Joint DOE / NIH Workshop
Advancing Medical Care through Discovery
in the Physical Sciences Workshop Series:
Radiation Detection
Jefferson Lab

direct Positron Emission Imaging (dPEI)

Sun Il Kwon
Department of Biomedical Engineering
University of California, Davis
March 16th, 2023

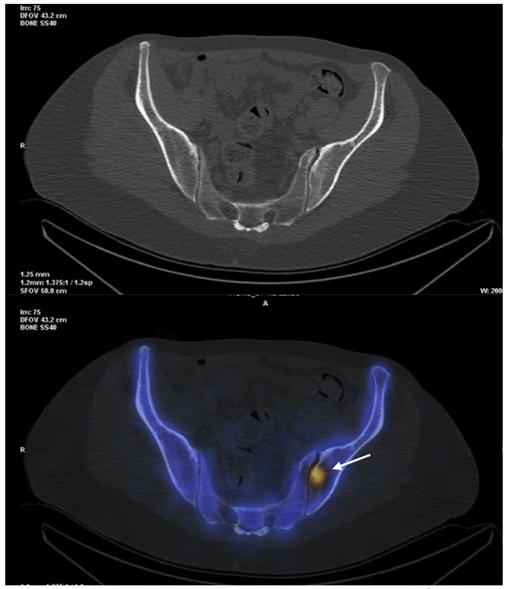
UCDAVIS

Three-dimensional Medical Imaging

X-ray Computed Tomography (X-ray CT)

Positron Emission Tomography (PET)

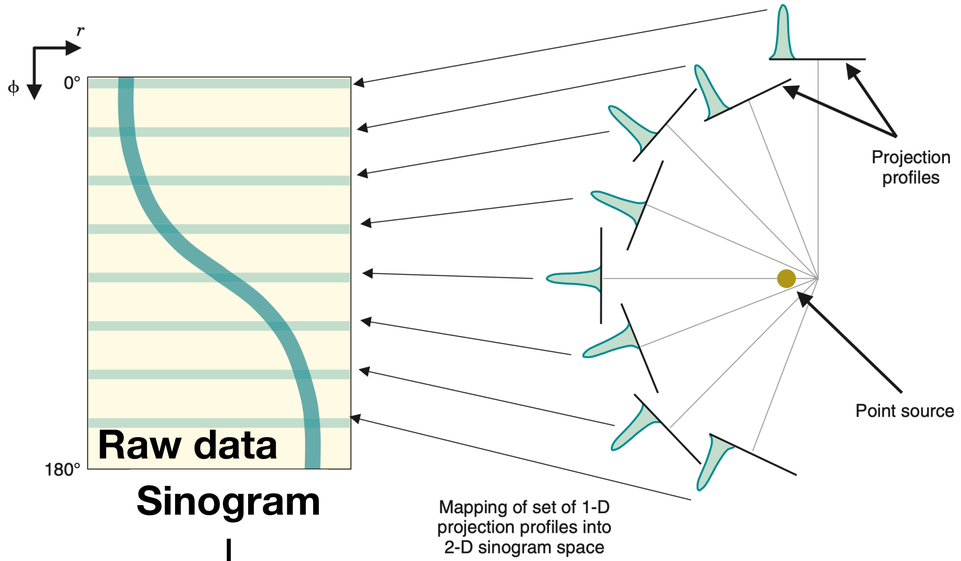
Single Photon Emission Computed Tomography (SPECT)

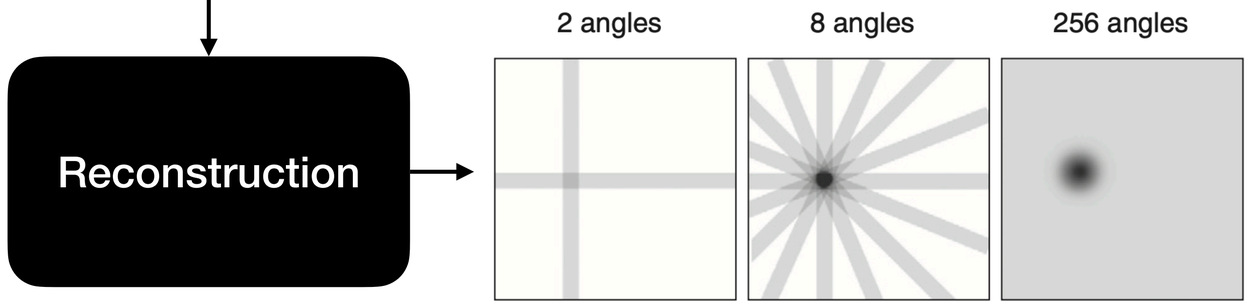


Flohr et al. Physica Medica 2020, Adusumilli et al. Clinical Radiology 2020

Tomography

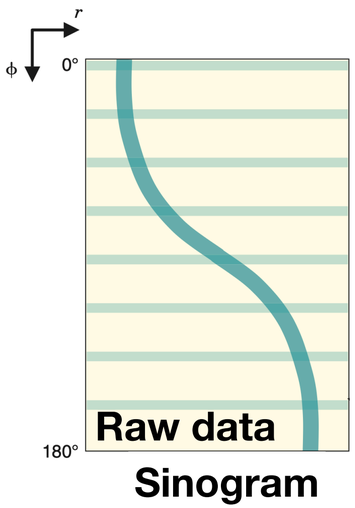

Projections of X or gamma rays
Reconstruction
3-D or cross-sectional images


r
ϕ
0°
180°
Raw data
Sinogram
Projection profiles
Point source
Mapping of set of 1-D projection profiles into 2-D sinogram space


Reconstruction
2 angles
8 angles
256 angles

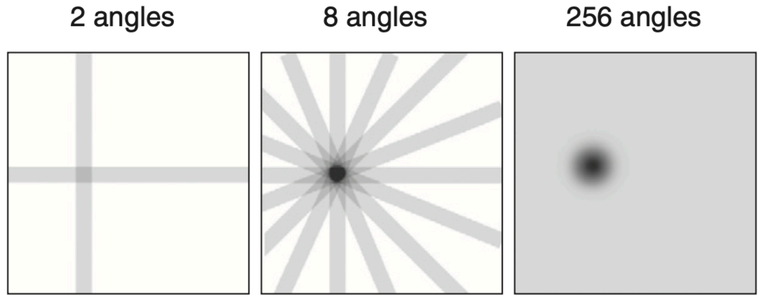
Tomography

Projections of X or gamma rays → Reconstruction → 3-D or cross-sectional images

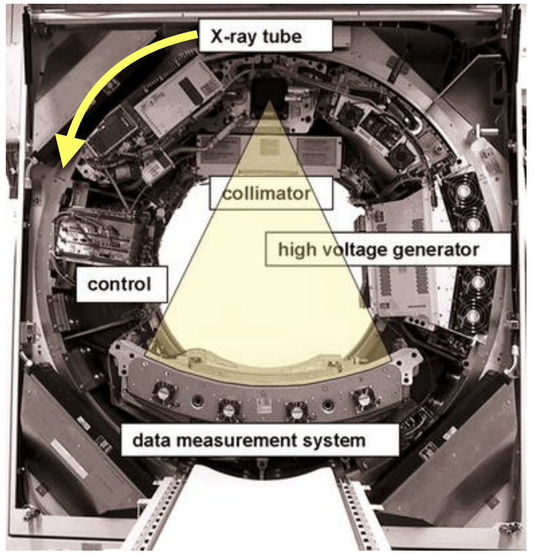


The reconstruction step amplifies noise levels. Adequate angular samplings are required for better reconstructed images.

