Time-of-Flight PET Detector development with SiPM

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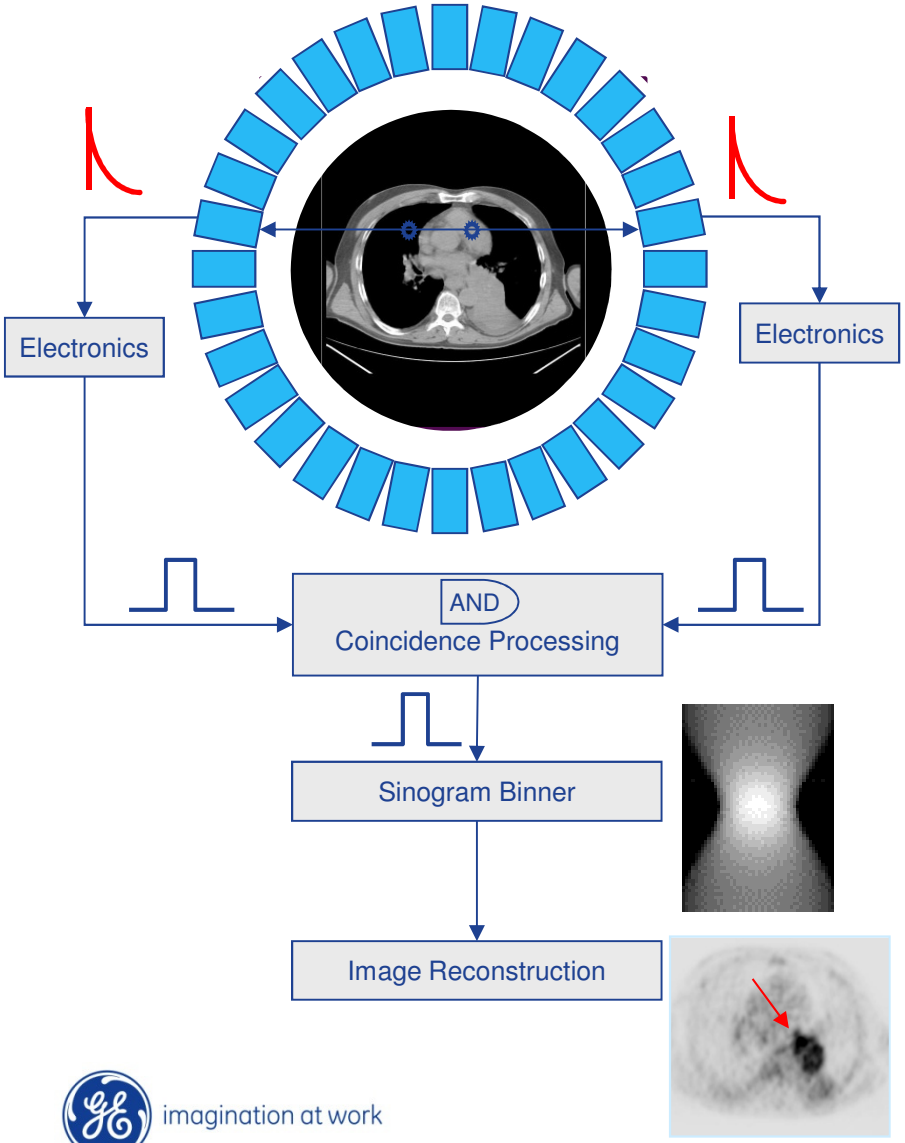
Functional Imaging – principle of operation



Functional imaging modality

– physiological and biochemical processes

Signal emitting tracers injected into patient

- compounds (like simple sugars) that participate in function

Scanner detects radiation signal

- detection of emitted radiation from positron-electron annihilation

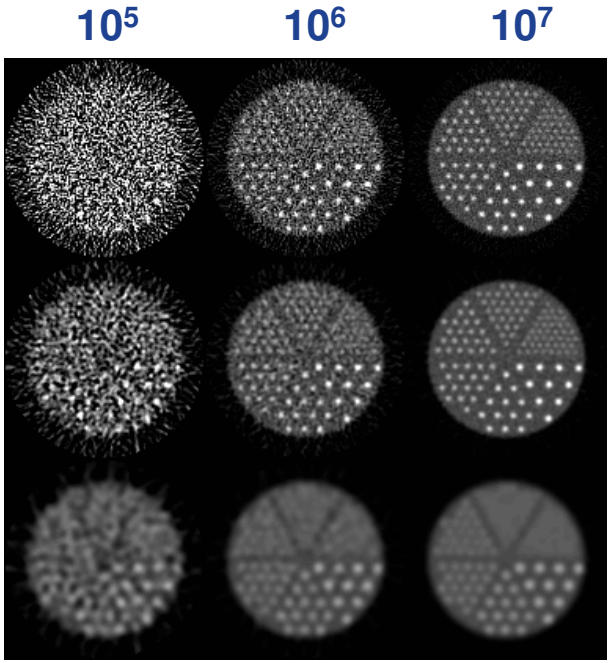
Tomographic image reconstruction

- multiple views of projection data transformed to 2D/3D image

Count limited imaging

Noise in PET images is dominated by the counting statistics of the coincidence events detected.

Reduce noise in images by using a smoothing window on ramp filter in image reconstruction, at the cost of image resolution.



