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SiPMs for PET –
An Important but not Exclusive Factor

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Siemens Healthcare, GE Global Research Center and Philips Advanced Molecular Imaging

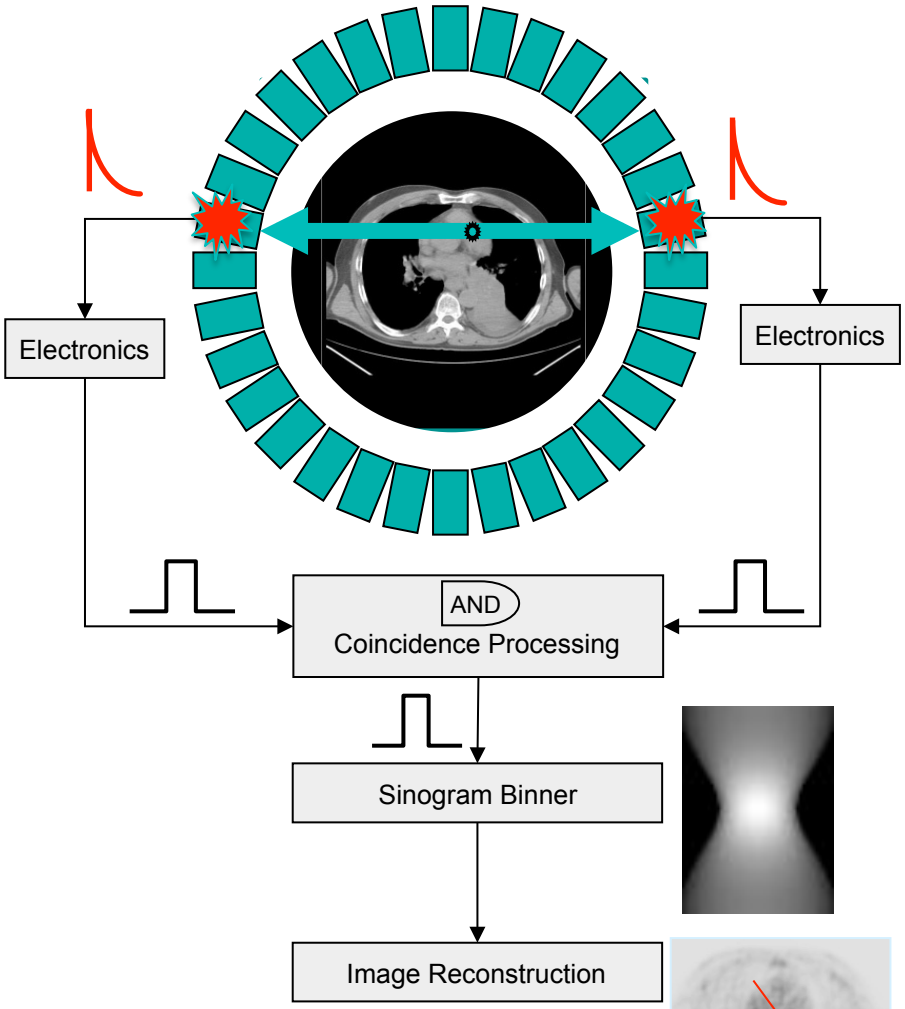
PET = **P**ositron **E**mission **T**omography

PET quantitatively and non-destructively measures the 3-D distribution of radiolabeled biomolecules *in vivo*

Primary tasks for technical developments:

1. detect as many events as possible (sensitivity)
2. put events in the right place (spatial resolution)
3. improve image quality (image contrast)
4. make corrections and reconstruct quantitative images (Bq/cc)

PET = Positron Emission Tomography
principle of operation



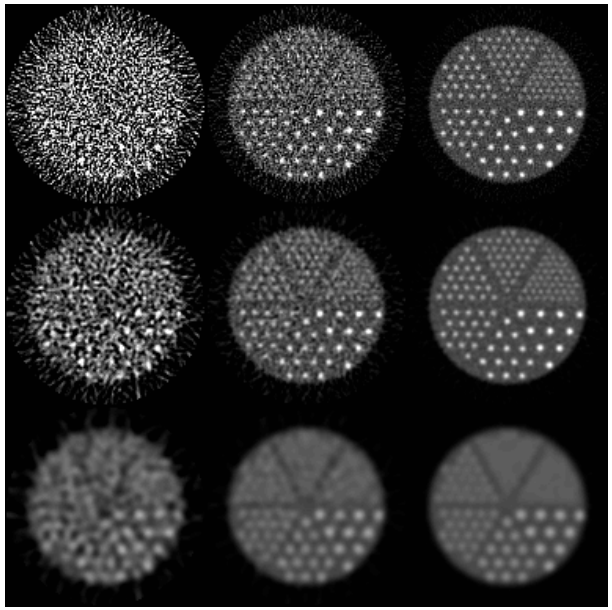
Courtesy by S.Dolinsky, GE

1. **Inject radiotracer**
2. **Detect** (scintillation detectors) two annihilation photons in coincidence
3. **Defines line** along which annihilation lies
4. **Collect** ~10^7-10^8 events
5. Use **reconstruction algorithms** to compute image of radiotracer distribution using multiple views of projection data
6. **Analyze data**
   a) *Lesion detection*
   b) *Quantify radiotracer distribution*
   c) *Tracer kinetics*

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.



Courtesy by S.Dolinsky, GE

Progress in PET Image Quality

2000 — 2005 — 2007

Iterative Image Reconstruction

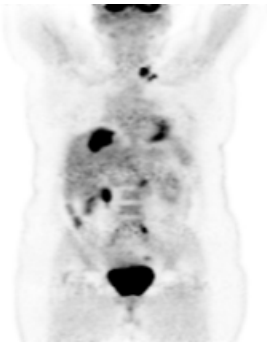
Filtered Back-Projection

Iterative Reconstruction

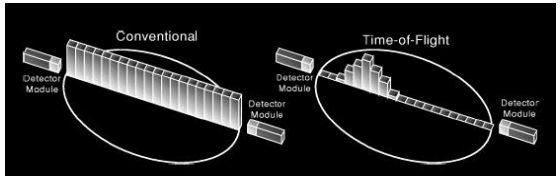
3D Acquisition & Reconstruction

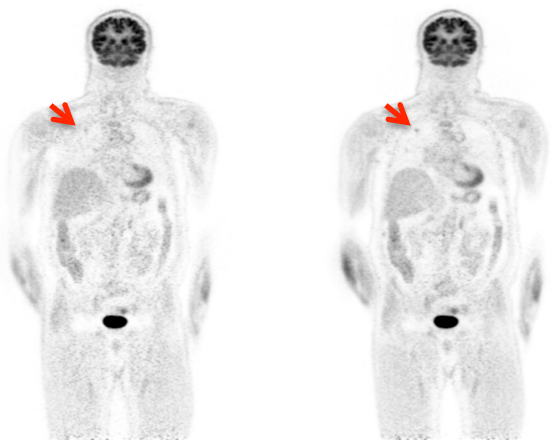
***FO**urier **RE**binning* + 2D Iterative Recon

Fully 3D Iterative Reconstruction



Time-of-Flight PET



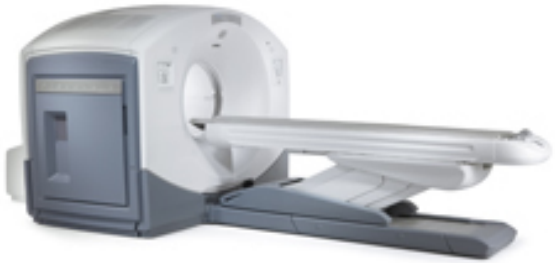


Conventional ***TOF-PET***

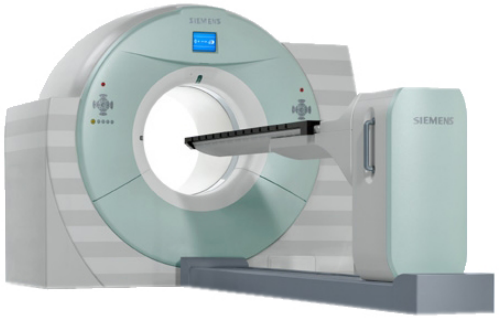
Courtesy by S.Dolinsky, GE

Time-of-Flight PET/CT is the standard

D690→710



mCT 128 True V



Ingenuity TF 128

PMT based PET 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.