Reconstruction



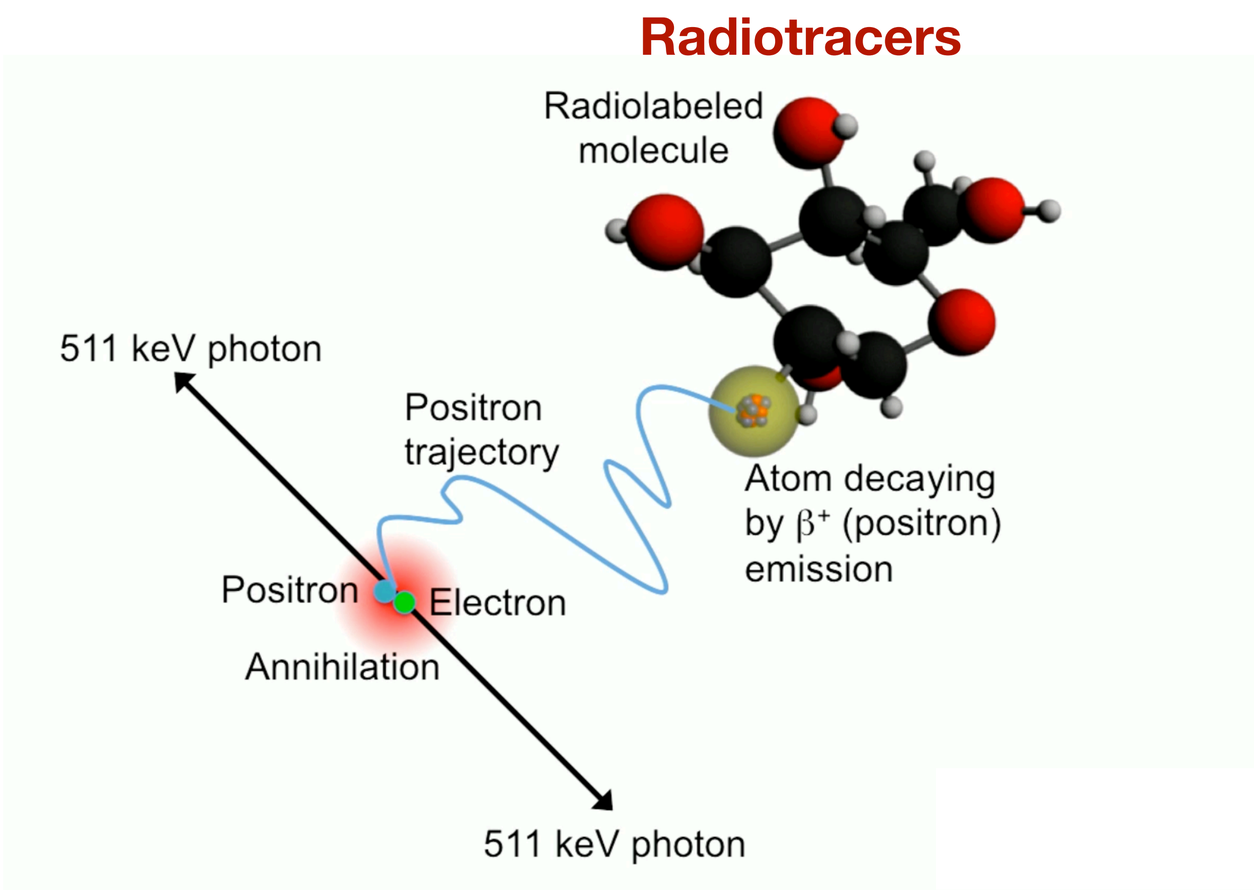
X-ray CT

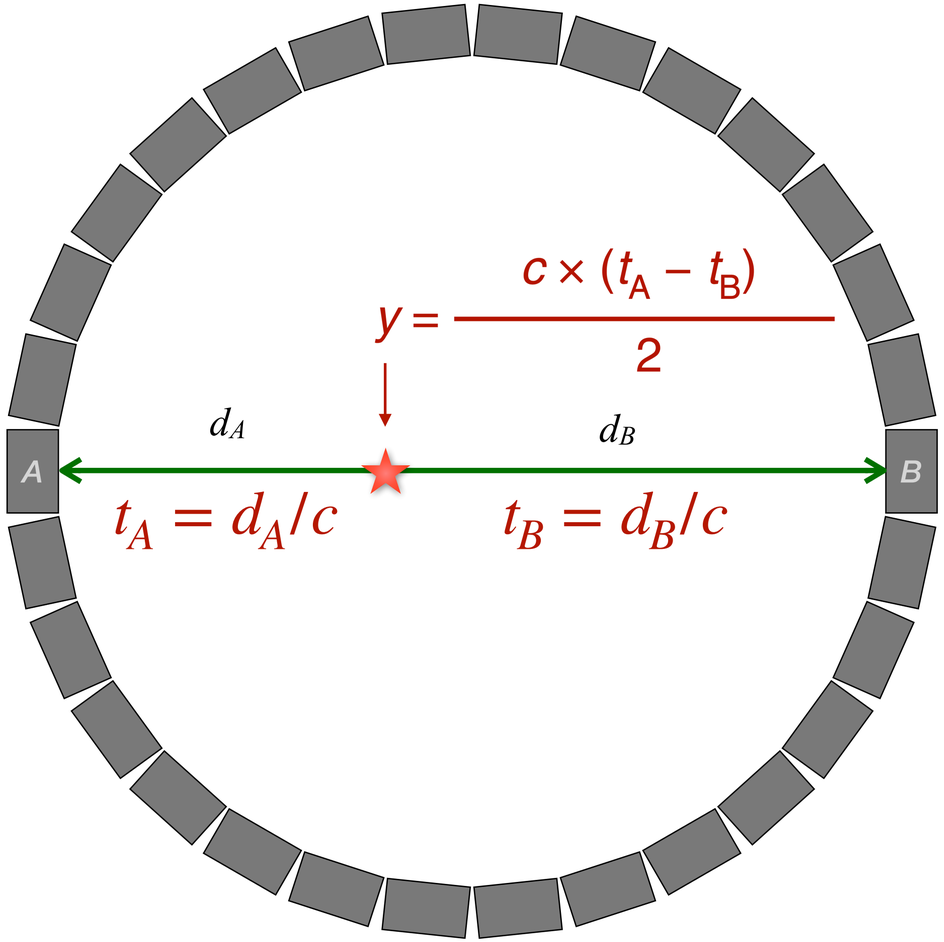


PET

Physics in Nuclear Medicine, Flohr, T. CT Systems. Curr Radiol Rep 2013

Positron Emission Tomography (PET)





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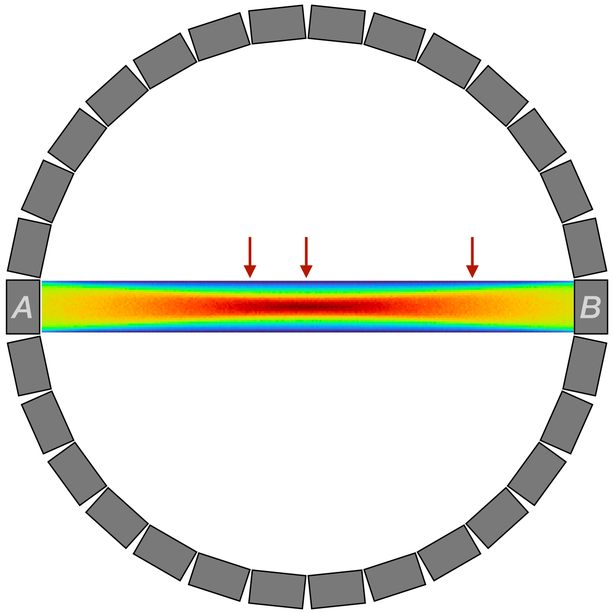
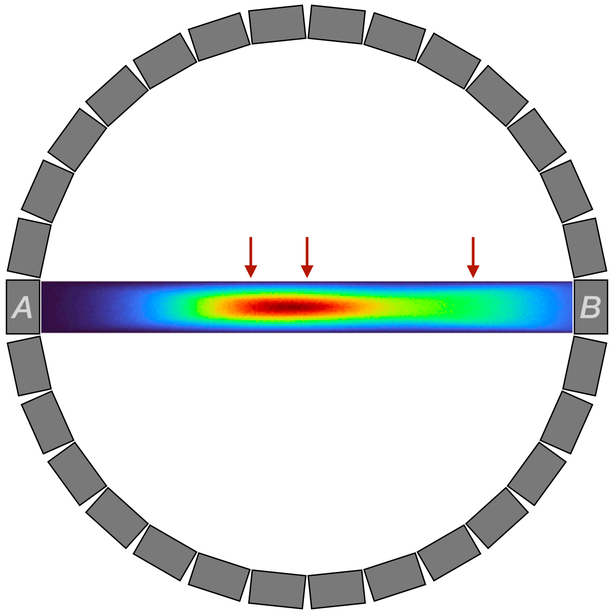


Conventional PET

No time measurement

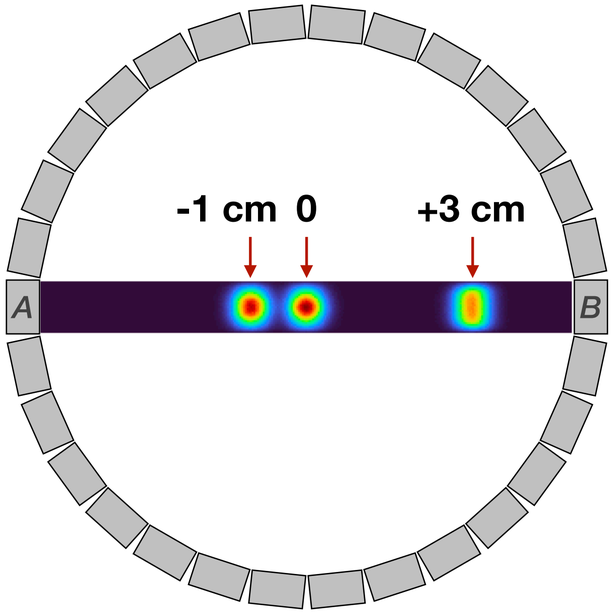


Time-of-flight PET

(CTR = 210 ps (10^{-12} sec) FWHM)

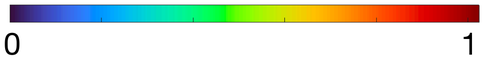
Spatial precision 31.5 mm FWHM

Reconstruction steps are still required



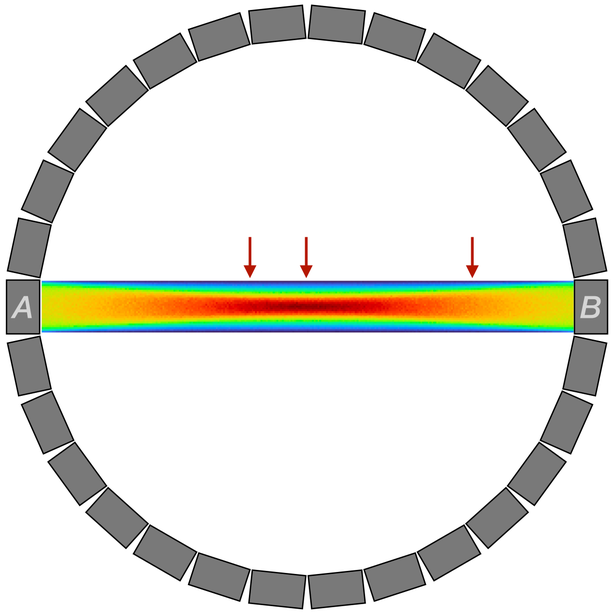
(CTR = **~30 ps FWHM**)

~4.5 mm FWHM



The probability distribution of source locations for a detected event

PET and direct Positron Emission Imaging (dPEI)



