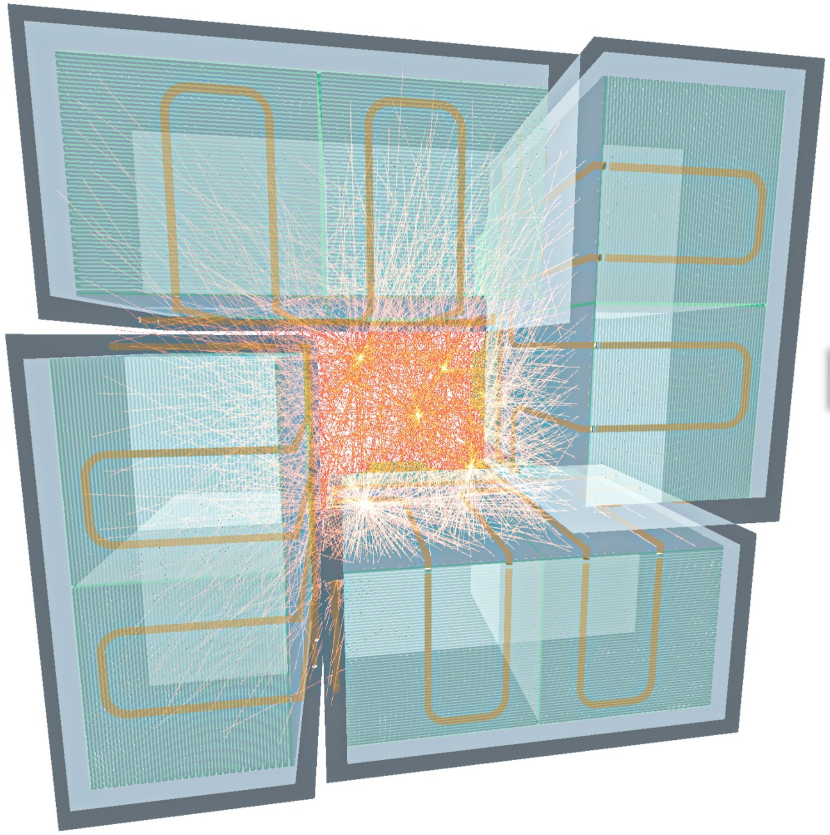


Simulation of the next generation PET scanner with monolithic silicon pixel sensors

Jihad Saidi

On behalf of the 100µPET collaborators

4th Allpix Squared User Workshop
22–23 May 2023
DESY, Hamburg, Germany

100µPET
Molecular Imaging at Ultra-High Resolution

Faculty of Science
Physics department

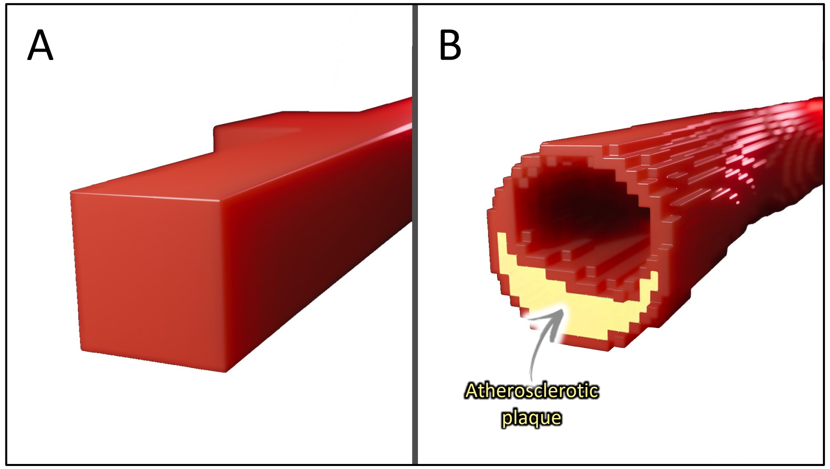
UNIVERSITÉ DE GENÈVE

The 100µPET Project

SNSF SINERGIA granted project to deliver a small-animal PET Scanner with monolithic silicon pixel detectors and pioneer ultra-high resolution imaging

Talk Outline:

- Introduction to PET Imaging
- Simulation’s workflow showcase
- Simulation’s results
- Imaging capabilities



Images: © Xavier Ravinet - UNIGE

With today's PET technology, small blood vessels can only be visualized in their entirety (A). The proposed new PET technology will allow the study of changes in the walls of small blood vessels, such as atherosclerotic plaques (B).