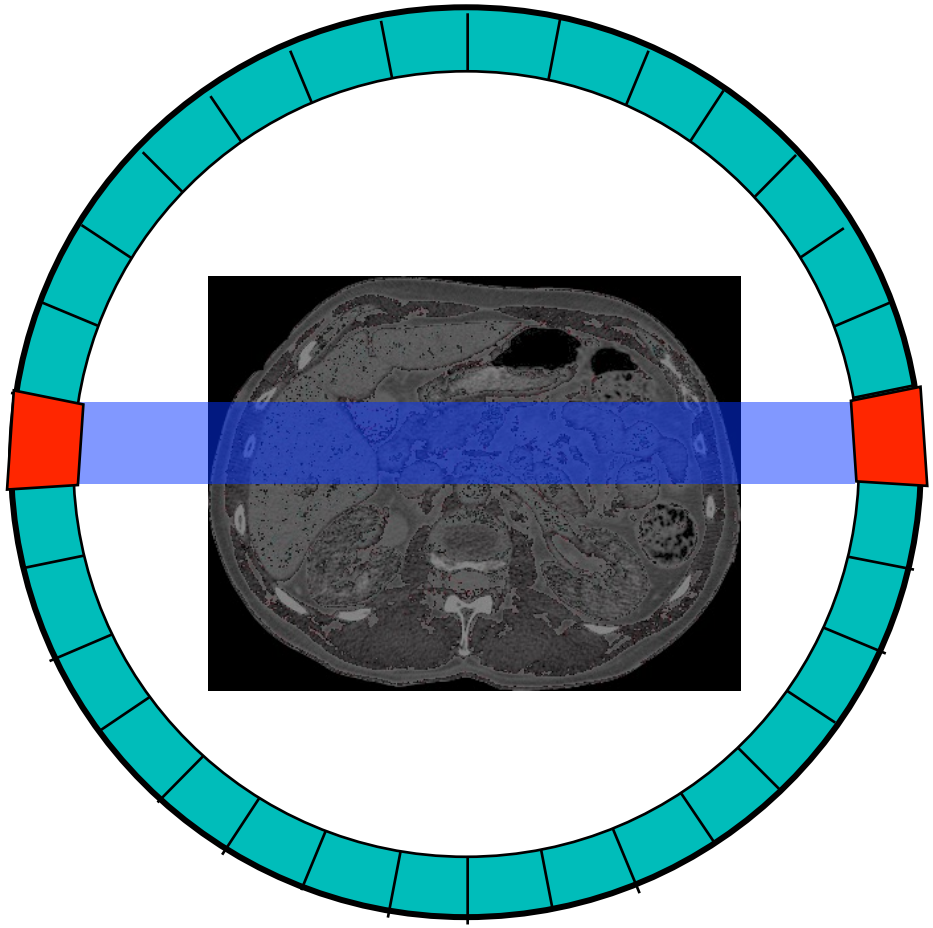
- The benefit is an improved reconstructed "signal-to-noise" ratio.
- The benefit depends critically on the *size of the part of the patient* being imaged.

but Time-of-flight does not :

- affect intrinsic spatial resolution.
- improve counting statistics

Spatial Resolution and Sensitivity

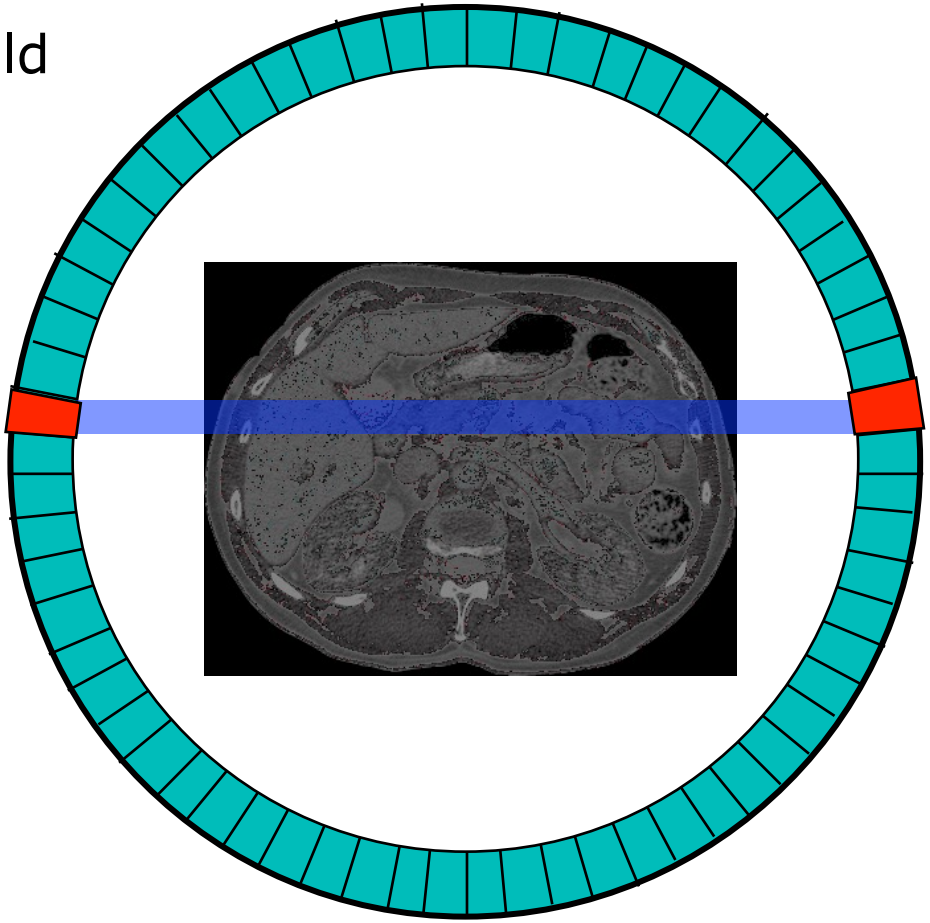
Intrinsic spatial resolution determined by **detector width**



Courtesy by S.Cherry, UC Davis

Spatial Resolution and Sensitivity

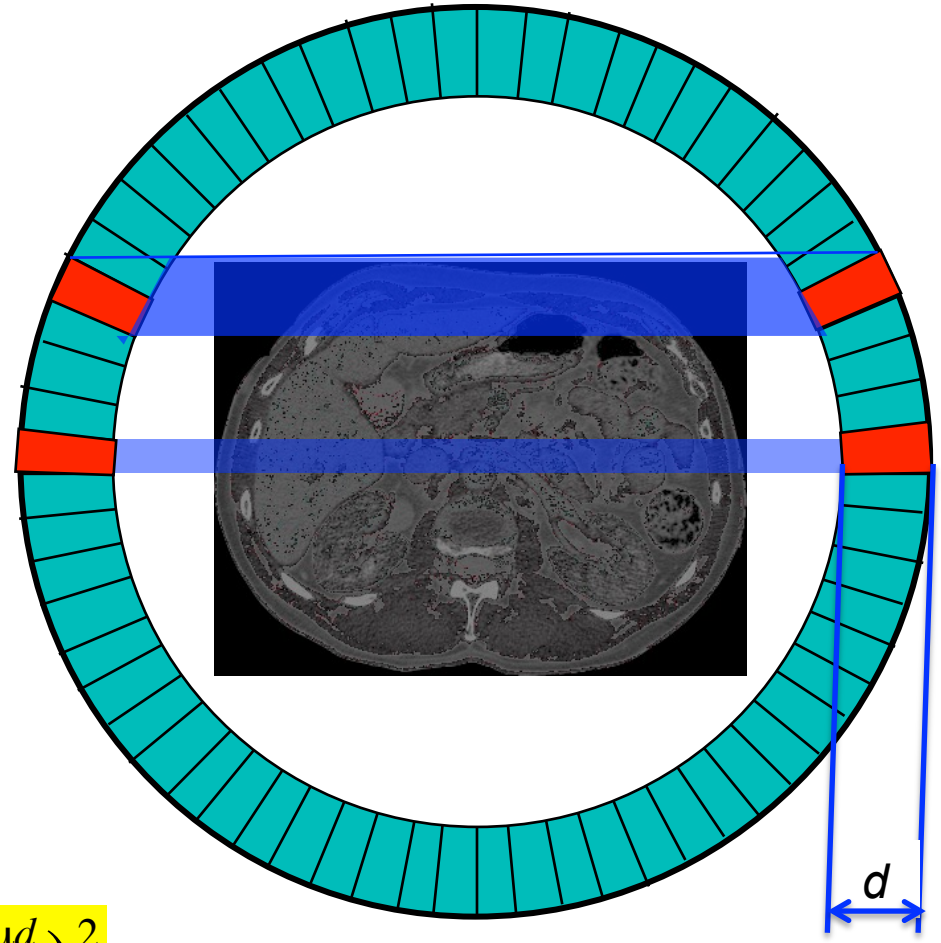
smaller detectors yield
better resolution and
better sampling