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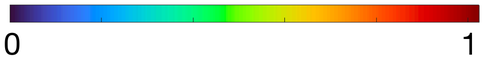

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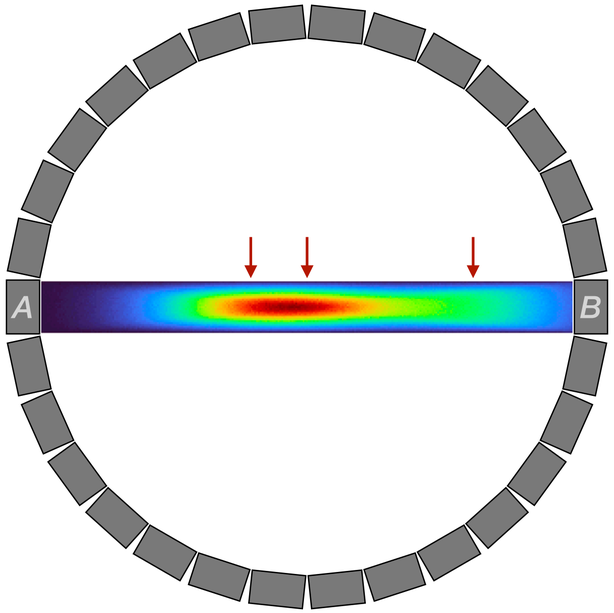

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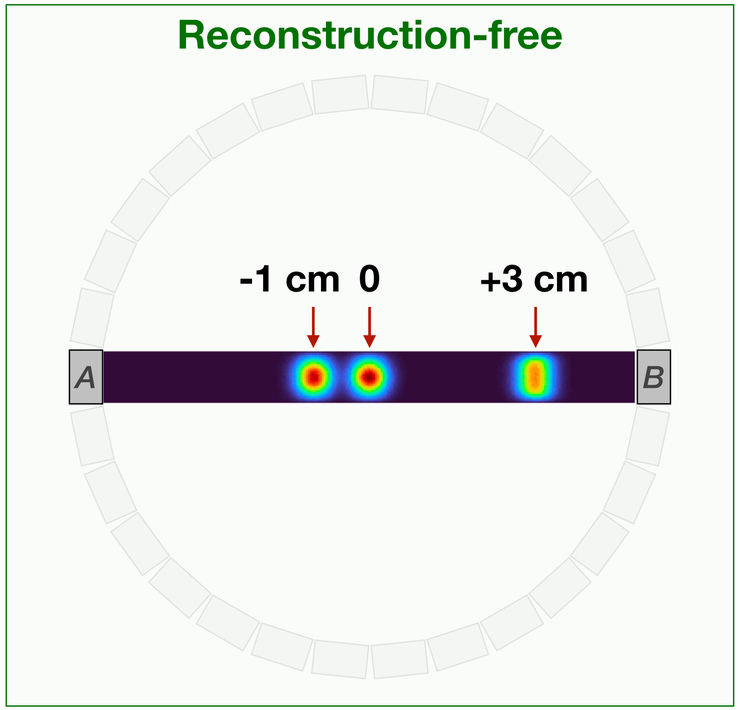


direct Positron Emission Imaging (dPEI)

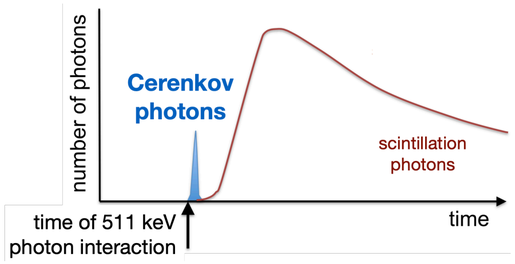
(CTR = **~30 ps FWHM**)

~4.5 mm FWHM

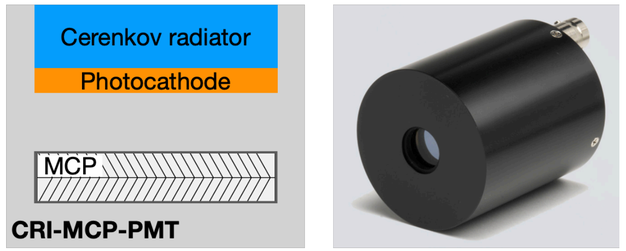
direct Positron Emission Imaging (dPEI)

~30 ps Timing Resolution

Fast signal generation (Cerenkov)

