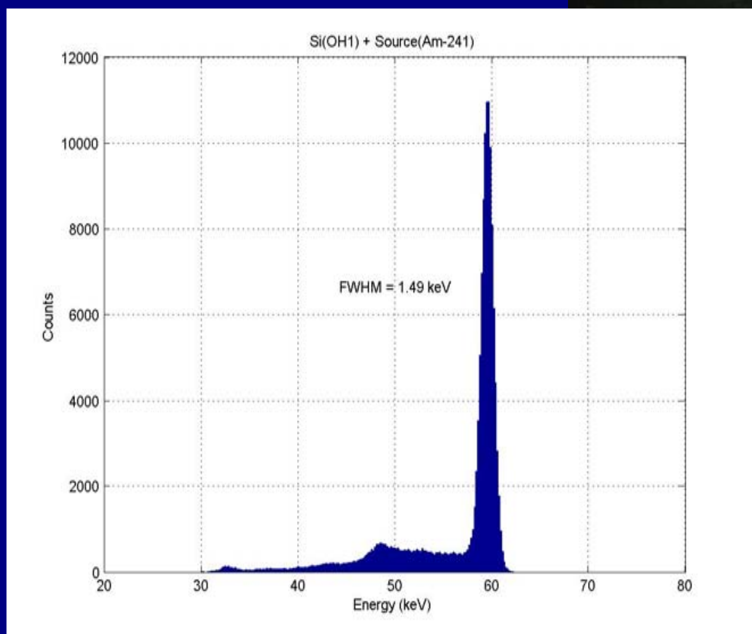


DOI uncertainty included in *both* images

Energy Resolution of Si Pad Detector

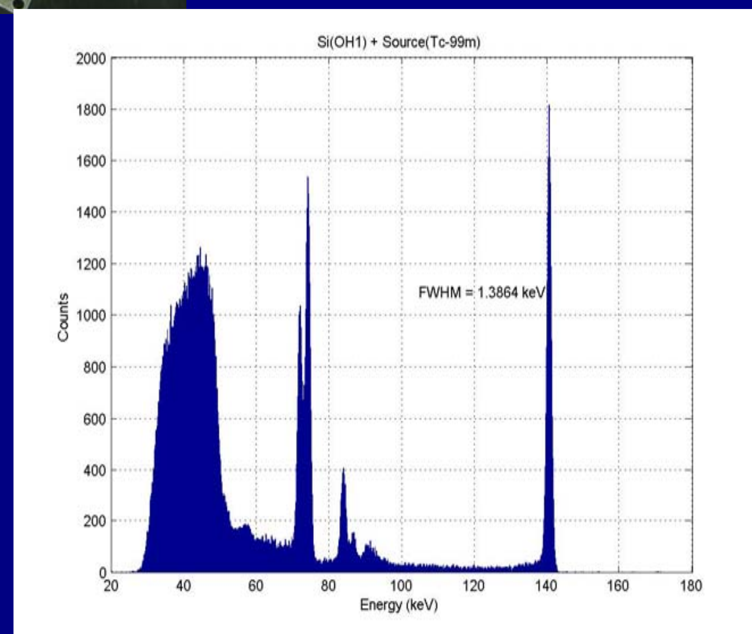


Am-241 (59.5 keV)



FWHM = 1.49 keV (2.5 %)

Tc-99m (140.5 keV)