Courtesy by S.Cherry, UC Davis

Spatial Resolution and Sensitivity

Thicker detectors improve sensitivity, but spatial resolution degrades due to **parallax effects**

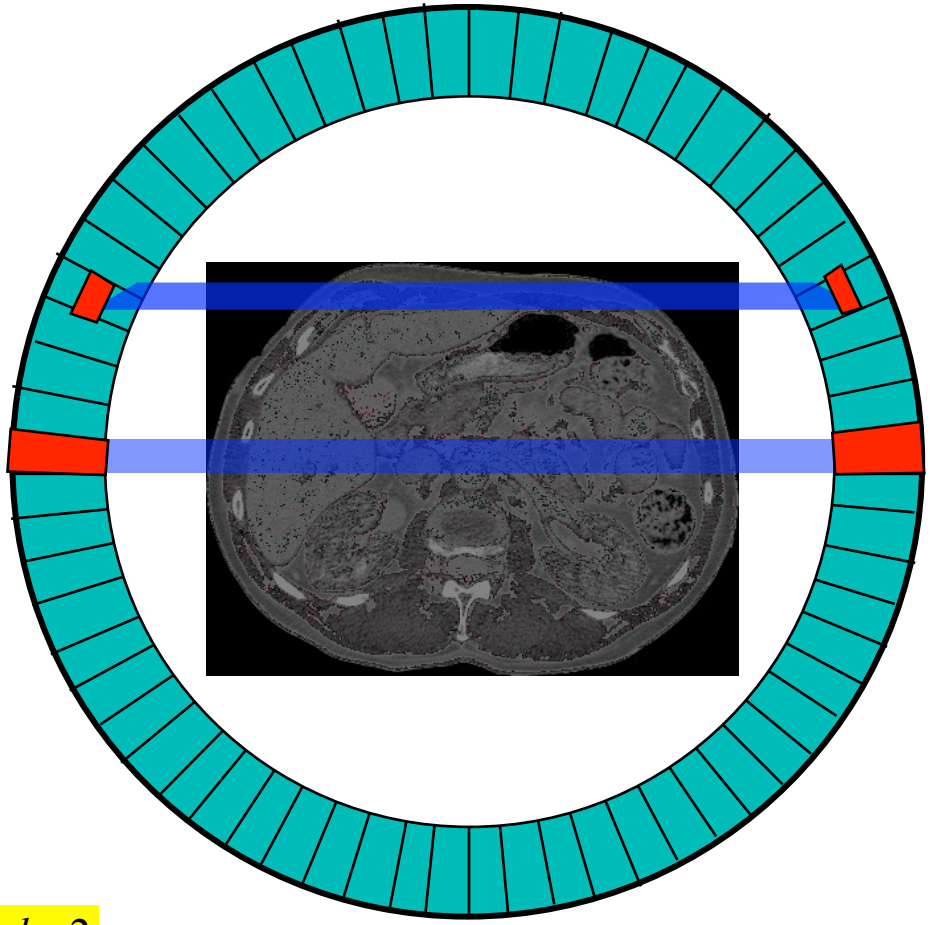


$$sensitivity \propto (1 - e^{-\mu d})^2$$

Courtesy by S.Cherry, UC Davis

Spatial Resolution and Sensitivity

Depth-of-information encoding reduces **parallax effects**



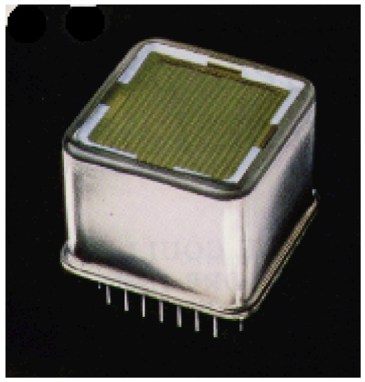
$$sensitivity \propto (1 - e^{-\mu d})^2$$

Courtesy by S.Cherry, UC Davis

Limitations

Resolution limited by

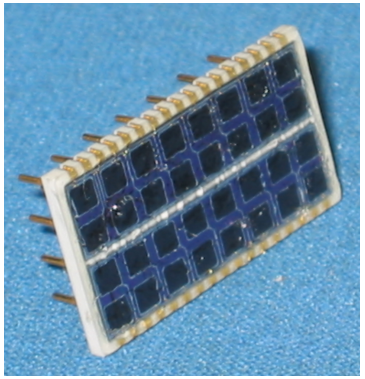
- brightness of scintillator
- light transport to PMT
- quantum efficiency of PMT (~20%)
- Size of anode structures (~ 2-4 mm)



Hamamatsu PMT M64

Solution - **solid state detectors**?

- Finer feature sizes
- Higher quantum efficiency
- Considerations
  - > Gain, noise, timing, area, # of channels…

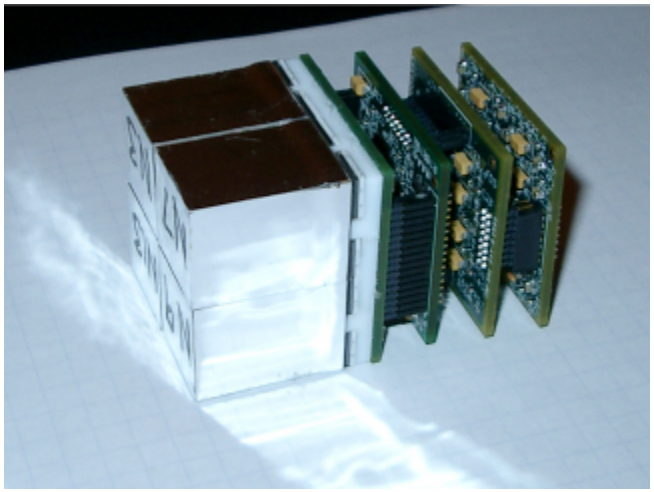


Hamamatsu S8550 APD

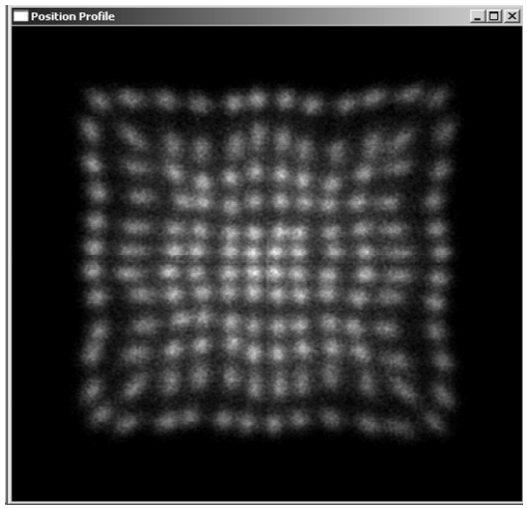
2006 – First step into Solid State Detectors

APD detector arrays

- magnetic field insensitive
- higher QE as PMT but lower gain
- compact Si devices
- sensitive to temperature and bias voltage



new integrated detector block



Crystal identification map of 12 x 12 LSO array using 3 x 3 APDs

2006 – First step into Solid State Detectors from a PET supplier

Siemens MAGNETOM-Trio with BrainPET Insert

PET insert

4 installation sides world wide for clinical research:

- University Tübingen, Germany
- Boston, USA
- Forschungszentrum Jülich, Germany (3T and 9.4T)
- Emory Center for Systems Imaging, Atlanta, USA

Why MRI-PET Hybrid Imaging?