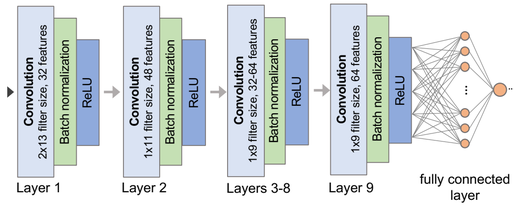


Fast signal detection



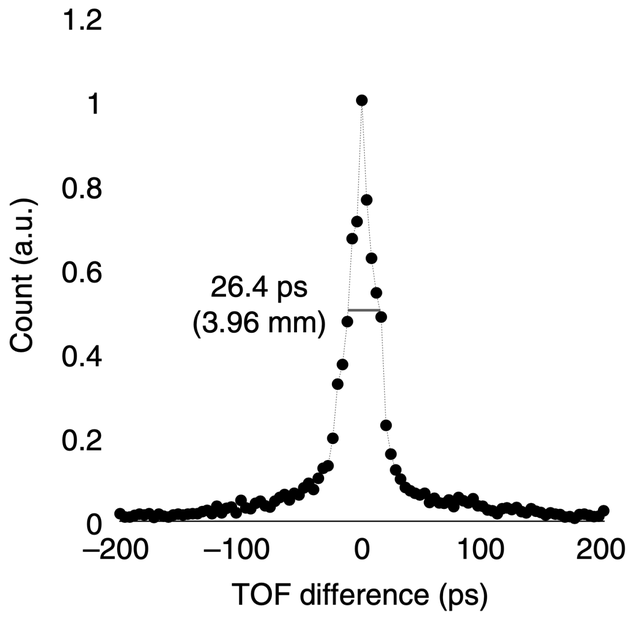
Ota et al. PMB 2021

Optimized waveform processing



AI based timing method

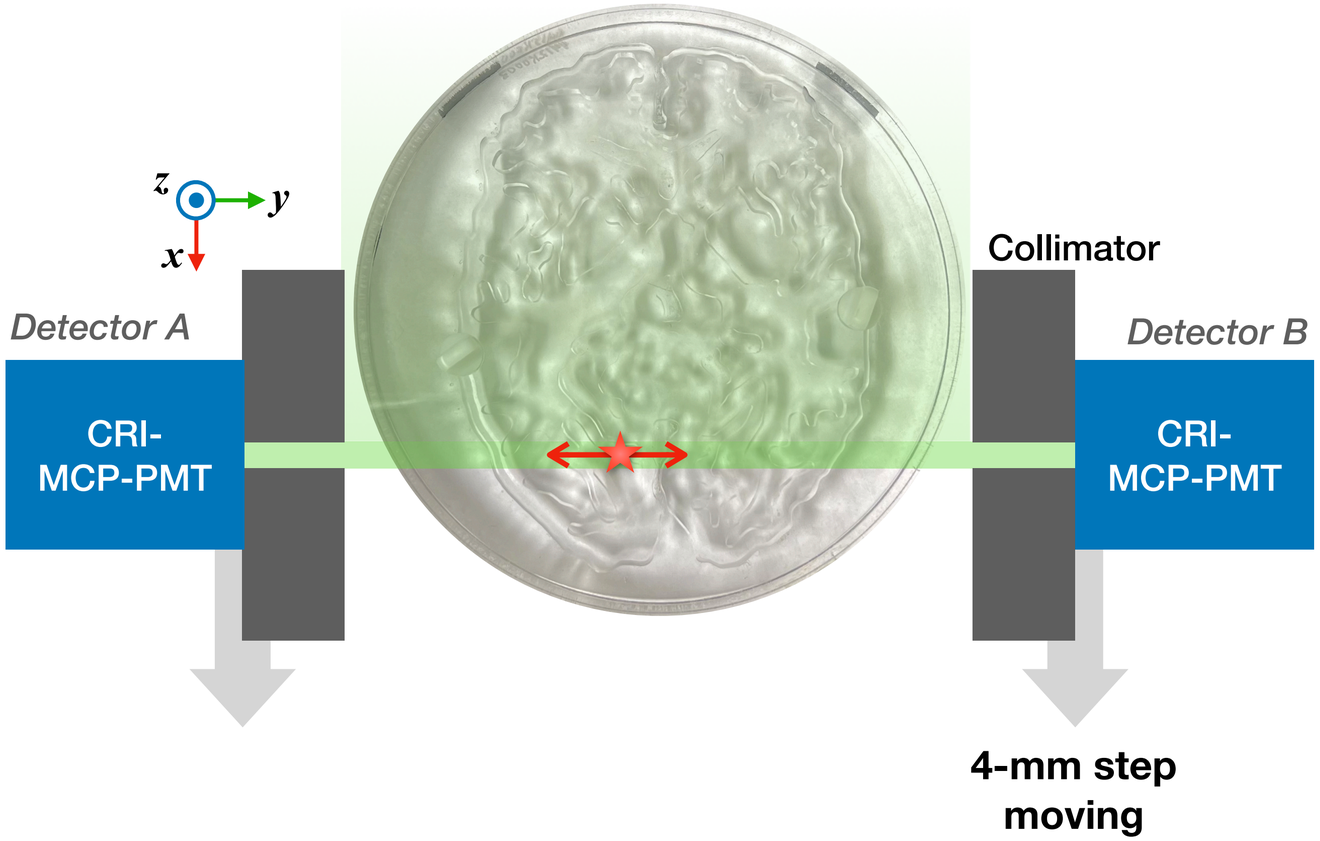
Berg et al. PMB 2018

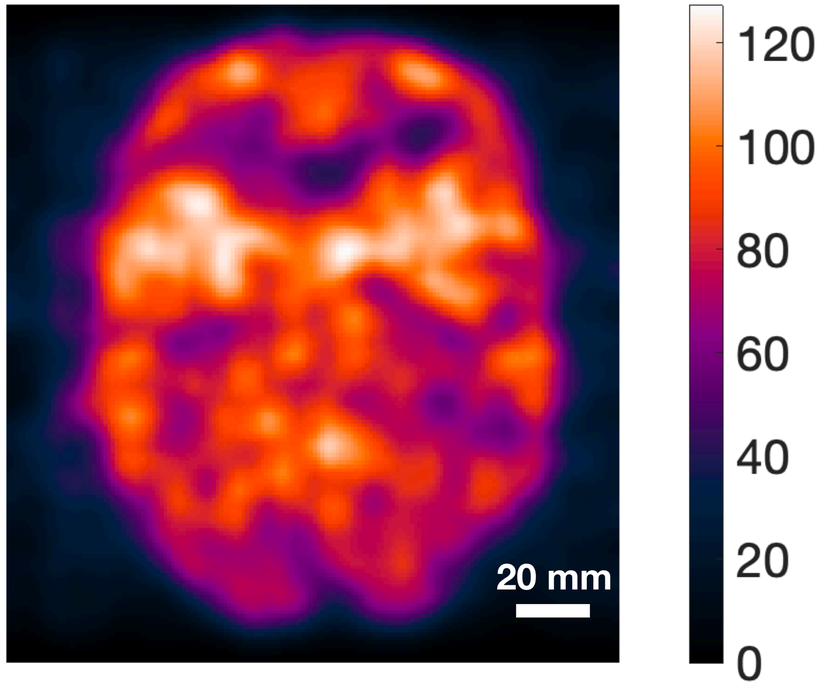


Average timing resolution:
<u>32 ps</u> FWHM

Kwon et al. Nature Photonics 2021

direct Positron Emission Imaging (dPEI)



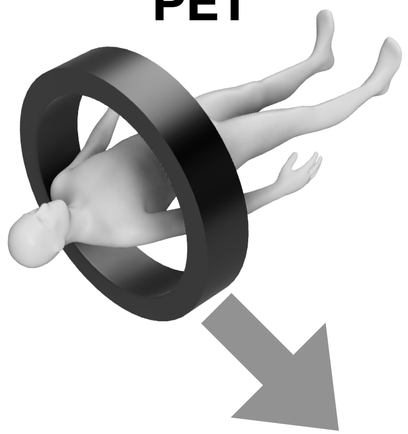


Kwon et al. Nature Photonics 2021

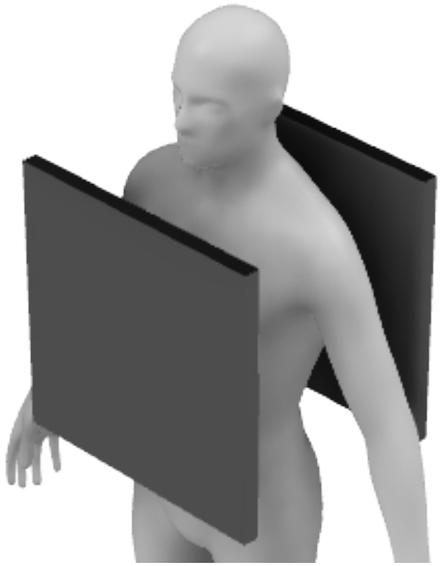
New Opportunities

From PET to dPEI

PET



dPEI



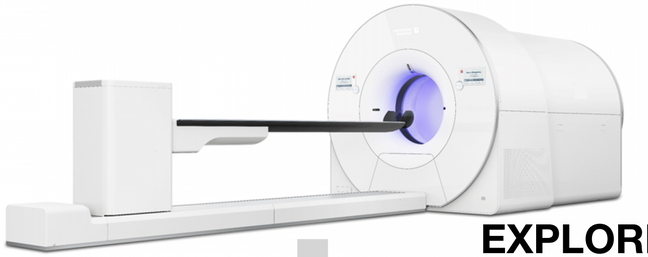
Whole-body

- Free of geometric constraints for tomography
- High solid angle coverage with smaller detector area
- Unprecedented SNR by ultrafast timing
- Real-time sub-second dynamic imaging

Sun Il Kwon (sunkwon@ucdavis.edu)

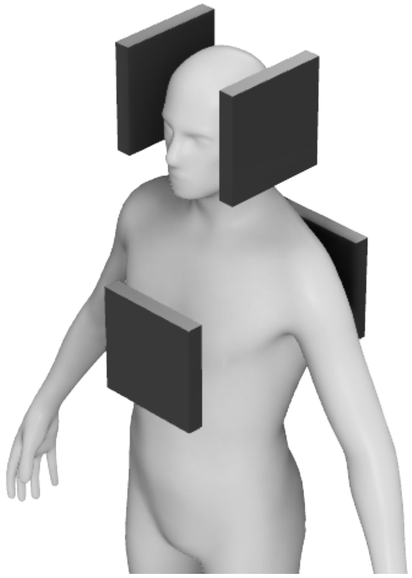
New Opportunities

New Designs for Biomedical Imaging

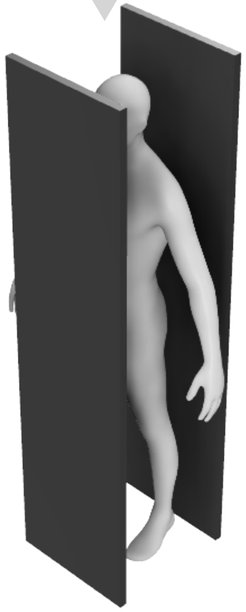


EXPLORER
2-m long PET scanner

dPEI



Multi-organs



Total-body

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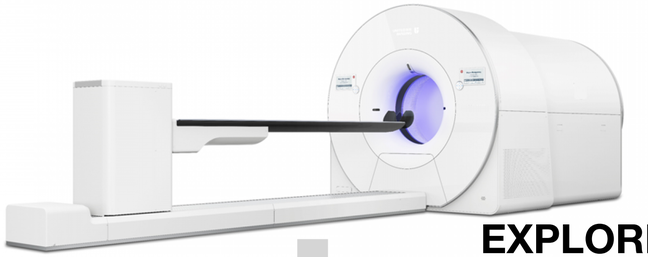
New Opportunities

New Designs for Biomedical Imaging



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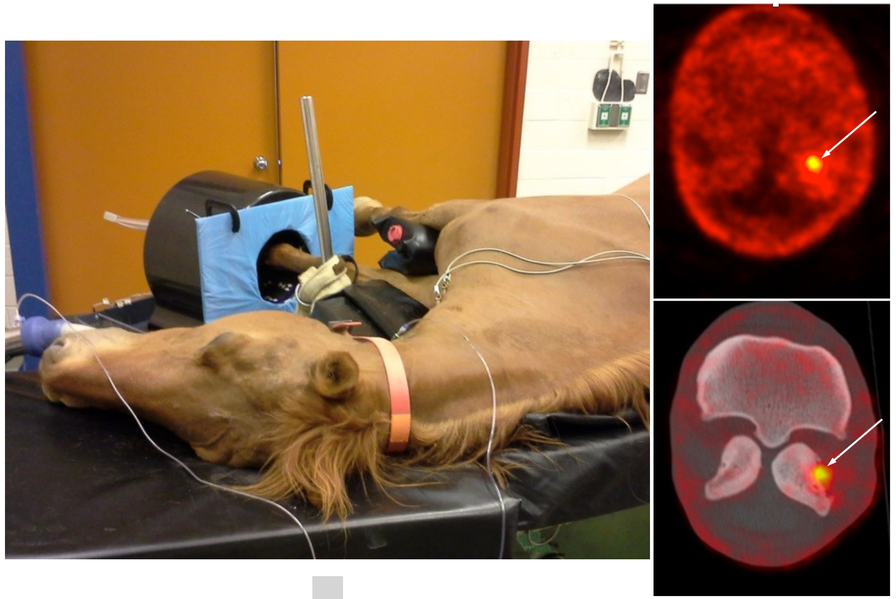
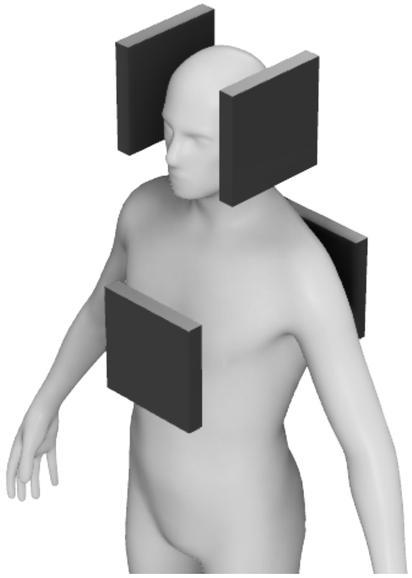


dPEI



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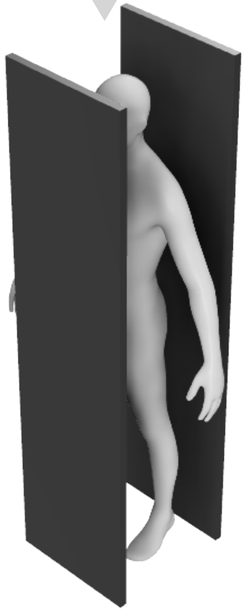
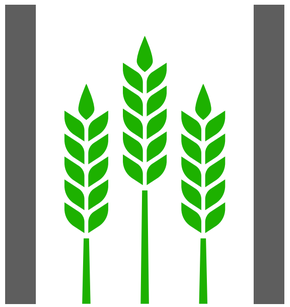
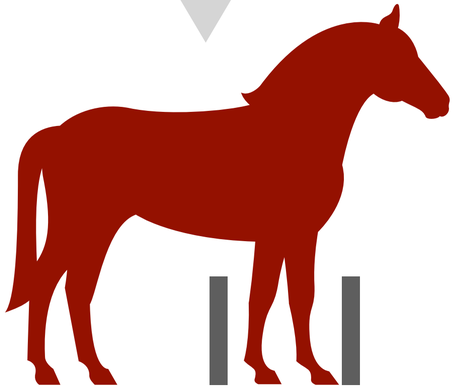


Total-body



Plants



Animal

… and more!!