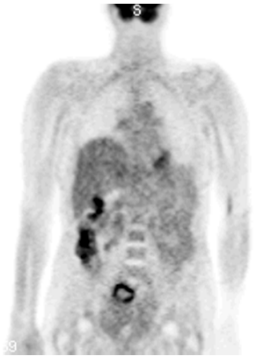
Progress in PET Image Quality

2000 2005 2007

Iterative Image Reconstruction

Filtered Back-Projection

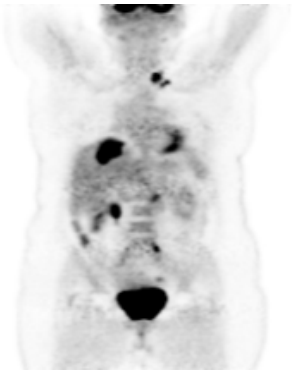
Iterative Reconstruction



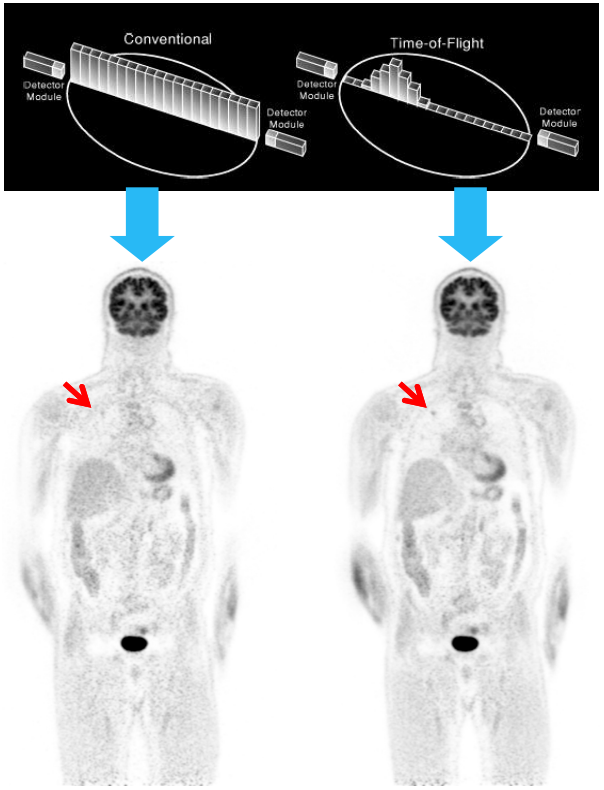
3D Acquisition & Reconstruction

***FO**urier **RE**binning + 2D Iterative Recon*

***Fully 3D** Iterative Reconstruction*



Time-of-Flight PET



Conventional ***TOF-PET***

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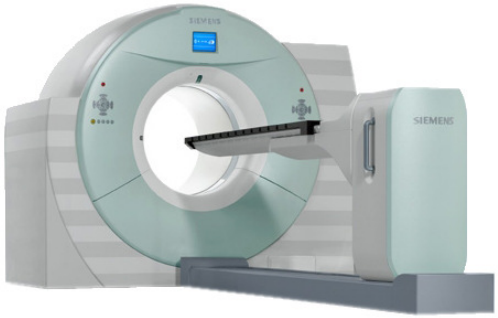
Time-of-Flight PET/CT is the standard

D690→710

SIEMENS

mCT 128 True V



PHILIPS
sense and simplicity

Ingenuity TF 128

PMT based scanners, timing resolution ~ 500-550ps

Benefits of Time-of-Flight

When *all other things are equal*, a PET scanner using Time-of-Flight (TOF) produces better image quality than one without time-of-flight.

The amount of improvement is not easy to predict – it depends on many things.

The benefit is an improved Reconstructed "signal-to-noise" ratio.

The benefit depends critically on the *size of the part of the patient* being imaged.

Time-of-flight doesn't affect intrinsic spatial resolution.

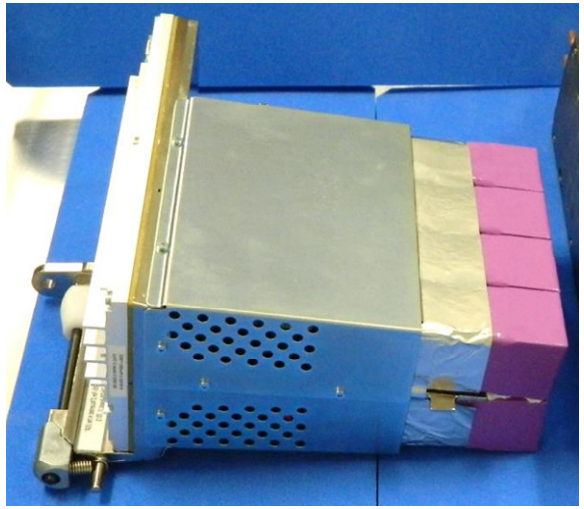
Time-of-flight does Not Improve Count Rate Performance