- Want true simultaneous data acquisition in a single device
- Want combined functional and morphological data acquisition at the same time
- Want multi modal functional acquisitions at the same time (fMRI / MRS - PET)
- Want to cross-validate activations measured with PET and fMRI under the same conditions, at the same time, in the same status

Beyond APDs - SiPMs

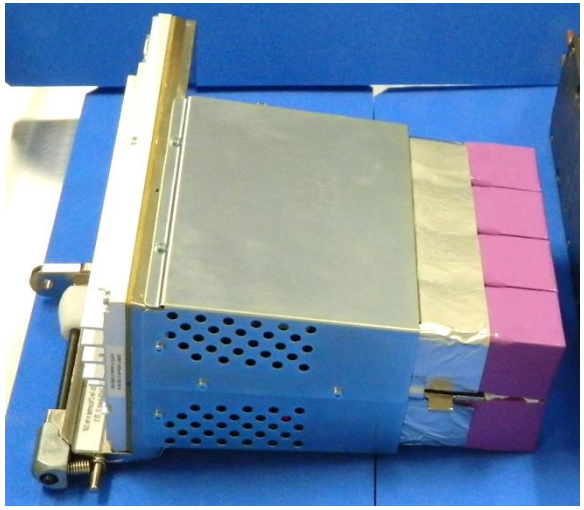
Silicon Photomultipliers

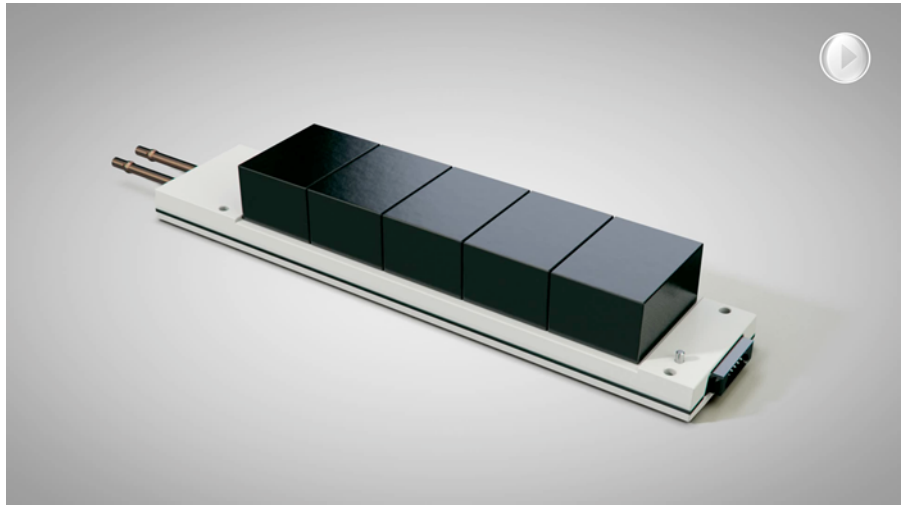
- Higher gain
- Faster response time
- Low bias voltage (tens of volts)
- Less dependence on bias and temperature

SensL Array

- Non-linearity at higher light levels
- Dark noise a problem at very low light levels
- Less mature technology

2012: Transformation of PET Detectors





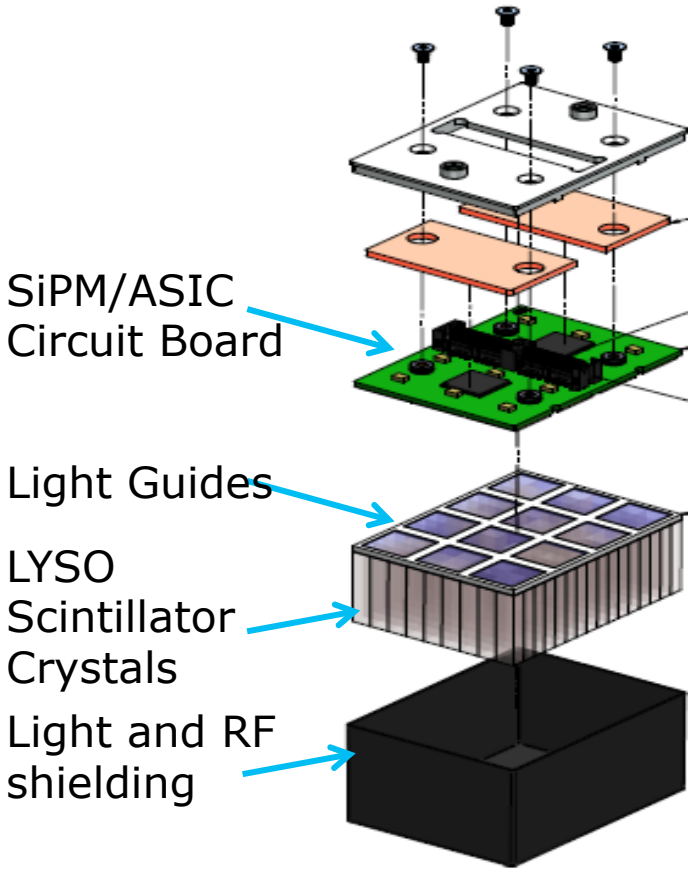
40 year old technology
→ One of last remaining vacuum tube based detector

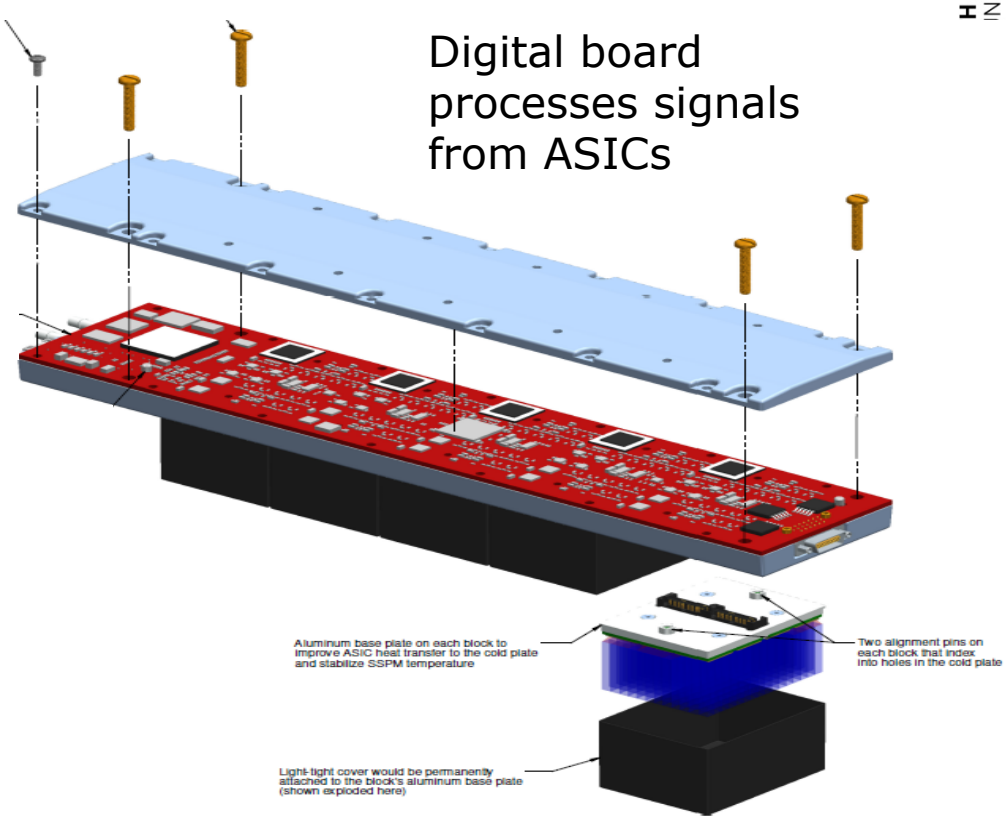
- Limited performance
- Detection efficiency
- Average ToF: 550 ps
- Magnetic sensitivity
- Bulky