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New Opportunities

Clinical Research Applications

Quantitative physiology (^{15}O!)

- perfusion
- blood volume
- hypoxia

Metabolism

- oxygen
- glucose
- fatty acid

Immune cell distribution, functional status and trafficking

Theranostics - quantifying tumor cell load, distribution, response to treatment, dosimetry

Single subject research

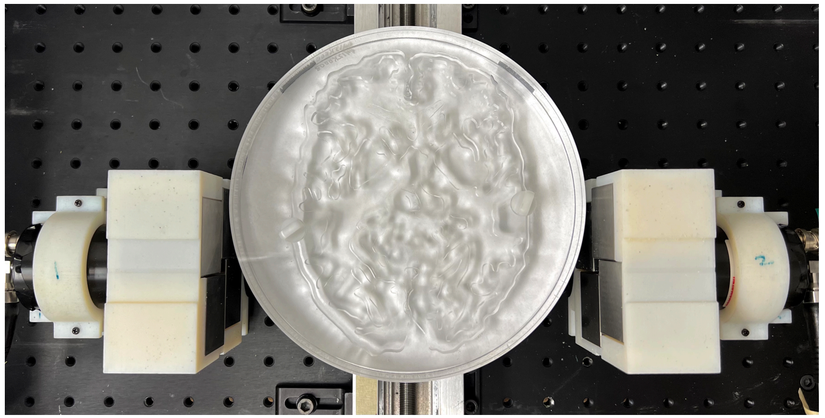
Challenge/Activation paradigms
Physiologic
Pharmacologic
Immunologic
Environmental

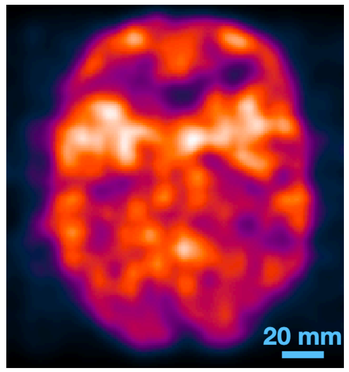
Quantifying lifestyle interventions in health and disease
Nutrition, diet, exercise, stress reduction etc.

Slide courtesy of Dr. Simon R. Cherry

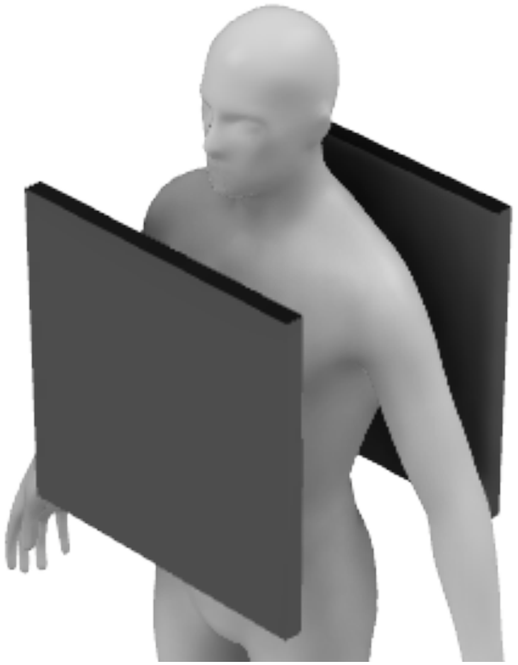
Toward Clinical dPEI System

Demonstration of
reconstruction-free
direct Positron Emission Imaging (dPEI)





Clinical dPEI system



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Toward Clinical dPEI System

NIH National Institutes of Health
Turning Discovery Into Health

NIH NIBIB R01 EB033536

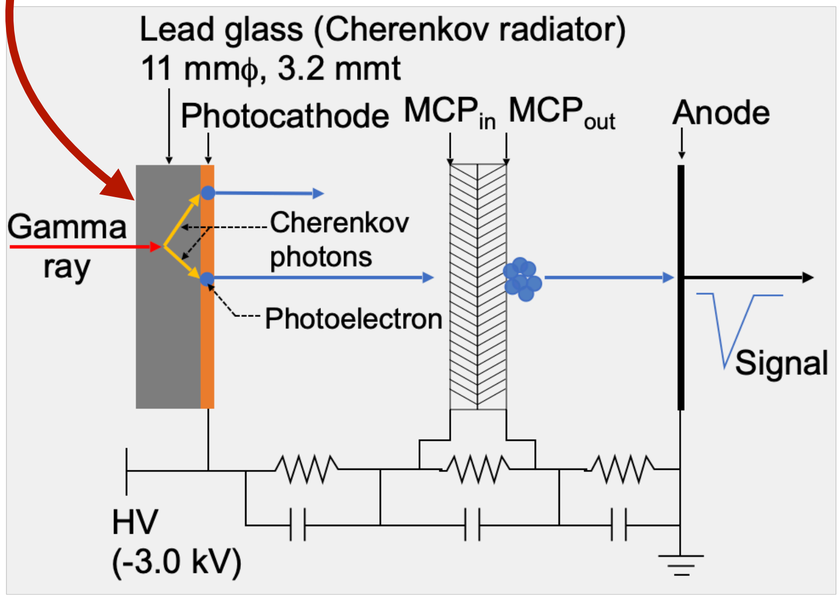
UCDAVIS HAMAMATSU
PHOTON IS OUR BUSINESS

1) Multi-channel dPEI detector modules
2) Ultrahigh timing resolution digitizers
3) Comprehensive computation algorithms

Developing Multi-channel dPEI detector modules

Gamma Detection Material

Current single channel dPEI detector (CRI-MCP-PMT)

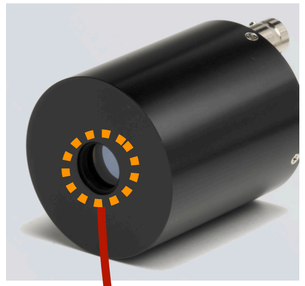


	Lead glass (currently in dPEI detectors)	**Bismuth germanate (BGO)**
Density (g/cm^3)	3.9	7.1
Attenuation coefficient for 511 keV (cm^{-1})	**0.45**	**0.96**
# estimated Cerenkov photon by a 511 keV gamma ray	**~8.7**	**~15.6**
Energy information	**poor**	**enough by scintillation photons**

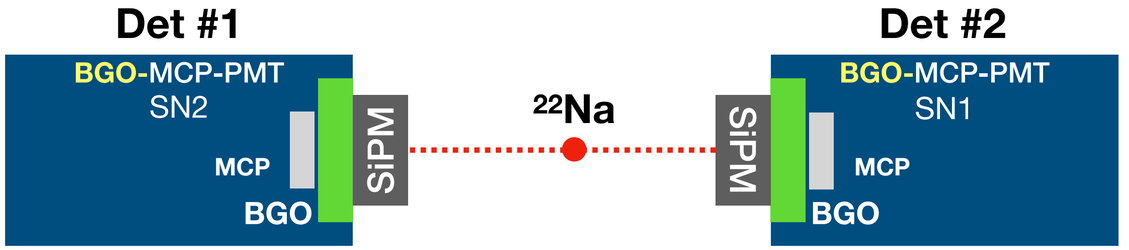
Lead-glass material may not be appropriate for practical dPEI systems.