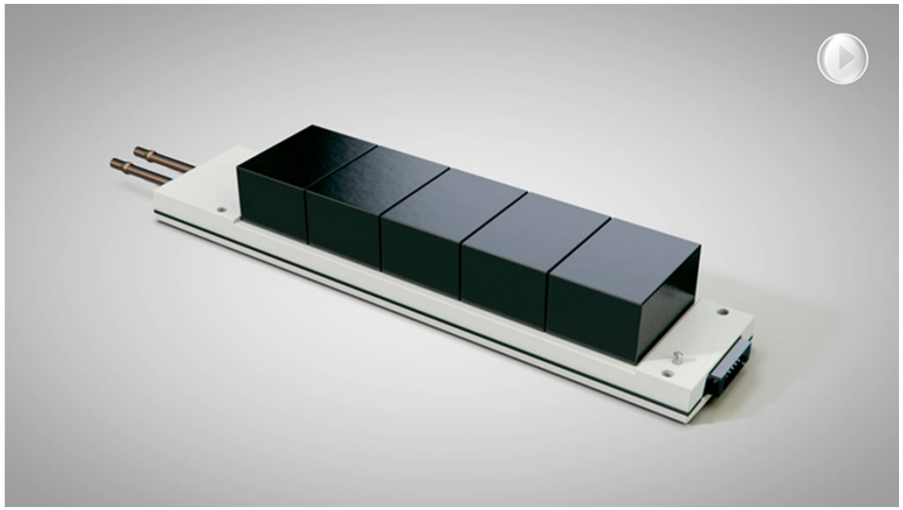
Brownell concludes in 1969 that with the then state-of-the-art scintillators and photomultiplier tubes, **TOF was useful for elephants**, but not yet humans.

"TOF scanners are just entering clinical use, it will be probably several years until they are widely available. It can be assumed that over the next few years the timing resolution will continue to improve and will lead to better image quality for heavy patients and shorter imaging times as well. "

G. Muehllehner and J.Karp "Positron emission tomography"
Phys. Med. Biol. 51 (2006) R117–R137

2012: Transformation of PET Detectors





40 year old technology
→ One of last remaining vacuum tube based detector

Limited performance
Detection efficiency
Average ToF: 550 ps
Magnetic sensitivity
Bulky

Silicon Photomultiplier: new solid state photosensor

Superior performance
Excellent image quality
Best in class ToF: ~250-400 ps
Ideal for PET-MR

State-of-the-art ToF PET Scanners

Silicon Photo-Multiplier (SiPM) can be fabricated from small silicon sub-pixels to replace PMTs making them attractive for PET+MR and TOF-PET:

- fast, low-jitter time response
- magnetic field immunity
- small form-factor

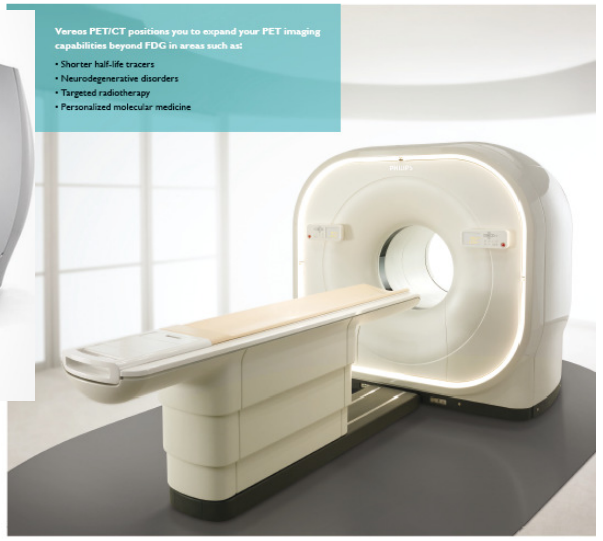
Technical challenges:

- Readout circuits/ASIC development
- Multiplexing options
- Temperature stabilization
- Handling multi-crystal events
- MR compatible architecture

Signa PET/MR

TOF 380ps

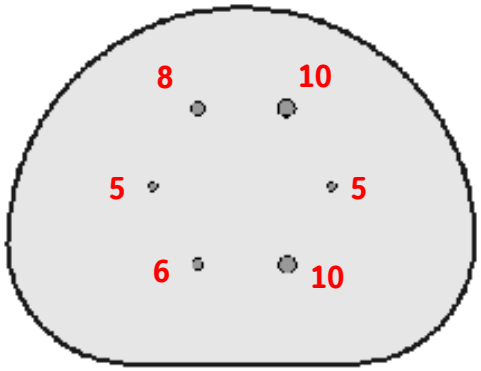
Vereos



TOF 345ps

Clear benefits of using ToF

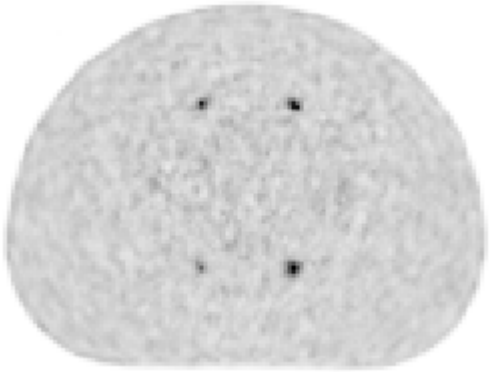
Simulated NEMA IQ Phantom



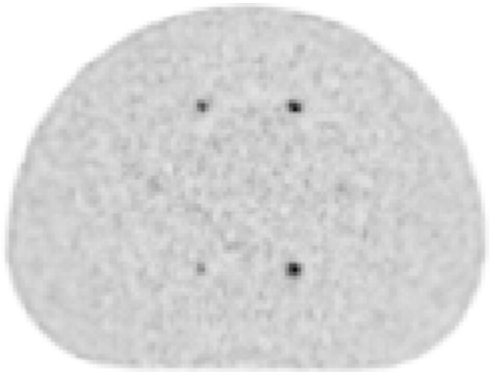
Simulated counts: 180M
Contrast: 4:1

OSEMS: 4 iterations, 28 subsets
TOFOSEMS: 2 iterations, 28 subsets
Recon FOV: 600mm on 256 pixel grid