The people behind this

100μPET
Molecular Imaging at Ultra-High Resolution

The 100μPET project

Giuseppe Iacobucci
- project P.I.
- System design

Lorenzo Paolozzi
- Sensor design
- Analog electronics

Didier Ferrere
- System integration
- Laboratory test

Sergio Gonzalez-Sevilla
- System integration
- Laboratory test

Martin Walter
- P. I.

Michäel Unser
- P. I.

Yannick Favre
- Board design
- RO system

Stéphane Débieux
- Board design
- RO system

Franck Cadoux
- Mechanical design

Thanushan Kugathasan
- Lead chip design
- Digital electronics

Pablo Jané
- Nuclear Medicine
- PET imaging
- Translational imaging

Pol del Aguila Pla
- Statistical signal processing

Roberto Cardella
- Sensor design
- Laboratory test

Mateus Vicente
- System integration
- Laboratory test

Jihad Saidi
- Detector simulation
- Data analysis

Luca Iodice
- Chip design
- Firmware

Vincent Taelman
- Molecular biology
- Radiopharmacy

Aleix Boquet-Pujadas
- Signal/image processing
- Physical modeling

Antonio Picardi
- Chip design
- Firmware

Stefano Zambito
- Laboratory test
- Data analysis

Matteo Milanesio
- Laboratory test
- Data analysis

Théo Moretti
- Laboratory test
- Data analysis

Carlo A. Fenoglio
- Chip design
- Firmware

Chiara Magliocca
- Laboratory test
- Data analysis

Jordi Sabater
- Detector simulation
- Laboratory test

Rafaella Kotitsa
- Sensor simulation

Andrea Pizarro
- Laboratory test
- Data analysis

UNIVERSITÉ DE GENÈVE

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EPFL

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Marzio Nessi
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European Research Council

Sinergia

ATTRACT

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Positron Emission Tomography (PET)

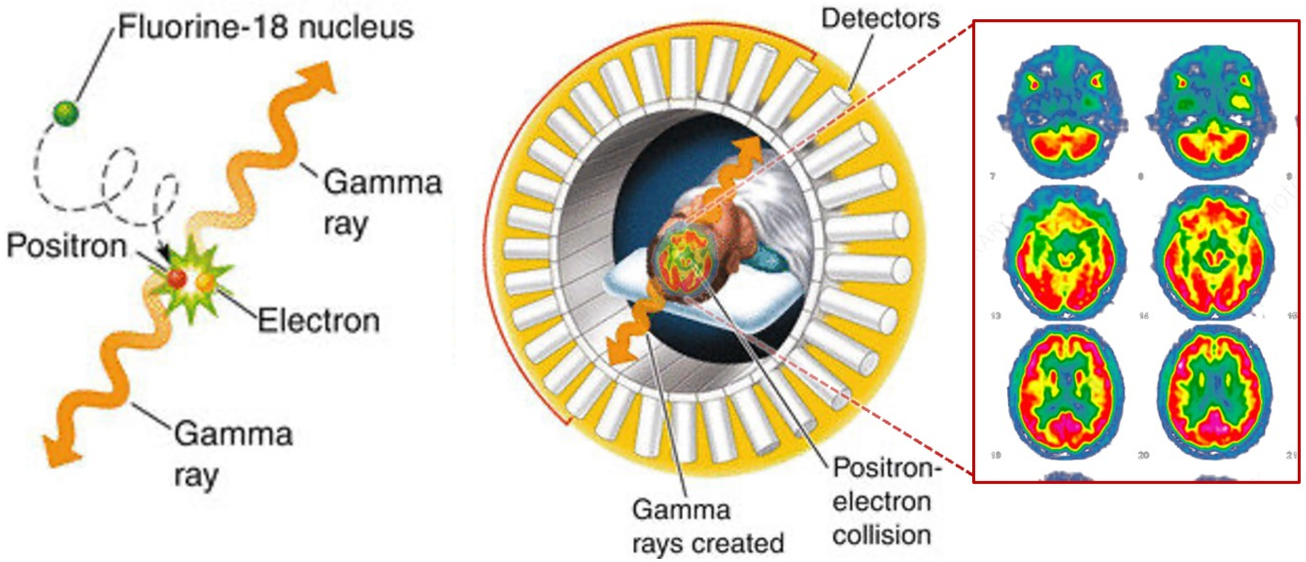
Imaging method that enables studies of metabolic mechanisms.

A radiotracer, β^+ source, is injected into body.

Positron from source and electron from tissues annihilate and create pair of 511 keV photons.