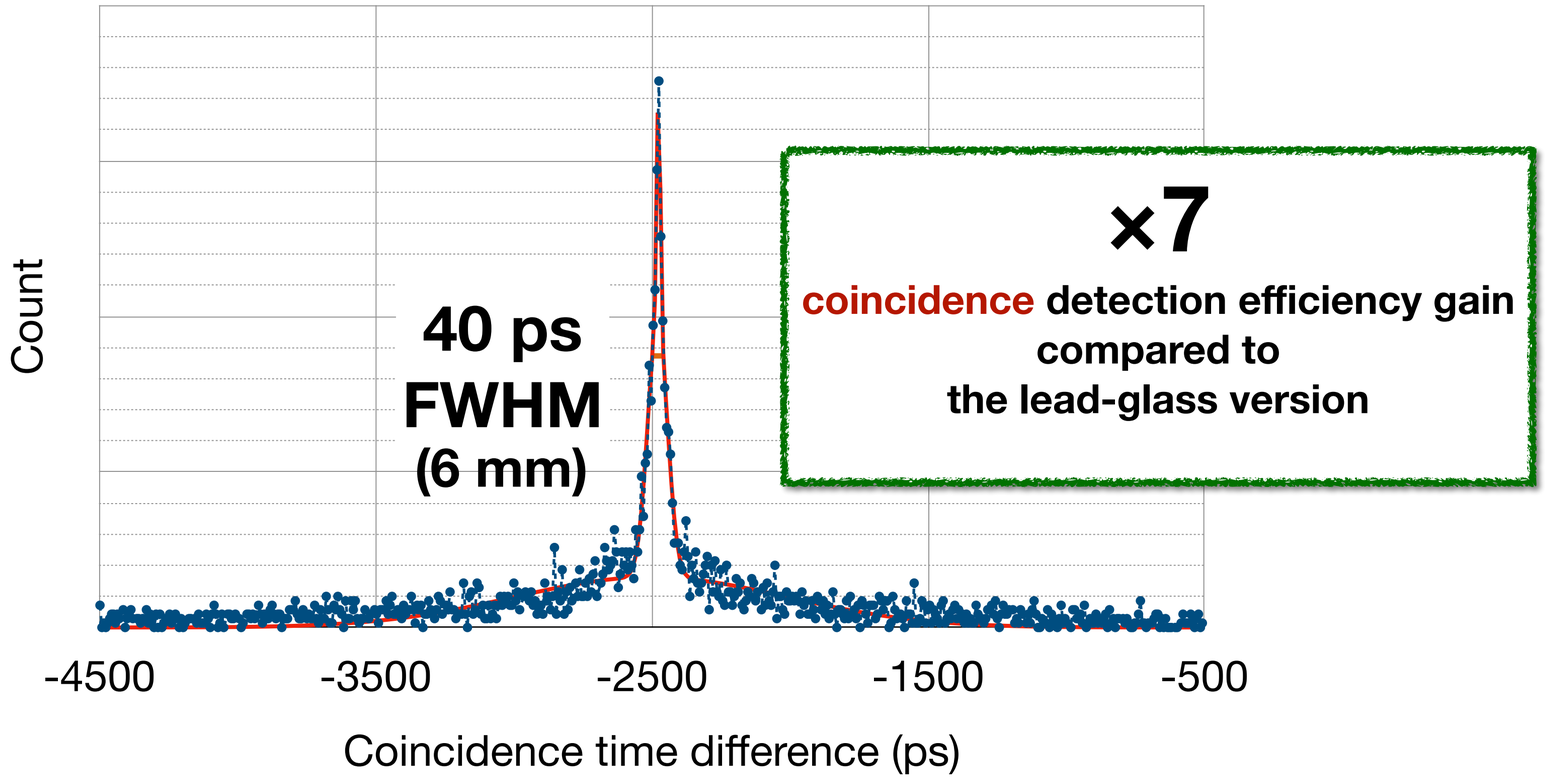
Developing Multi-channel dPEI detector modules

Gamma Detection Material



lead-glass (1st version) → **BGO**





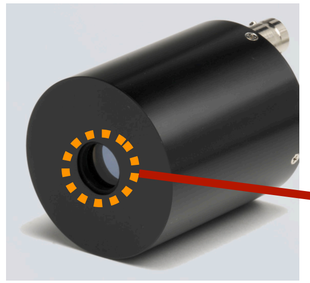
×7

coincidence detection efficiency gain compared to the lead-glass version

Kwon et al. IEEE NSS/MIC/RTSD 2021

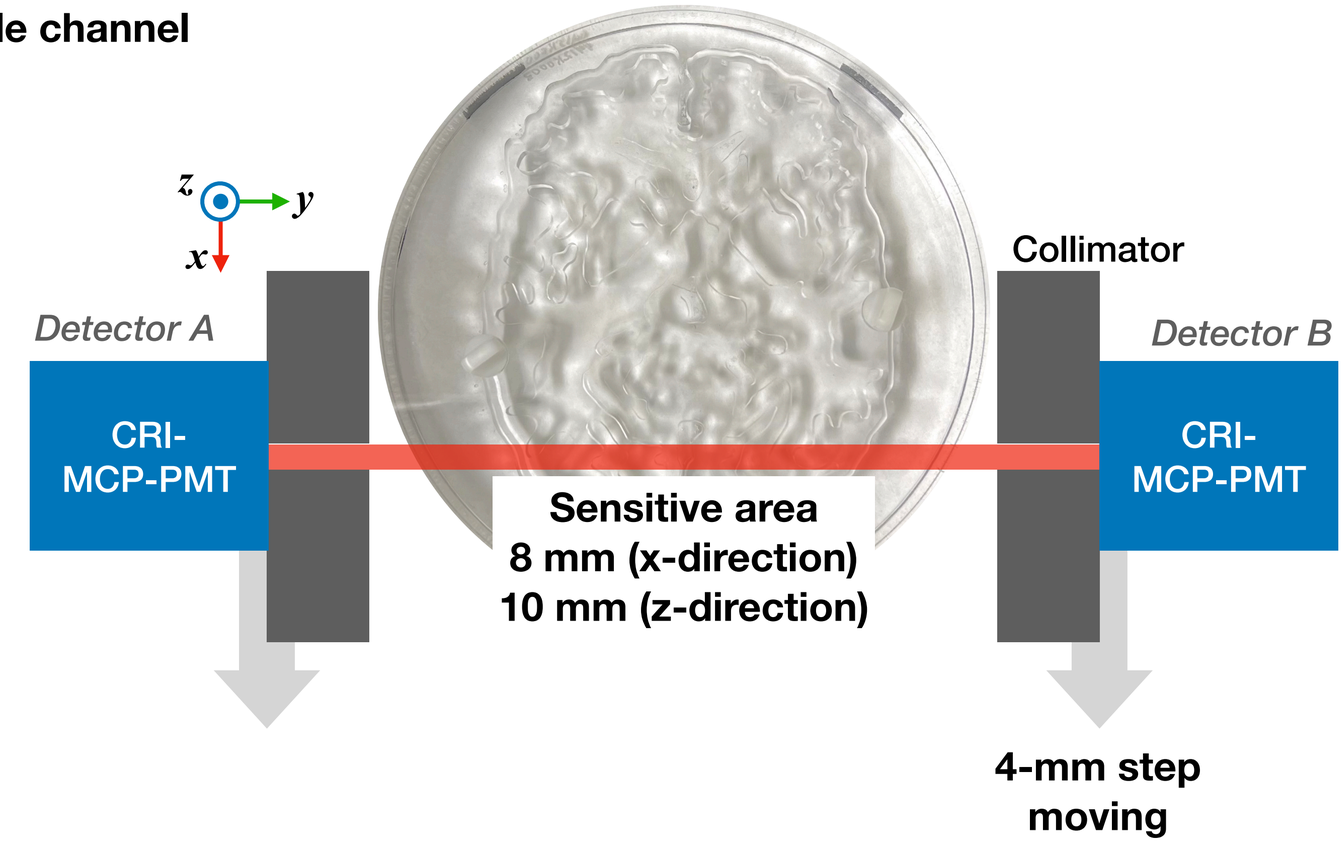
Developing Multi-channel dPEI detector modules

Large-area Multi-channel Modules



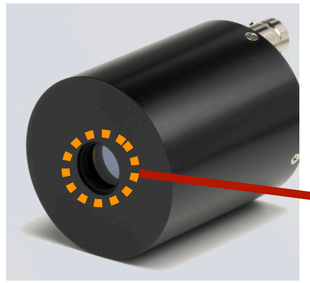
Current single channel dPEI detector (CRI-MCP-PMT)

11 mm diameter
Single channel



Developing Multi-channel dPEI detector modules

Large-area Multi-channel Modules



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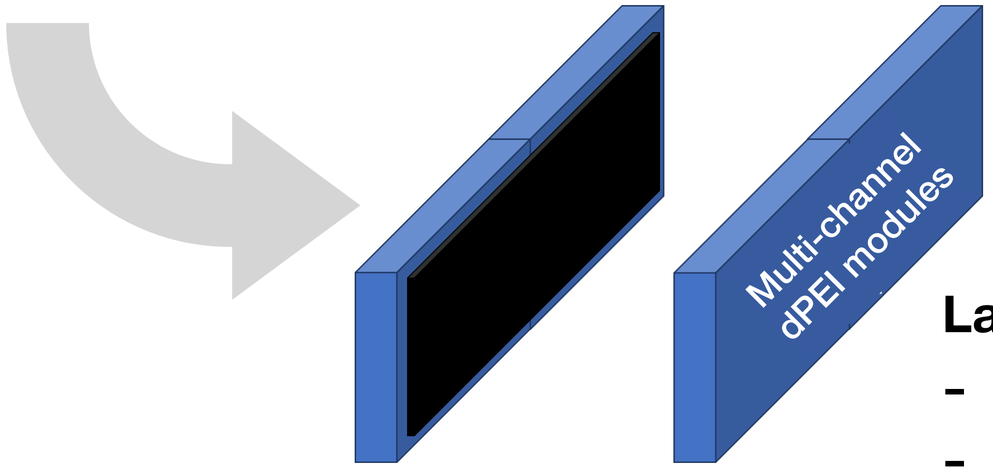
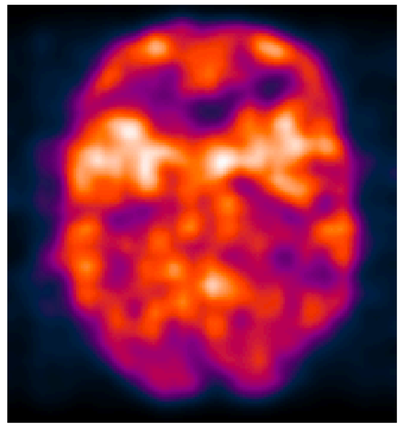