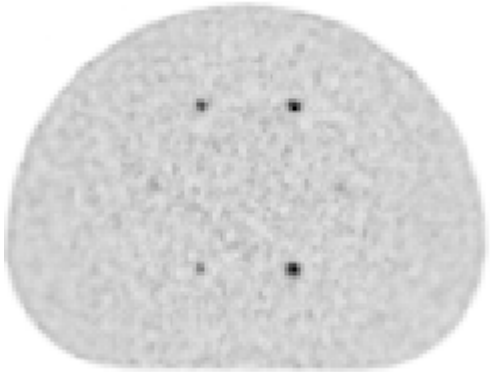
Non-TOF



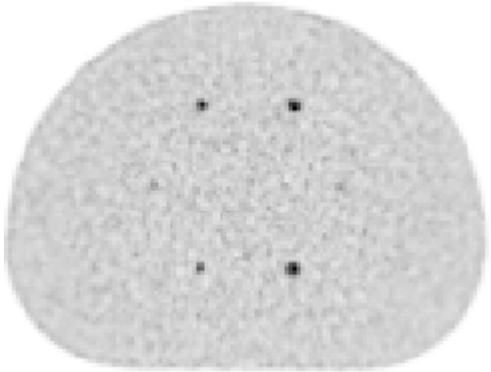
550ps



380ps



200ps



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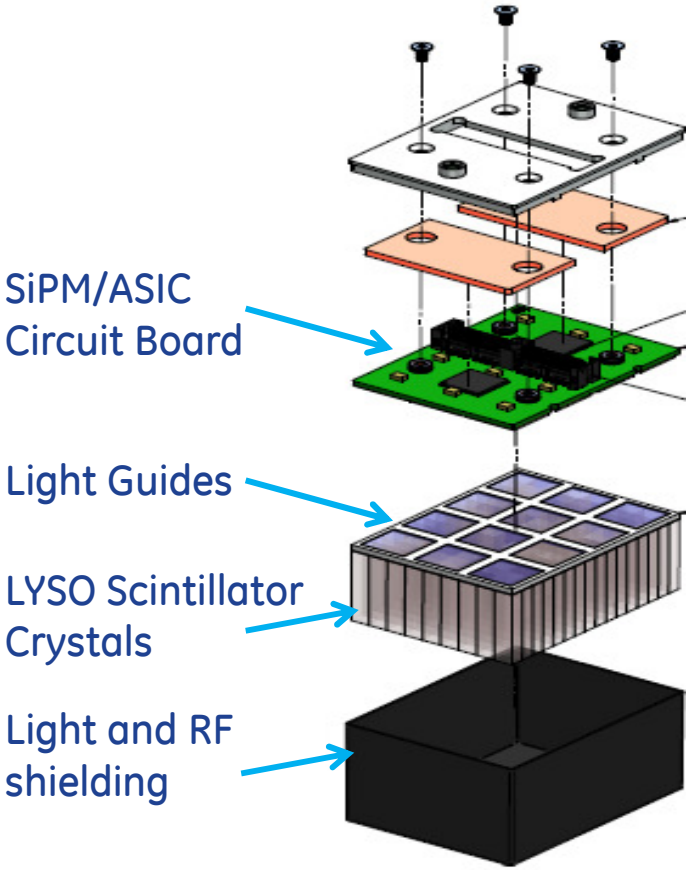
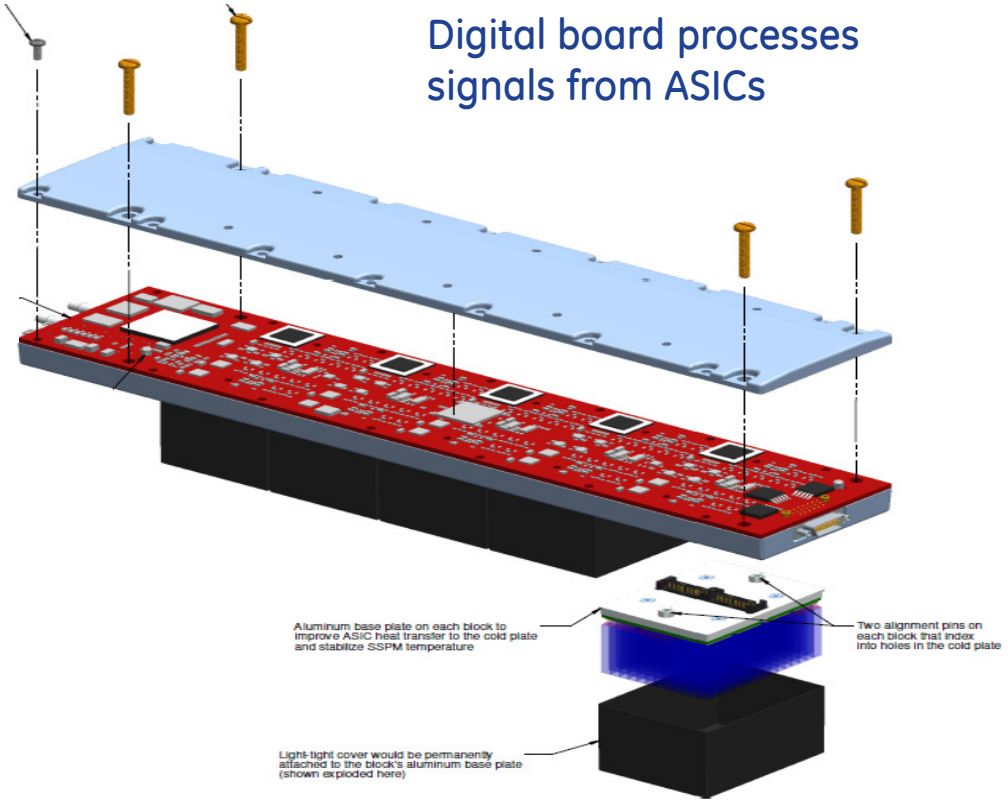
PET/MR module Concept