Silicon Photomultiplier:
new solid state photosensor

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

PET/MR module Concept



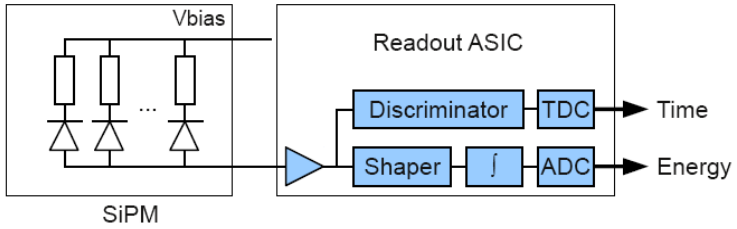


Courtesy by Sergei Dolinsky , GE Global Research Center

Differences of analog and digital SiPMs

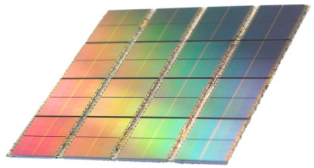
Analog SiPM

Analog Silicon Photomultiplier Detector

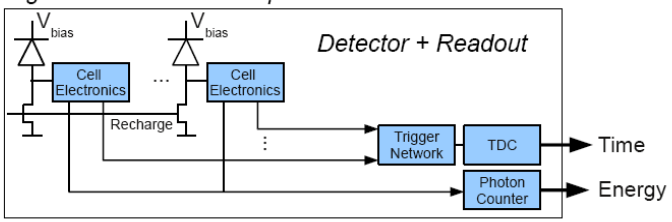


- discrete, limited integration
- analog signals to be digitized
- dedicated ASIC needed
- difficult to scale, high power cons.

Digital Photon Counter



Digital Silicon Photomultiplier Detector

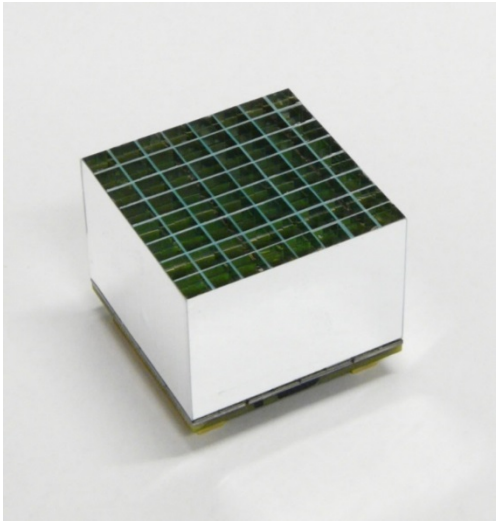


- fully integrated
- fully digital signals
- no ASIC needed
- fully scalable, low power

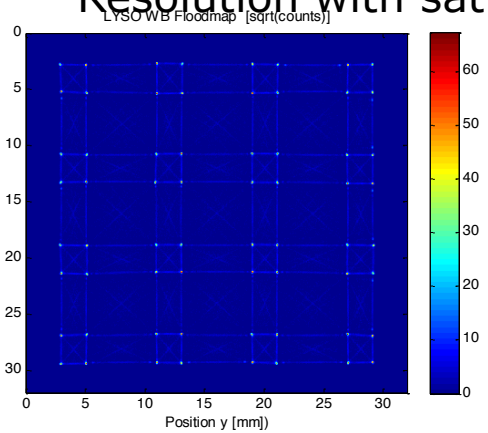
Courtesy by T.Solf, Philips Digital Photon Counting

Typical PET Performance

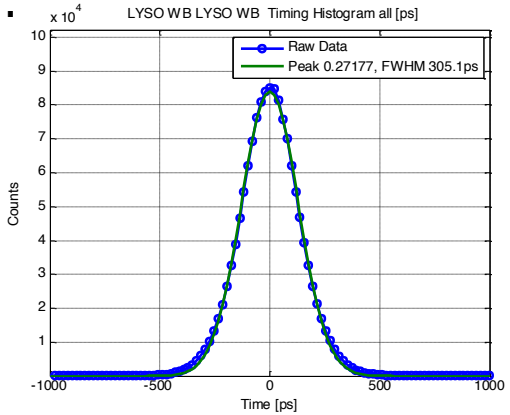
for 19mm LYSO Arrays in coincidence



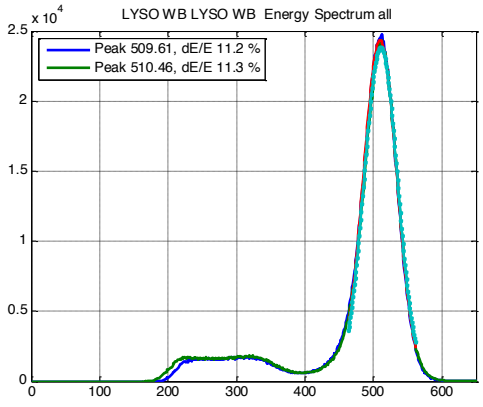
Floodmap Resolution with sat. corr.



Timing Resolution for Trig 2



Energy



PHILIPS

True Digital

DPC for VEREOS

Analog PET scan*

Vereos digital PET scan

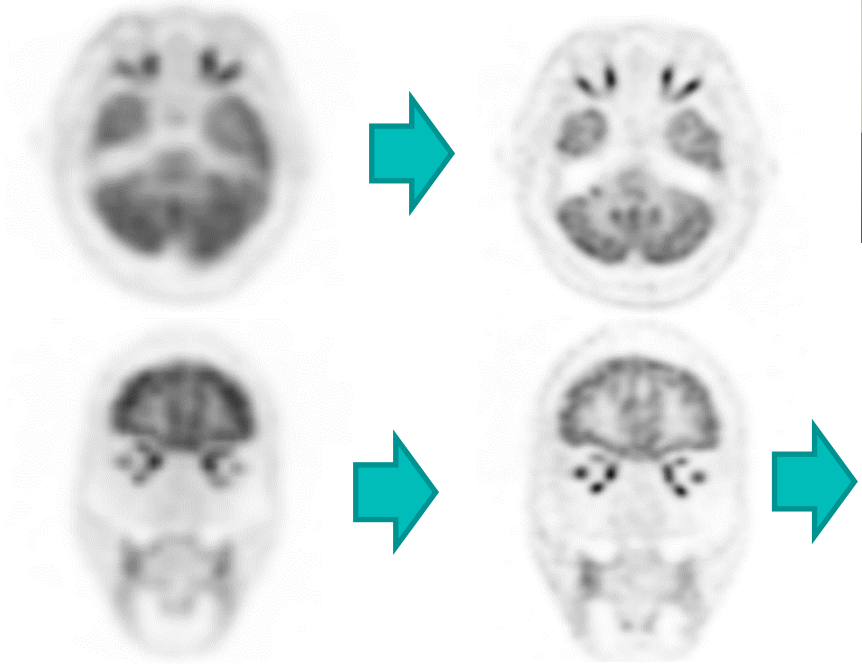


Image Quality Improvements

≈ 2x volumetric resolution

≈ 2x sensitivity gain

≈ 2x quantitative accuracy

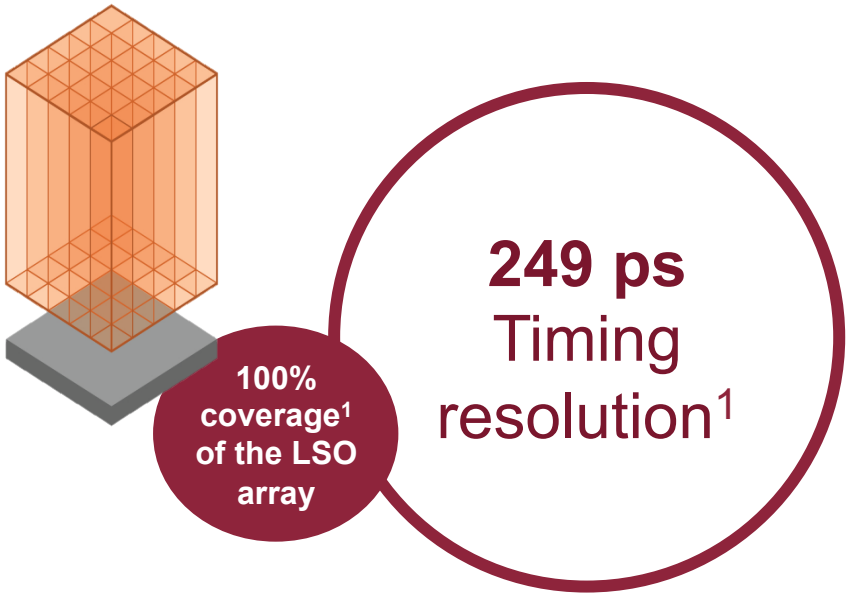
Images courtesy of University Hospitals Cleveland