Large-area multi-channel dPEI detector modules

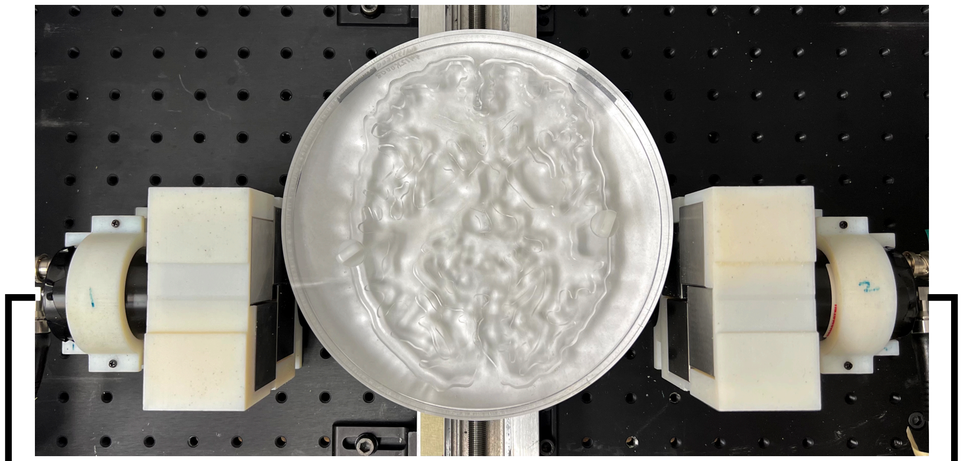
- Cover more area with less or no detector movement
- Collect more events
- Reduce scan time and/or injected dose
- Scan multi-slices simultaneously
- Will be fundamental components for clinical dPEI scanners

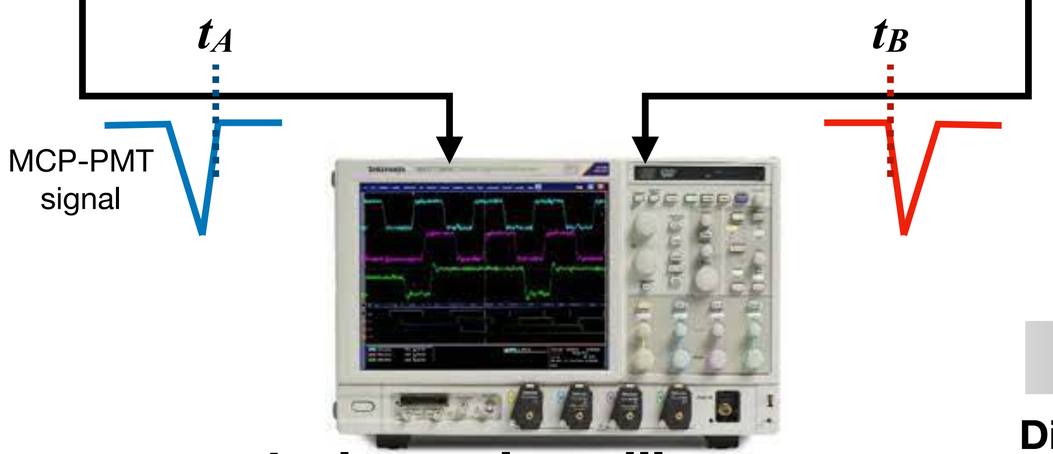
Sun Il Kwon (sunkwon@ucdavis.edu)

Developing Ultrahigh Timing Resolution Digitizers



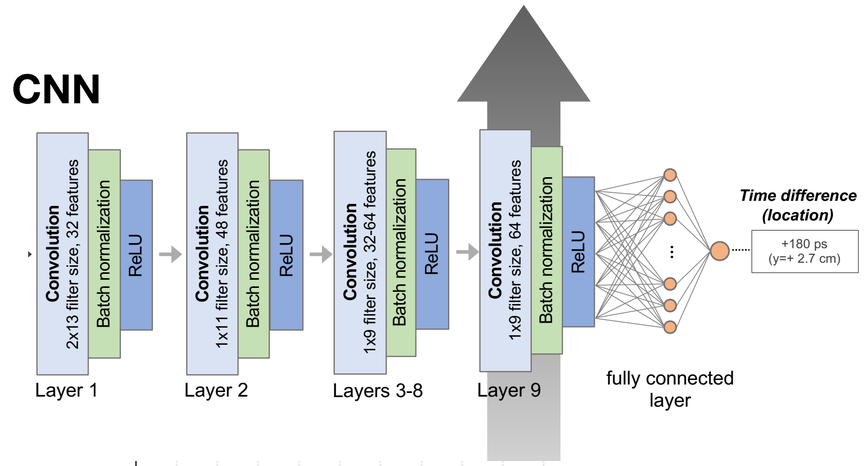
Current version

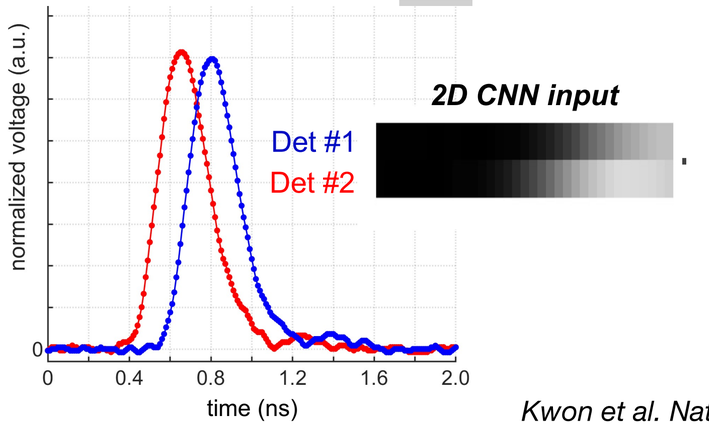




4-channel oscilloscope
12.5 GHz bandwidth, 50 GSPS
>$100,000

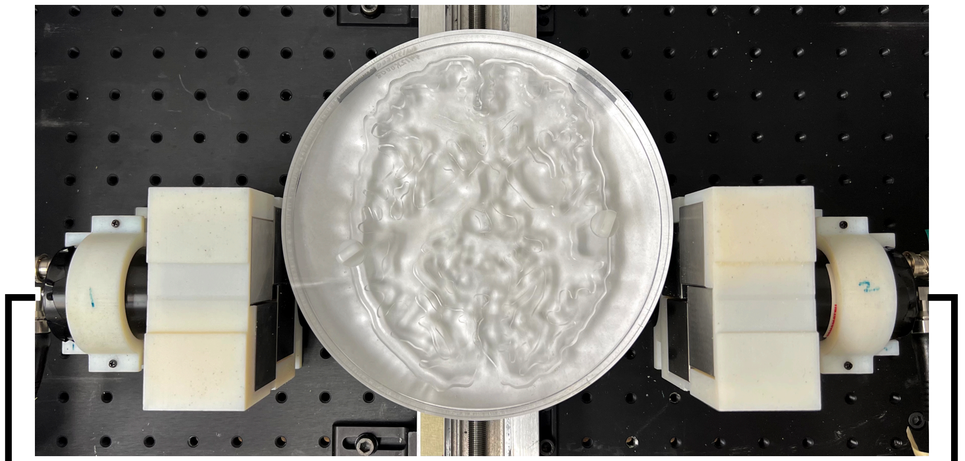
Digitizing each signal
every 20 ps





Kwon et al. Nature Photonics 2021

Developing Ultrahigh Timing Resolution Digitizers



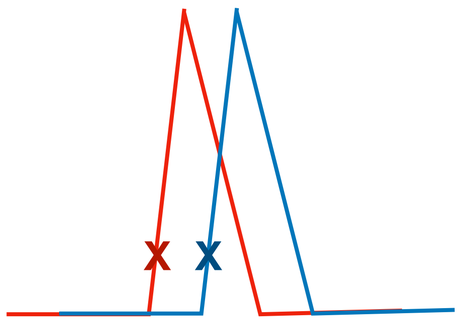
t_A t_B

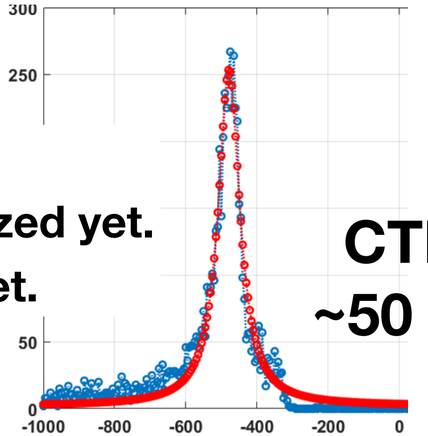
MCP-PMT signal

Multi-channel digitizer using FPGA

FPGA: field-programmable gate array

Digitizing each signal
only first few points





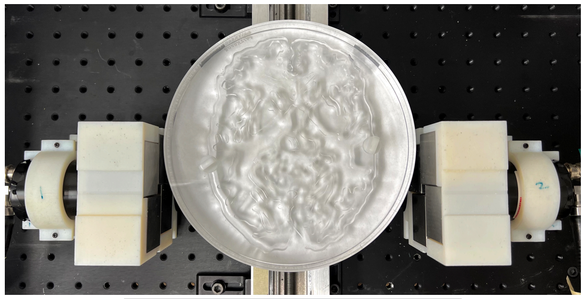
Preliminary result!
Parameters are not optimized yet.
CNN is not applied yet.