Digital board processes signals from ASICs



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Timing resolution of PET detector-photo sensor requirements

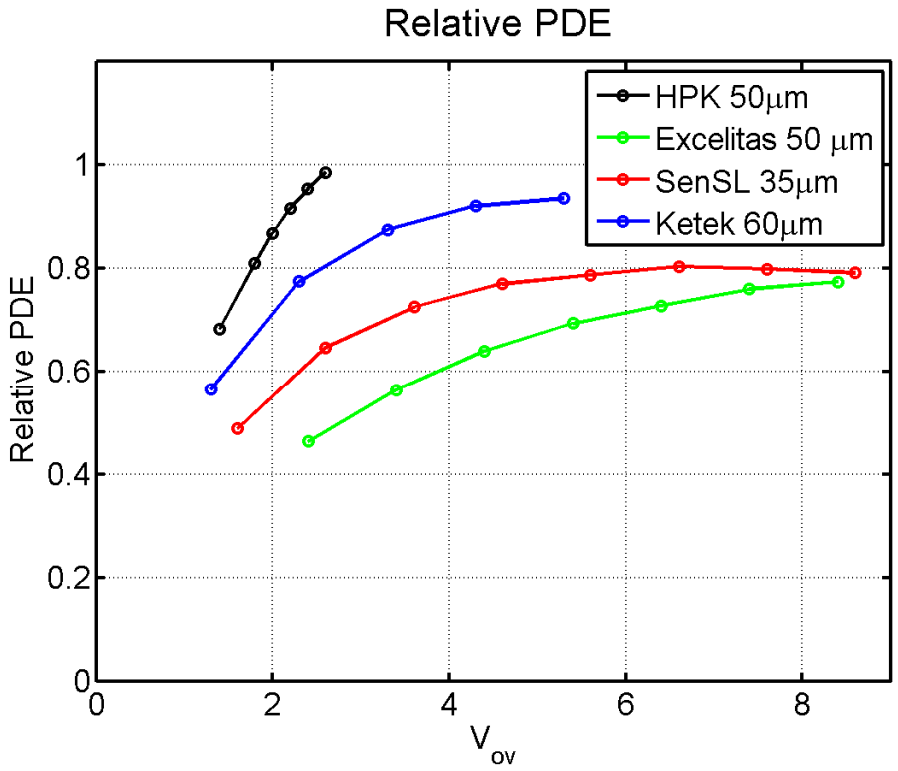
SiPM from different vendors have a wide range of PDE, dark counts, pulse shape and other parameters critical for timing performance in PET application

Critical parameters for timing resolution:

- PDE
- SPE pulse shape
- Transit Time Delay (across SiPM) and SPAD jitter
- Dark count (for block multiplexing)
- Gain
- Optical cross talk and after pulses

We measure Coincidence Resolving Time (CRT) of LYSO/SiPM PET detectors at identical conditions

Relative PDE

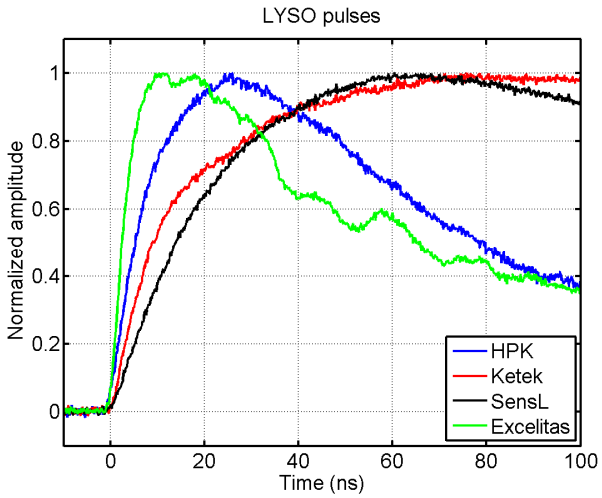


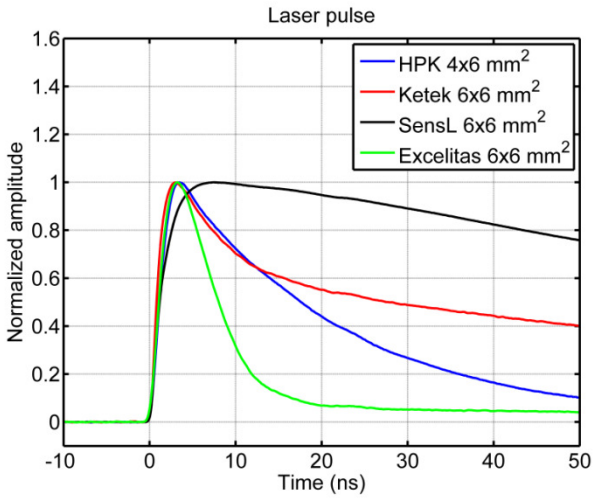
- Weak laser pulse (<1 spe), uniformly illuminate SiPM
- Measure N(0)
- Measure N_{dark}
- Calculate* n_{pe}