PHILIPS

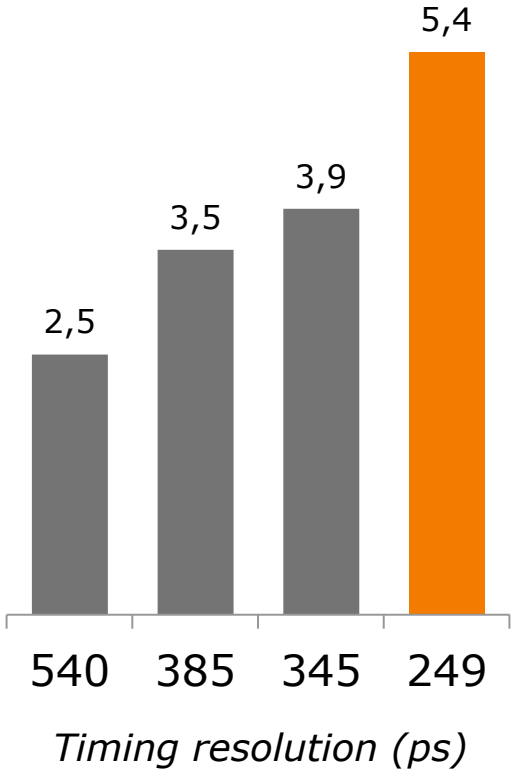
Faster time-of-flight amplifies scanner sensitivity

Noise Equivalent Count Rate is given by:

$$NEC_{TOF} = \frac{2D}{ct_{CRT}} \frac{T^2}{(T + Sc + R)}$$



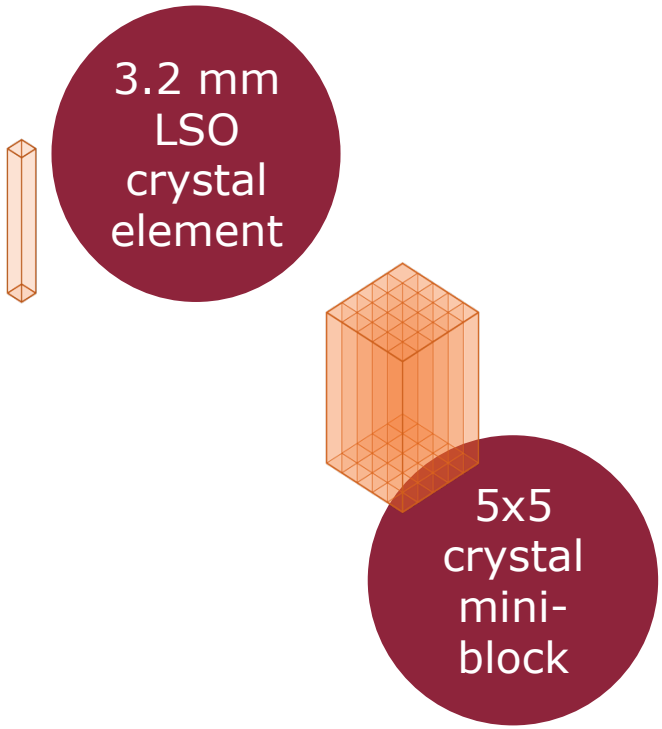
Time-of-flight sensitivity gain[2]



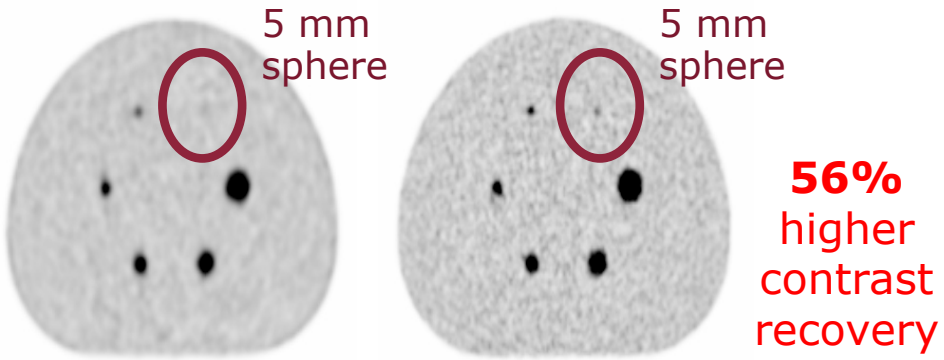
[1]Based on internal measurements available at time of publication. Data on file.;
[2]Gain calculated for a 20 cm cylindrical object.

SIEMENS Healthineers

Reducing crystal size improves spatial resolution and contrast recovery thus improving detectability



4 mm crystal Biograph Vision



56% higher contrast recovery

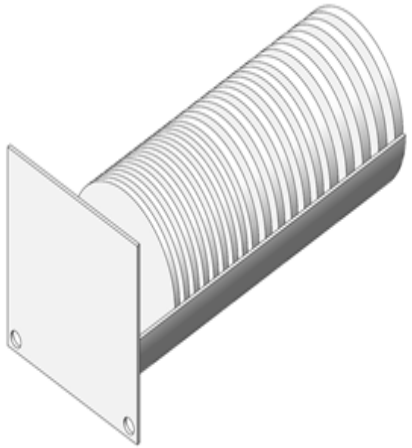
High-Resolution Torso Phantom

- Sphere size (mm):
  5.0, 7.9, 9.9, 12.4, 15.4, 19.8
- 6:1 contrast-to-background
- 300 second acquisition

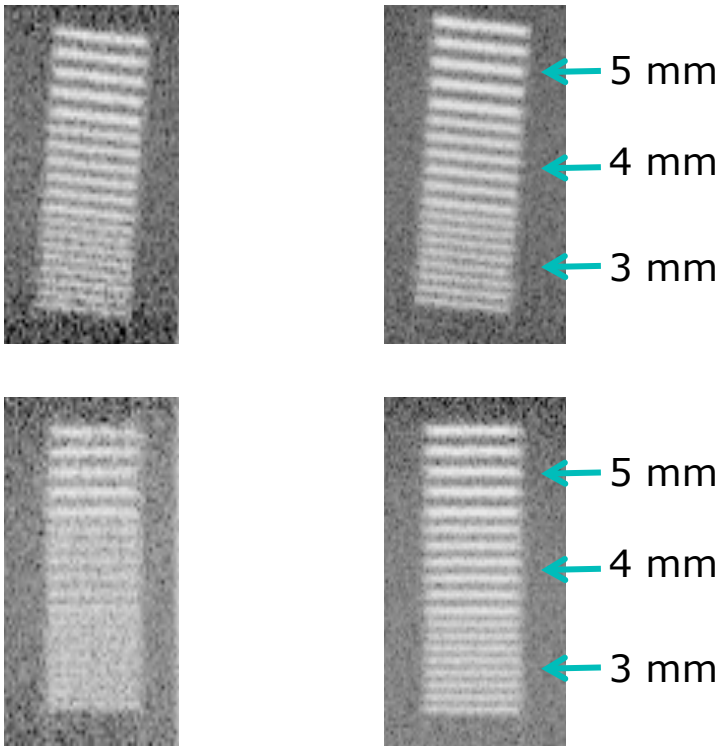
Biograph Vision is not commercially available in all countries. Due to regulatory reasons, its future availability cannot be guaranteed. Please contact your local Siemens organization for further details.