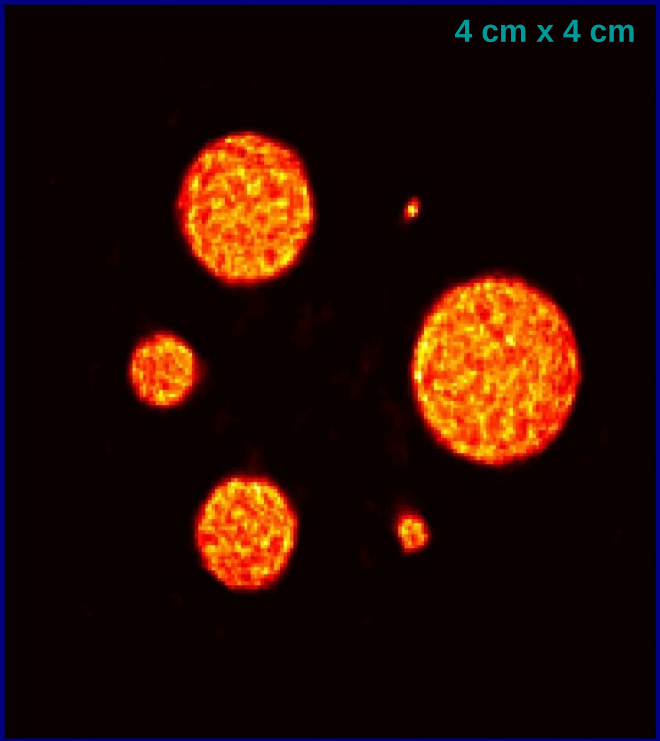


FWHM = 1.39 keV (0.99%)

Pb $K_{\alpha 1}$ = 74.969 keV, $K_{\alpha 2}$ = 72.804 keV, $K_{\beta 1}$ = 84.936 keV, and Compton edge = 49.8 keV

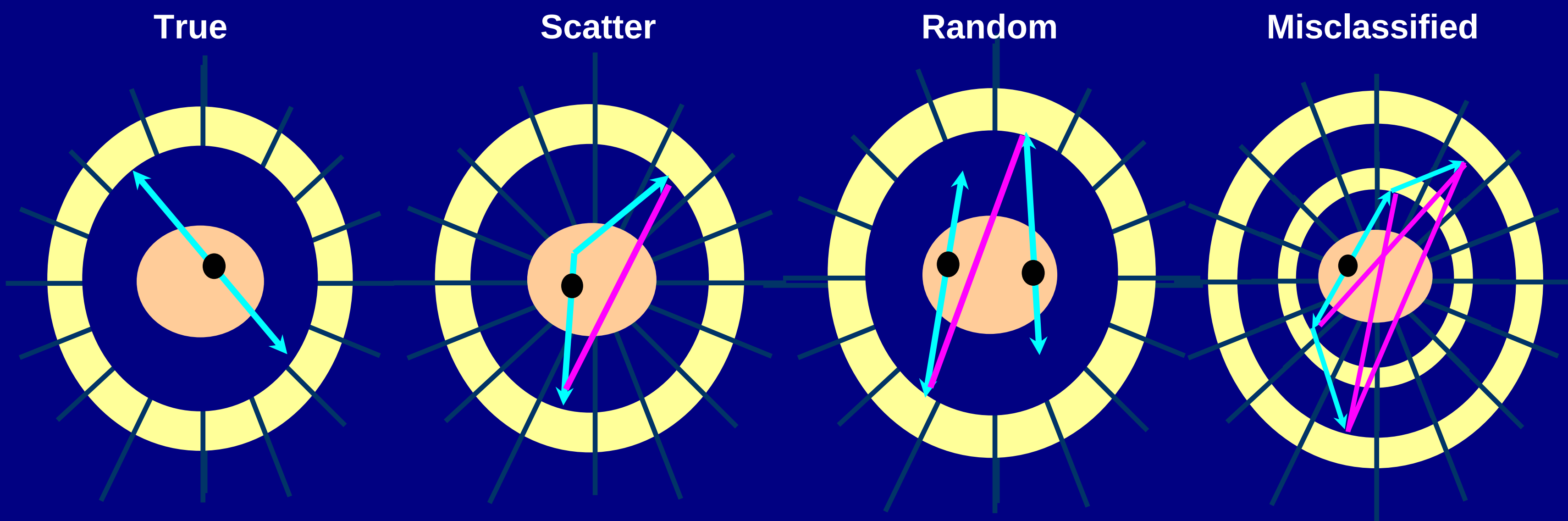
Simulated ComptonPet Image

- **Combined with Maximum likelihood Expectation Maximization (ML-EM)**
- **Iteration number = 200**



Si-Si (160k) + Si-BGO (1.4M) + BGO-BGO (3.1M)