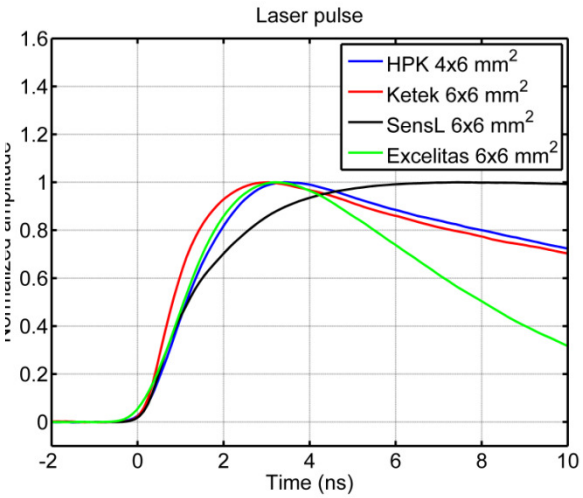
$$n_{pe} = -ln\left(\frac{N_0}{N_{total}}\right) + ln\left(\frac{N_0^{dark}}{N_{total}^{dark}}\right)$$

Systematic error ~5% due to misalignment

Pulse shapes

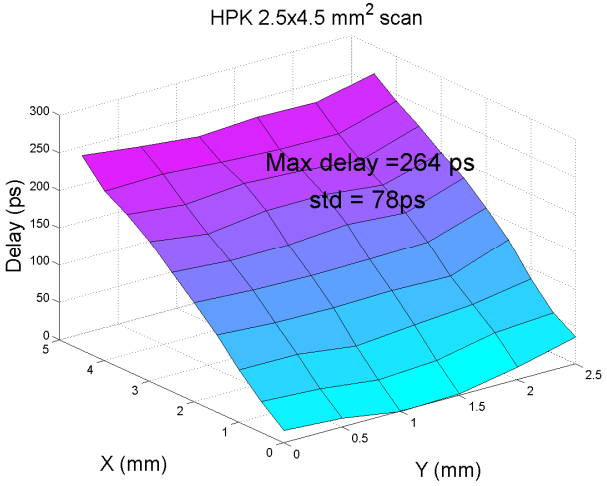


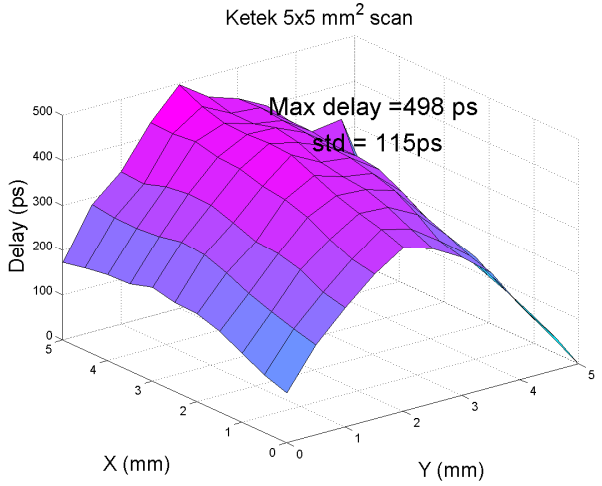




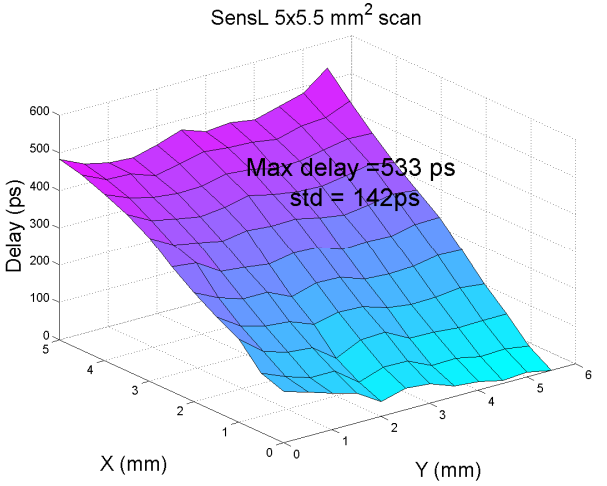
	HPK 3x3/4x6 mm²	SensL 6x6mm²	Ketek 3x3/6x6mm²	Excelitas 3x3/6x6mm²
Rise time 20-80%	0.7/1.4 ns	2ns	0.5/1.0 ns	0.5/1.3ns
$\tau_{int}=C_d*R_q$	11 ns	96 ns	180ns	70/100 ns
R_q	126 kΩ	660 kΩ	~420kΩ	630/1000 kΩ
% Fast component	-	-	10%	20-50%