All planes of a modified Defrise phantom are clearly visible with Biograph Vision, even off-center

Axial Resolution Phantom



SIEMENS Healthineers



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State-of-the-art ToF PET Scanners
based on Slicon Photo-Multiplier (SiPM)

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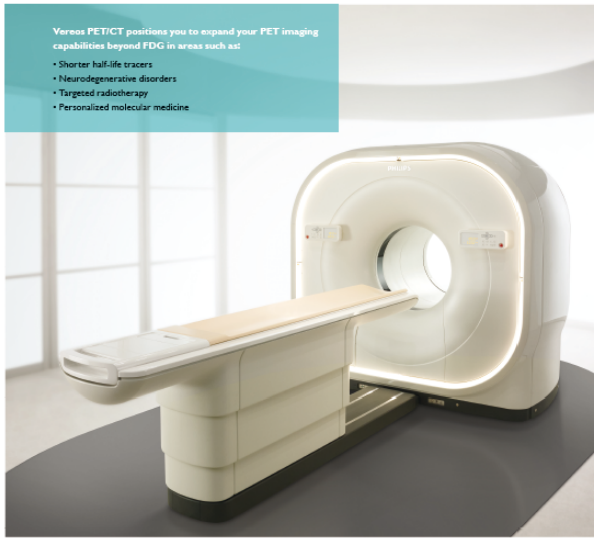
PHILIPS
sense and simplicity

Vereos



TOF 345ps

Signa PET/MR

TOF 380ps

SIEMENS Healthineers

Biograph Vision

TOF 249ps

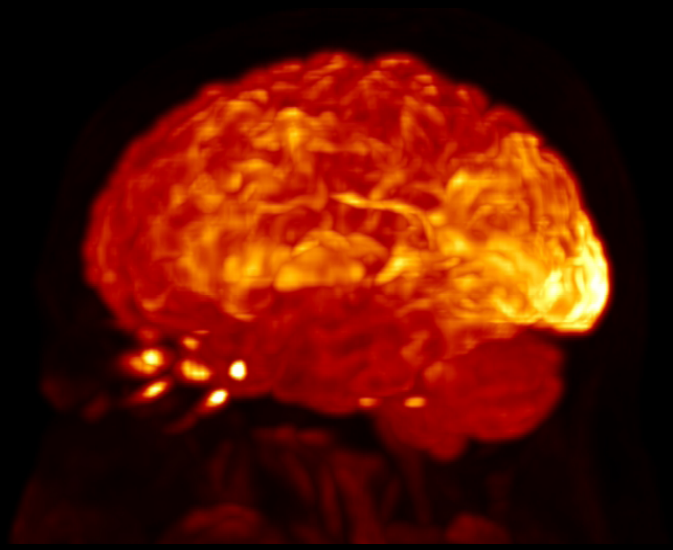
State-of-the-art ToF PET Scanners
based on Slicon Photo-Multiplier (SiPM)

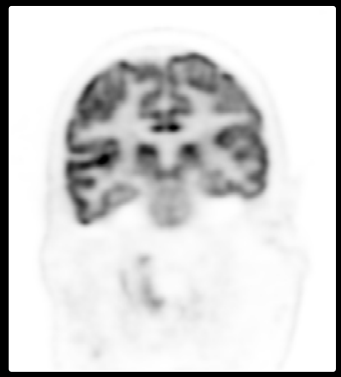
can be fabricated from small silicon sub-pixels to replace PMTs making them attractive for PET+MR and TOF-PET:

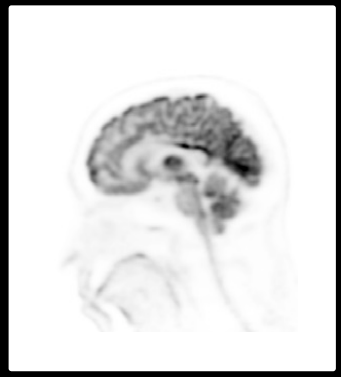
- fast, low-jitter time response
- magnetic field immunity
- small form-factor

Technical challenges:

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



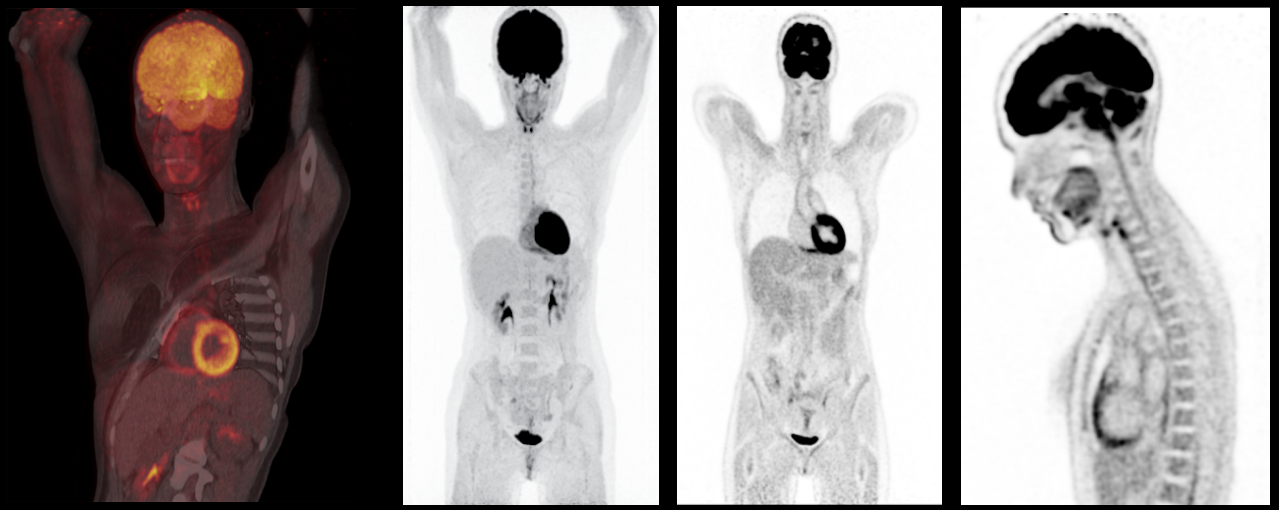




Sharply delineated cortical uptake, with high contrast between the gray and white matter. There is impressive definition of the gyri, basal ganglia and cerebellum.

Data acquired under IRB-approved protocol. Data on file.

Sharp delineation of the muscle and fat planes, vertebral margins and end plates, biliary radicals, renal calyces, aortic wall and papillary muscles of the heart.



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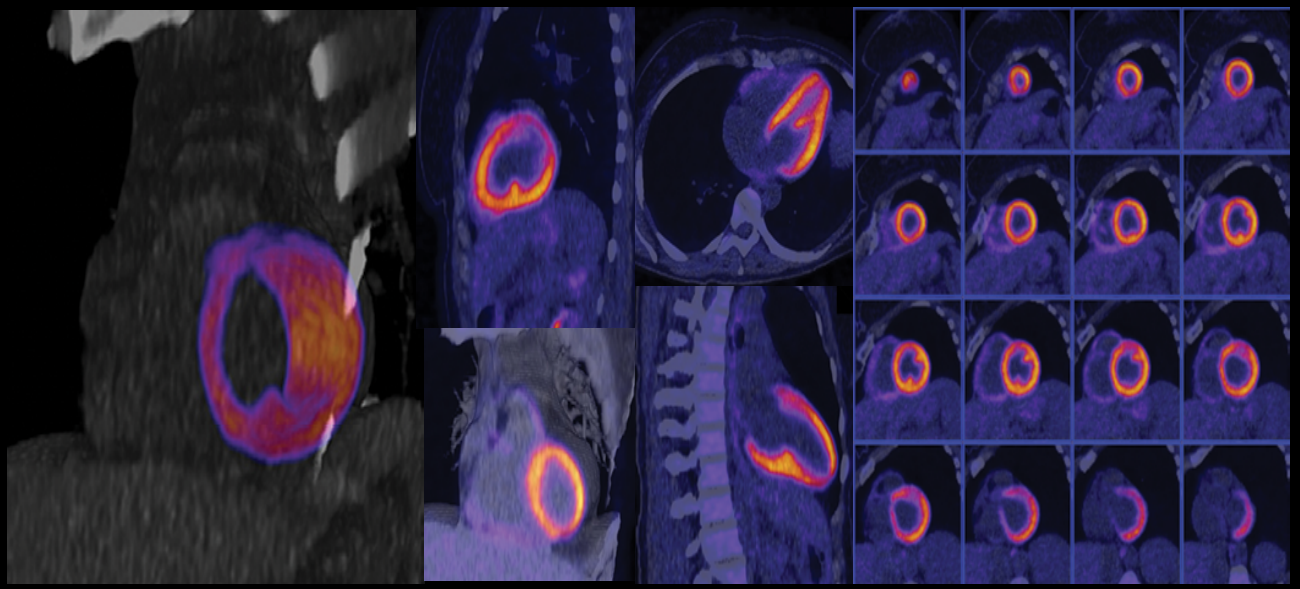


Visualization of the heart with impressive clarity, including remarkable delineation of the left ventricular edge and papillary muscles even without cardiac gating.