Detection of both photon in coincidence allows the creation of a Line of response (LOR)

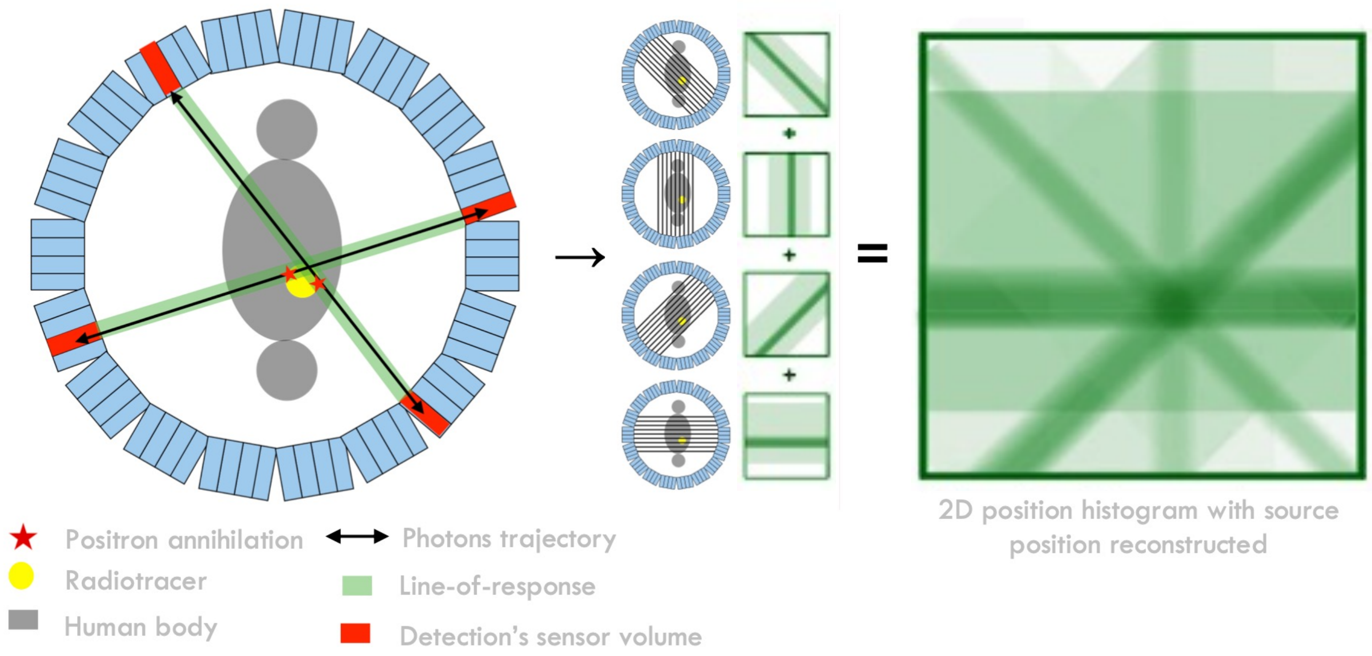
Figure from DOI:10.1007/978-1-4614-1997-6_82



Positron Emission Tomography (PET)

Detection of both photon in coincidence allows the creation of a Line of response (LOR)

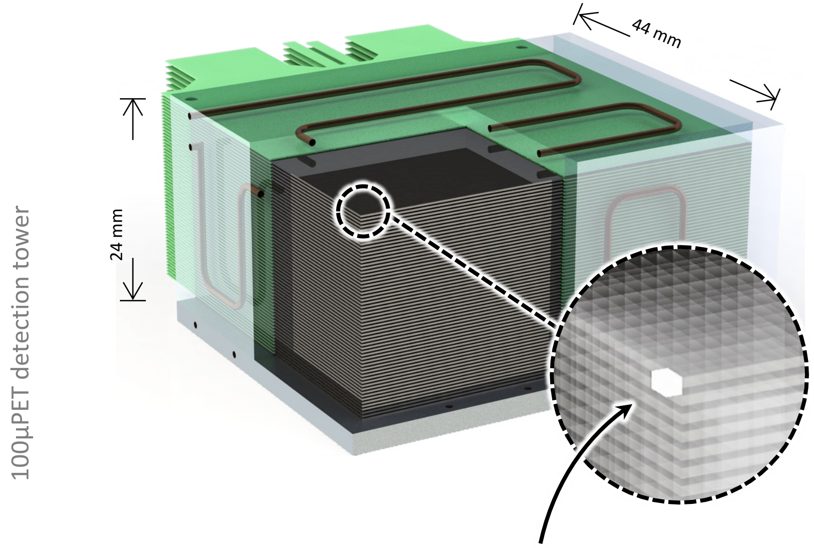
Combination of multiple LORs allows the reconstruction of the radionuclide distribution within Body