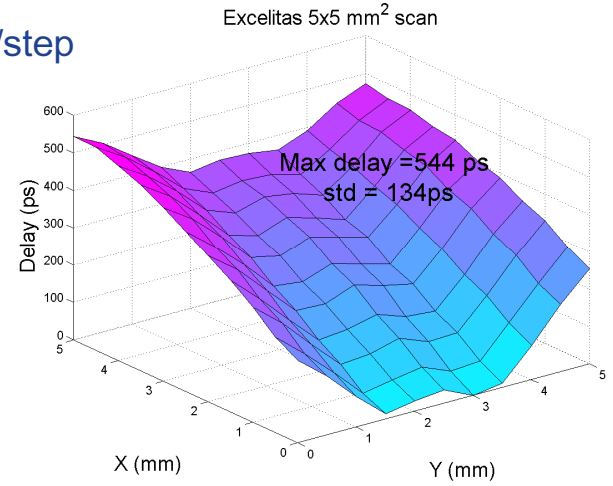
Transit time delay





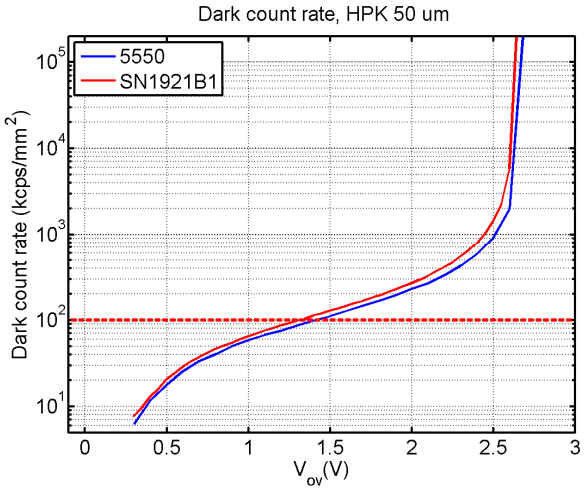
0.4 mm ∅,
~30 SPE pulse
X-Y scan 0.5 mm/step

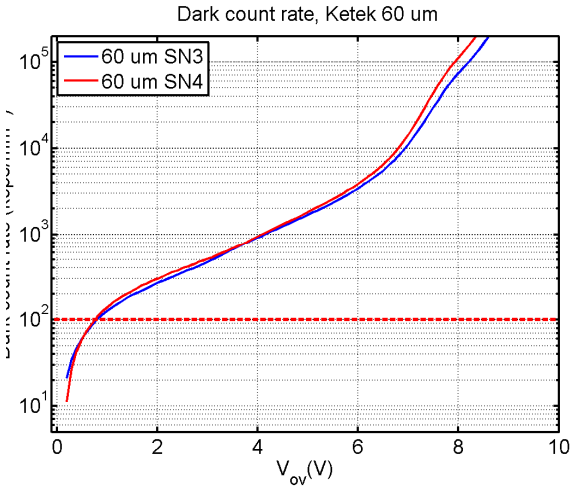


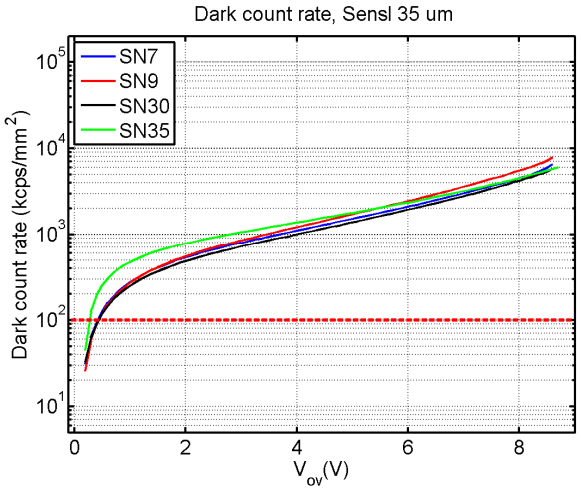


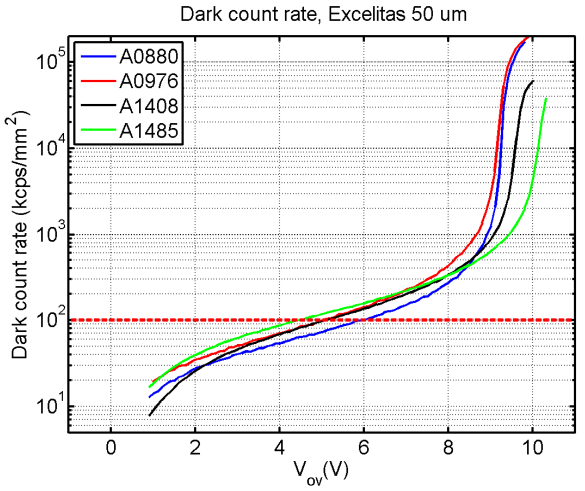
Delay ~100 ps/mm (50 ps/mm for HPK)