Data acquired under IRB-approved protocol. Data on file.

Timing resolution of PET detector – photo sensor requirements

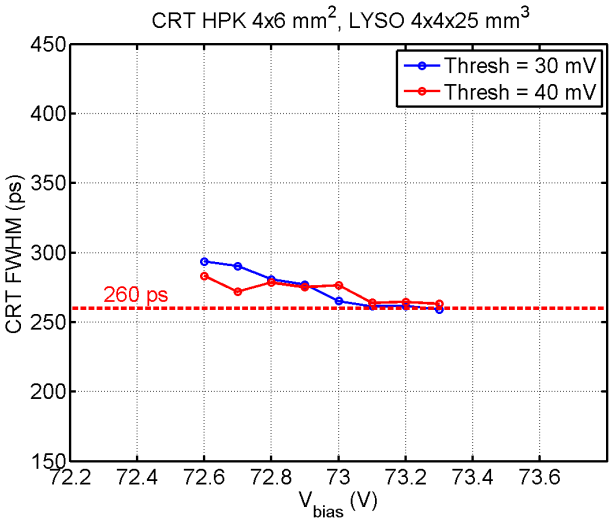
SiPM from different vendors have a wide of critical parameters for timing resolution:

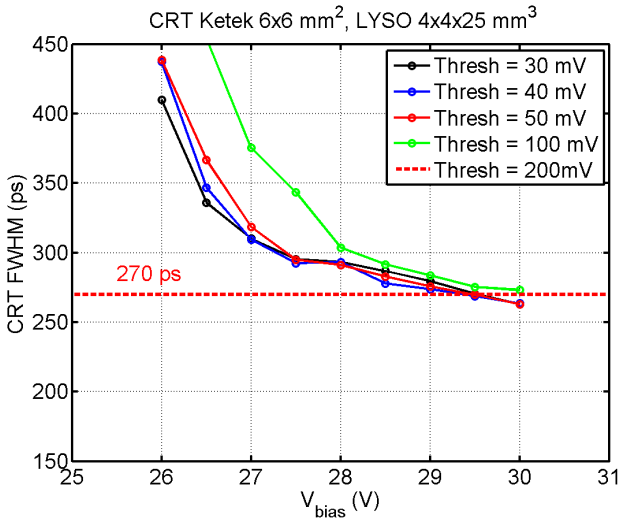
- PDE
- SPE pulse shape
- Transit Time Delay (across SiPM) and SPAD jitter
- Dark count (for block multiplexing)
- Gain
- Optical cross talk and after pulses

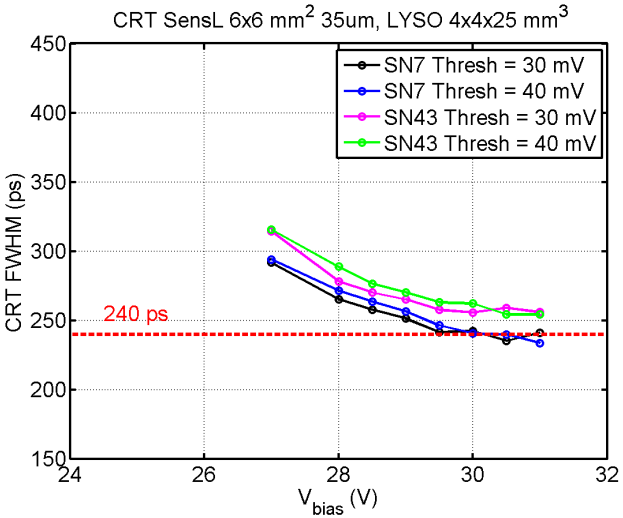
"We measure Coincidence Resolving Time (CRT) of LYSO/SiPM PET detectors at identical conditions"

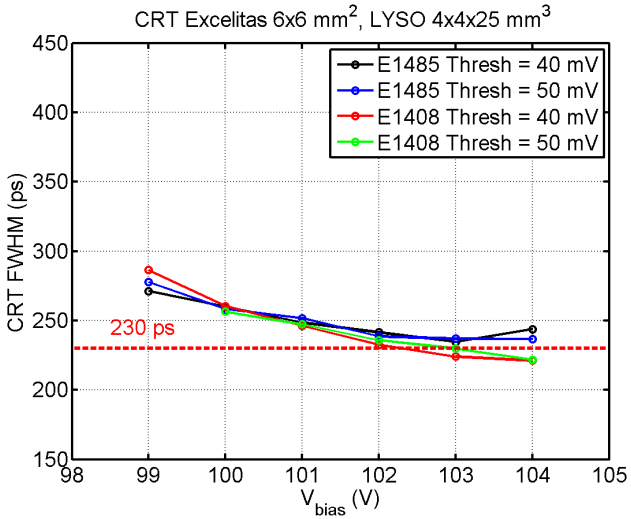
→ **Standardization process for Scintillation Detectors based on SiPM is necessary!**

CTR measurements - large SiPM, long crystal









Courtesy by Sergei Dolinsky , GE Global Research Center

Coincidence Timing Resolution - CTR

Future CTR of 10ps would be a big step

- **new ideas for light emitting materials,**
- **SiPM: technology leap is needed**
  > is it possible on the base of SPAD?
  Here we are already at <20ps in SPTR
- **Electronics**:
  > can the electronics handle <10ps FWHM
  > What's about jitter in arrays and
  > we need low power

Other photodetector technologies?

Requirements to the photon detectors

(+readout systems) for 10ps TOF-PET

- PDE (total with packaging) – the highest
- SPTR – as small as possible without sacrification of PDE
- Dark rate (temperature) moderate

Only an excellent quality SiPM properly connected to 65nm or smaller electronics part is able to fulfill the requirements

Today– packaging and connectors deteriorate
SiPM timing properties

→ **3D integration**

Summary – a View from Suppliers

- Technological Challenges to combine PET and MRI have been overcome
- TOF-PET scanners based on SiPM show clearly an improvement in image contrast and signal-to-noise ratio for all suppliers
- Higher packing fraction and smaller crystals lead to an increase of the sensitivity
- Better CTR leads to higher NEC performance

Summary – a View from a Supplier

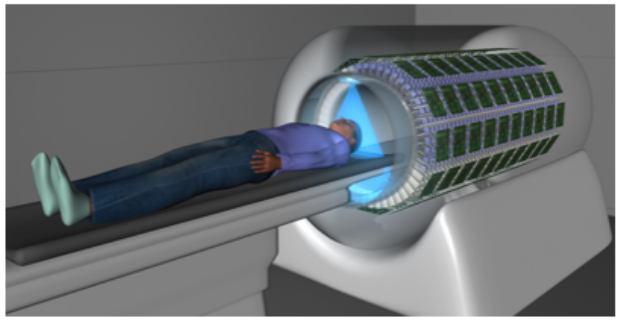
but

- The prize of a SiPM array should be reduced by a factor of a half or less to offer larger axial scanner views
  to increase the sensitivity of a PET scanner
  → *look at the EXPLORER project at UC Davis*

- Standardization process of SiPM is neccessary

- Not every development step into better SiPM performances ends up into a new system,
  → return of an invest

Total Body PET Scanner: 40x-80x?



http://explorer.ucdavis.edu/about-explorer/

- Reliability of a SiPM array is important to reduce service cost and time

- Availability of the same SiPM arrays and electronic read out over a large time scale is needable

On behalf of human PET scanner suppliers

Thank you

for your attention !!