CTR ~50 ps

Dr. Daehee Lee

Toward Clinical dPEI Systems

Demonstration of reconstruction-free direct Positron Emission Imaging (dPEI) → **Developing technological and algorithmic foundations** → Clinical dPEI systems



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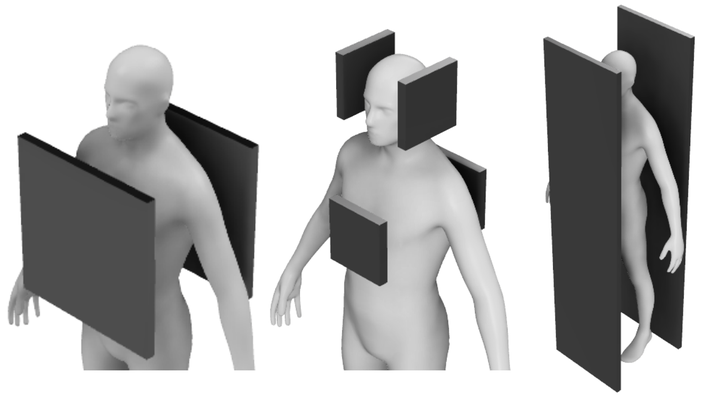

1) Multi-channel dPEI detector modules
2) Ultrahigh timing resolution digitizers
3) Comprehensive computation algorithms

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SSD members

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R01 EB033536

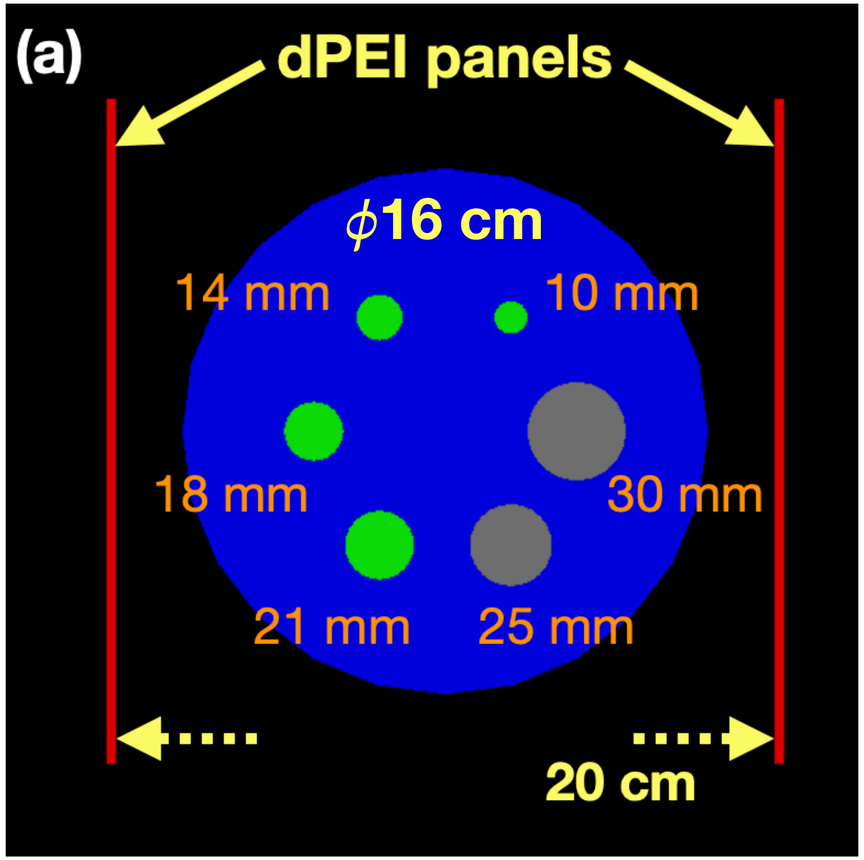
R35 CA197608

R03 EB027268

Thank you!

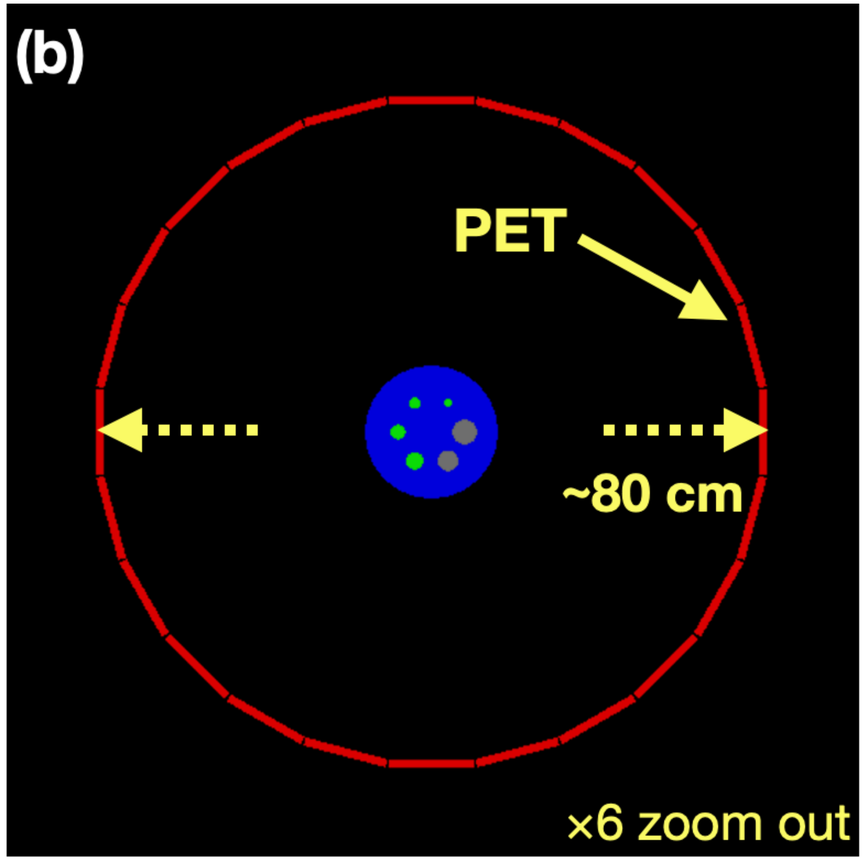
Simulation: dPEI *vs.* 210 ps TOF-PET

Two-panel dPEI scanner



Crystal size: 4.8 × 3.2 (trans-axial) x 10 (axial)
Pitch: 5.02 mm

TOF-PET (210 ps) clinical scanner



Crystal size: 4.8 × 10 (trans-axial) x 10 (axial)
Pitch: 5.02 mm

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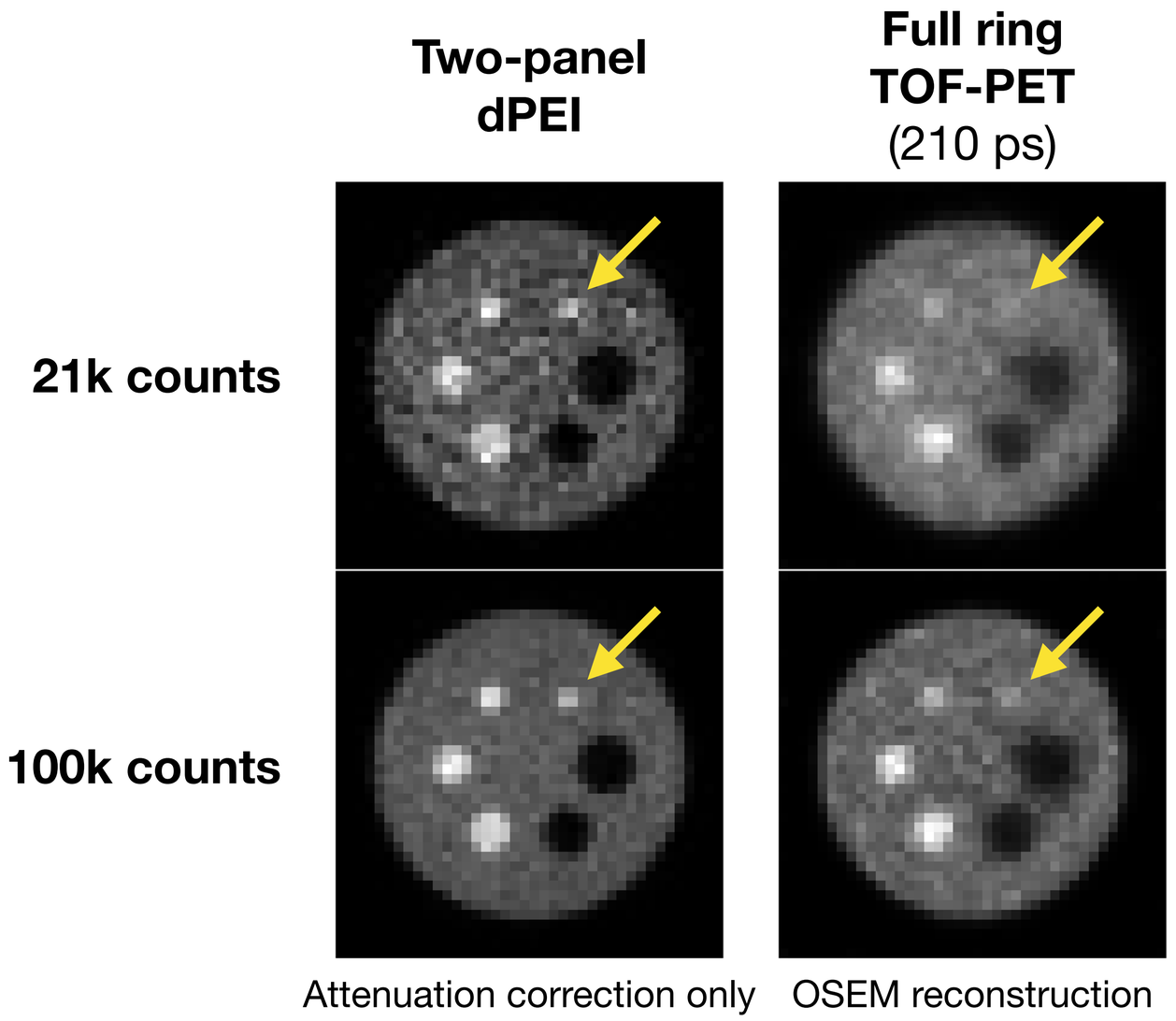
Simulation: dPEI *vs.* 210 ps TOF-PET



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