SiPM dark counts







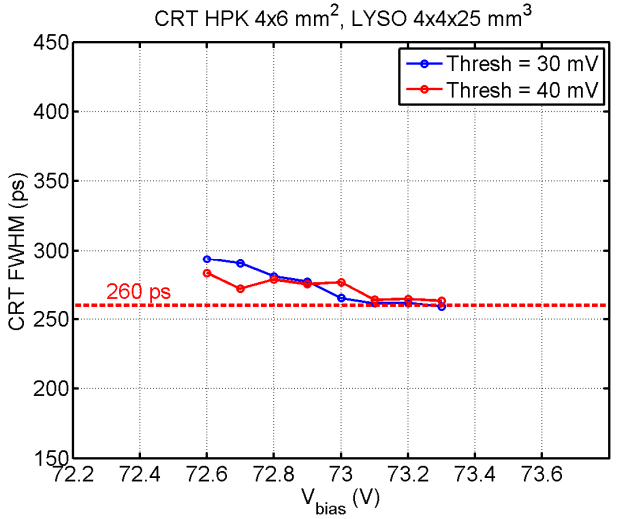


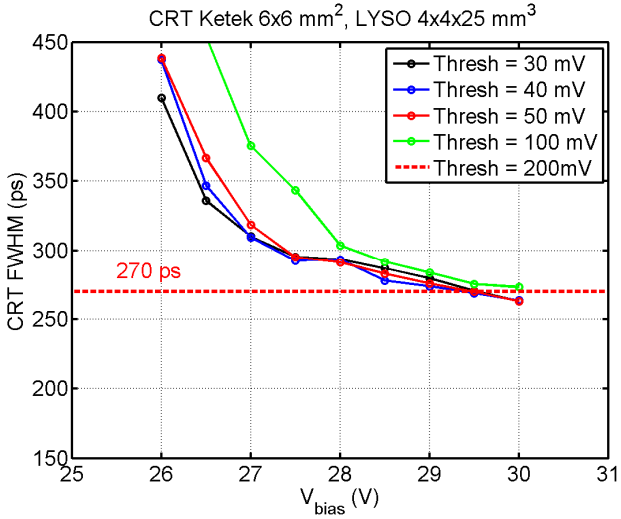
Dark count rate (DCR) recalculated from I_{dark}:
$DCR = I_{dark}/C_{diode}/V_{ov}$

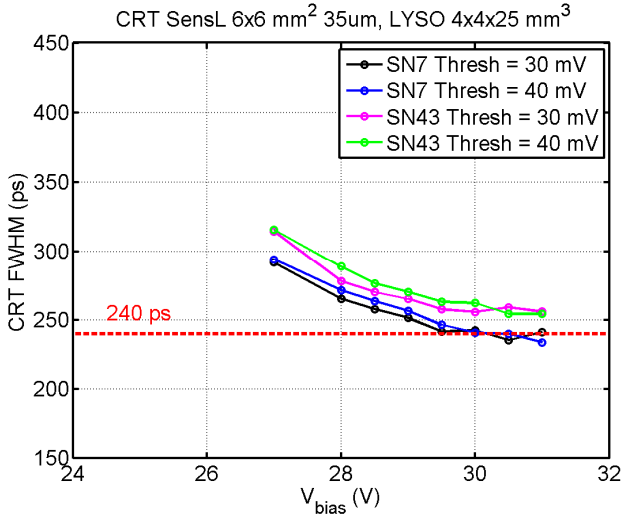
DCR includes after pulses and crosstalk

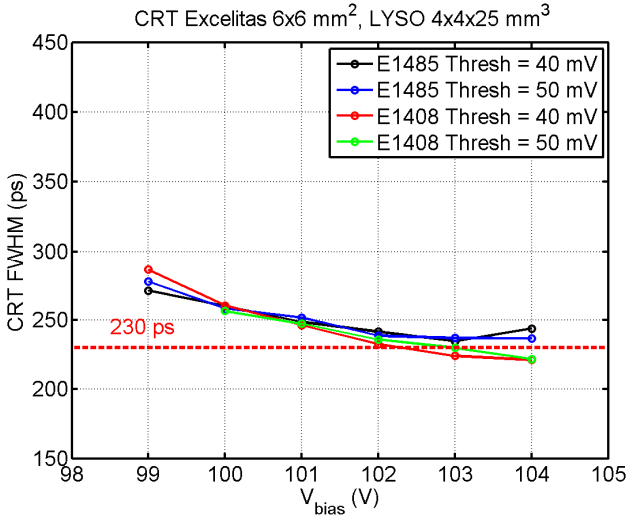
	HPK	SensL	Ketek	Excelitas
Vbr	~71V	~23.4V	~22.8V	~95V
Maximum V_{ov}	2.4V	6 V	5V	7V
Dark Counts kcps/mm^2 @ max V_{ov}	400	2000	2000	200
"Gain" ~ C_{diode}	85 fF	145 fF	380 fF	95fF

CRT measurements - large SiPM, long crystal









SiPM benchmark performance

		HPK*, 50 um	SensL-SB 35um	Ketek 60um	Excelitas
SiPM Device Pixel Size (mm^2)		3x3 ; 4x6	3x3 ; 6x6	3x3; 6x6	3x3; 6x6
Timing resolution	3x3x10 mm^3 LYSO – small SiPM	195 ps	180 ps	200 ps	170 ps
	3x3x10 mm^3 LYSO – large SiPM	230 ps	215 ps	210 ps	180 ps
	4x4x25 mm^3 LYSO - large SiPM	260 ps	240 ps	270 ps	230 ps
LYSO/SiPM pulse shape 3*τ (SPE pulse shape and after pulsing)		220 ns	450 ns	~1000 ns	250 ns
Photo Detection Efficiency (relative PDE)		1	0.8	0.95	0.75
V_{ov} range		2.4 V	6 V	5 V	7 V
Dark Counts ($kcps/mm^2$)		400	2000	2000	200

- Promising sub 300-ps ToF performance with SiPM
- Continuing improvements in SiPM from all vendors
  PDE, dark current, after-pulses, TTD, packaging etc

Thank You