Coincidence Events

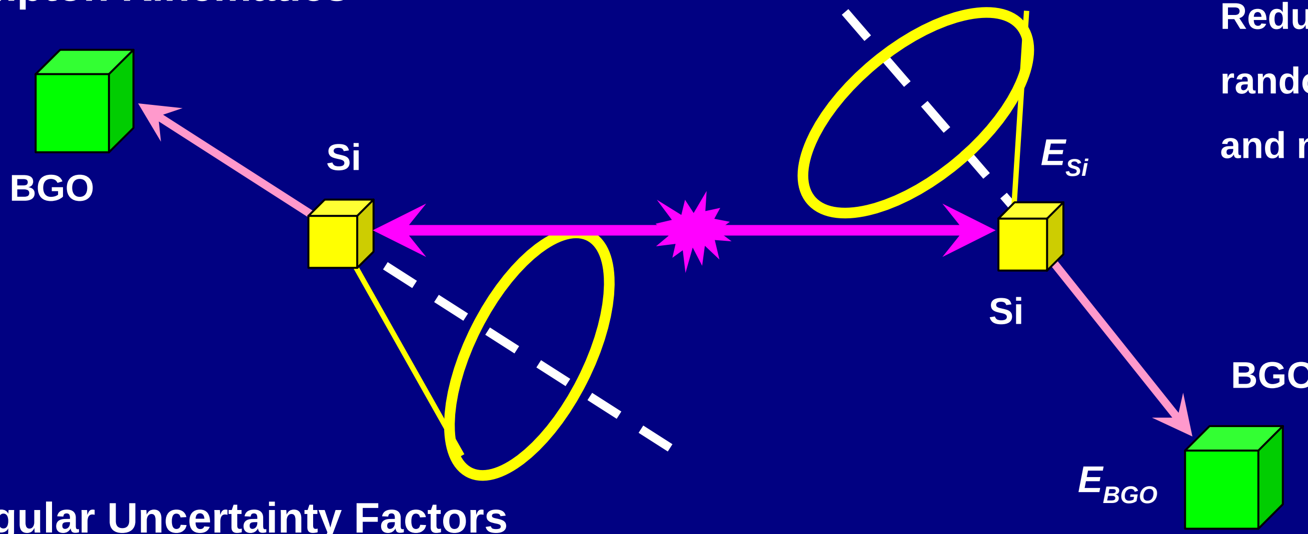


Noise Equivalent Count Rate (NECR)

$$NECR = \frac{r_{true}^{2}}{r_{true} + r_{scatter} + r_{random} + r_{misclassified}}$$

Compton Kinematics

Compton Kinematics



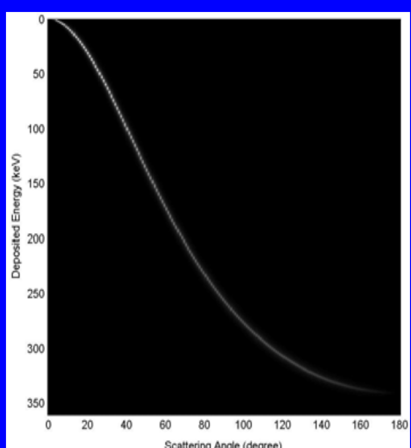
Reduction of scatter,

random,

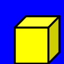
and misclassified events

Angular Uncertainty Factors

Doppler Broadening

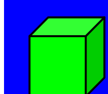


Detector Element Size



Si pad:

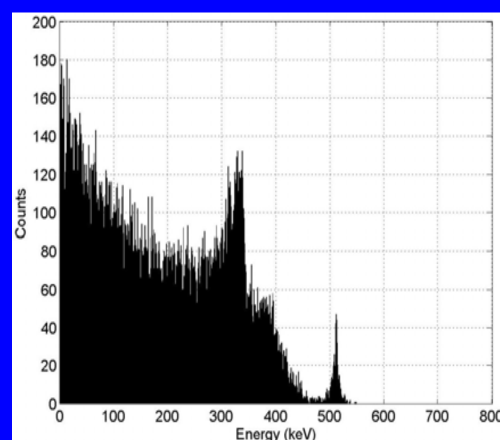
0.3 mm x .3 mm x 1 mm



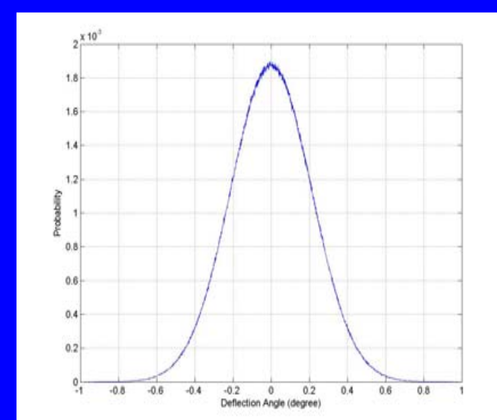
BGO crystal:

3 mm x 3 mm x 20 mm

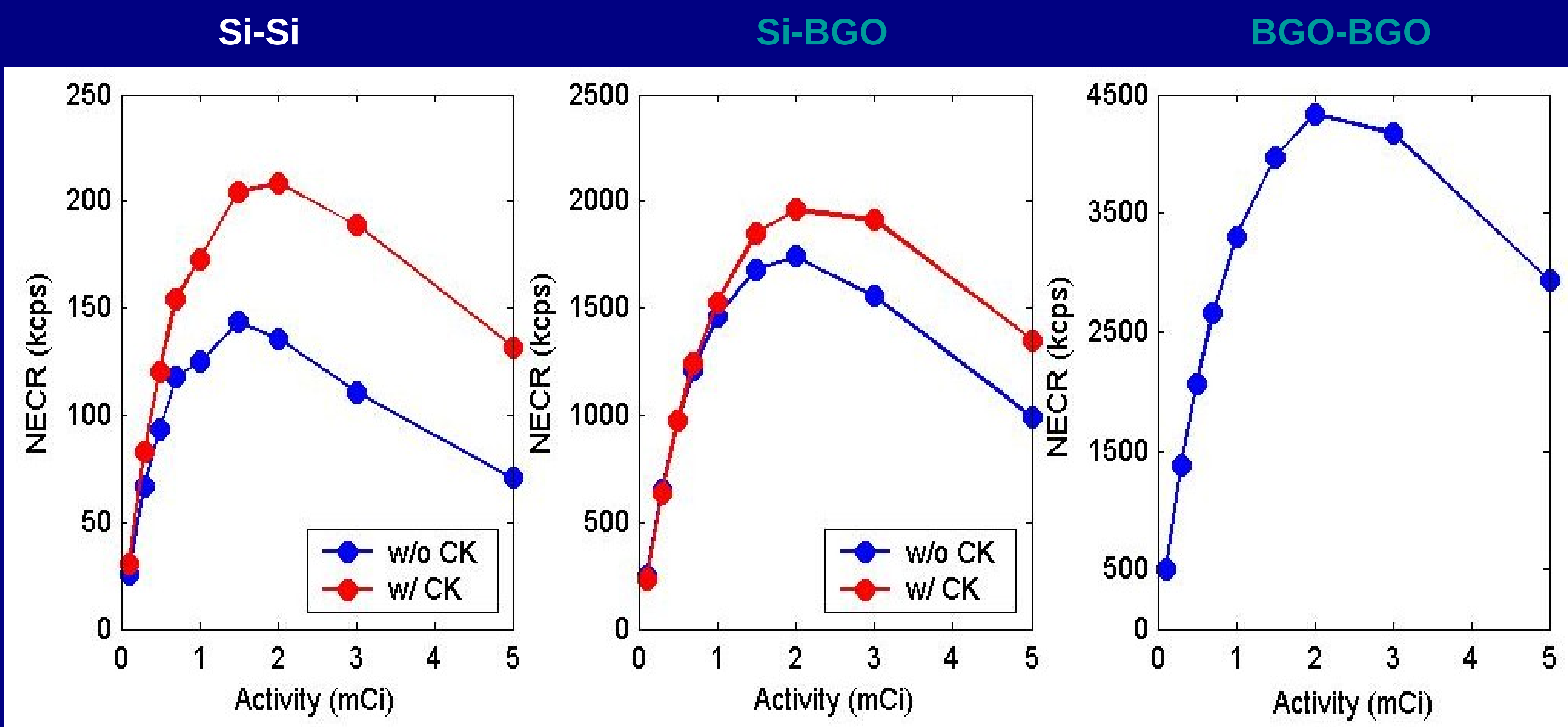
Energy Resolution



Photon Acolinearity



Improvement of NECR using Compton Kinematics



A = 0.1 mCi, Si = 5 ns FWHM, BGO = 1 e/ns,

E_W = ±50 %, T_W = 7 ns, A_W (Si-Si) = ±5 degree, A_W (Si-BGO) = ±7.5 degree

Improvement : Maximum 86 % for Si-Si and 36 % for Si-BGO at 5 mCi