Monolithic Silicon Pixel sensor for PET

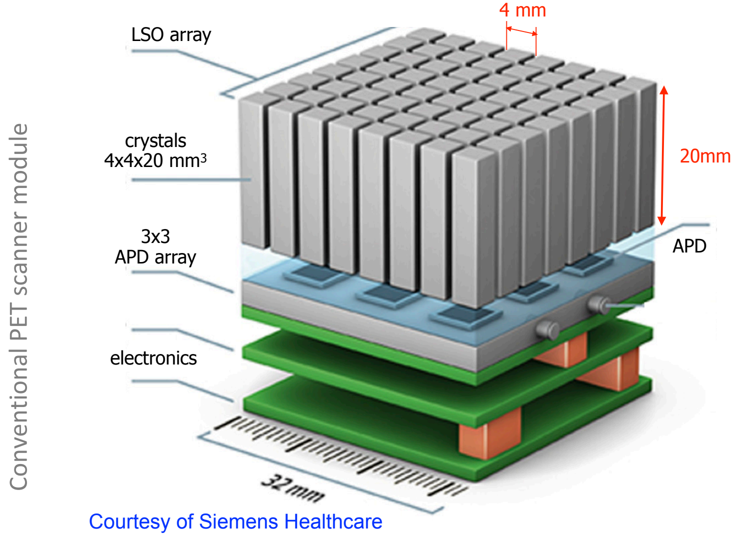
With multiple layers of Monolithic Silicon pixel detectors,
smaller sensitive volume element leads to smaller voxel volumes

Sensitive cell volume : 0.004 mm3



Pixel pitch: 100 µm | Thickness: 400 µm

Sensitive cell volume : 320 mm3



Crystal pitch: 4000 µm | Thickness: 20000 µm

Monte Carlo Simulations with Allpix^2

Allpix Squared allows streamlined simulations of
specific particle sources with complex silicon detector architectures.

- Custom sources generation,
- Detector geometry parameter scan:
  - Effect of High Z Material
  - Effect of Al Cooling thickness
  - Effect of Flexible Printed Circuits (FPC) thickness
- Figures of merit evaluated:
  - Detection Efficiency
  - LOR Resolution
  - Image Reconstruction

Monte Carlo Simulations with Allpix^2

More information from MC History were required, changes on `SensitiveDetectorActionG4` and `TrackInfoG4` :

- MC Tracks:
  - Initial and final direction added
- MC Particles:
  - Initial and final direction added
  - Kinetic and Total Energies added

100µPET Simulations with Allpix^2

Custom Module :

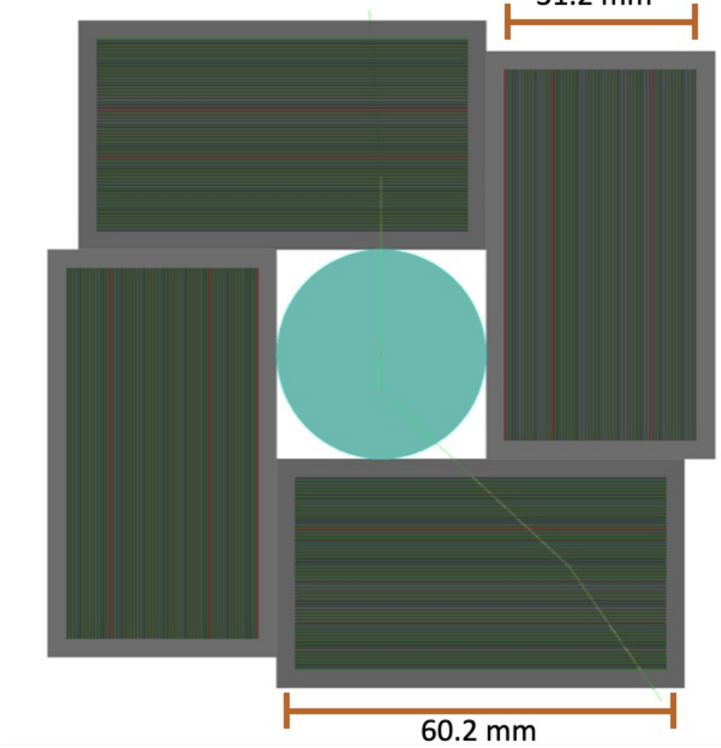
- Inputs: `[MCTrack,MCParticle,PixelHit]Messages`
- Performs Clustering with Geometric center or Charge weighted
  (Logic based on *`DetectorHistogrammer's doClustering()`*)
- Simulates scanner's logic to establish LORs
- Compatible with multithreading (Very fast)
- Outputs:
  - .root file with TTree containing information for data analysis
  - binary and text files with Expected Scanner output data
    Contains LOR end points coordinates and charge

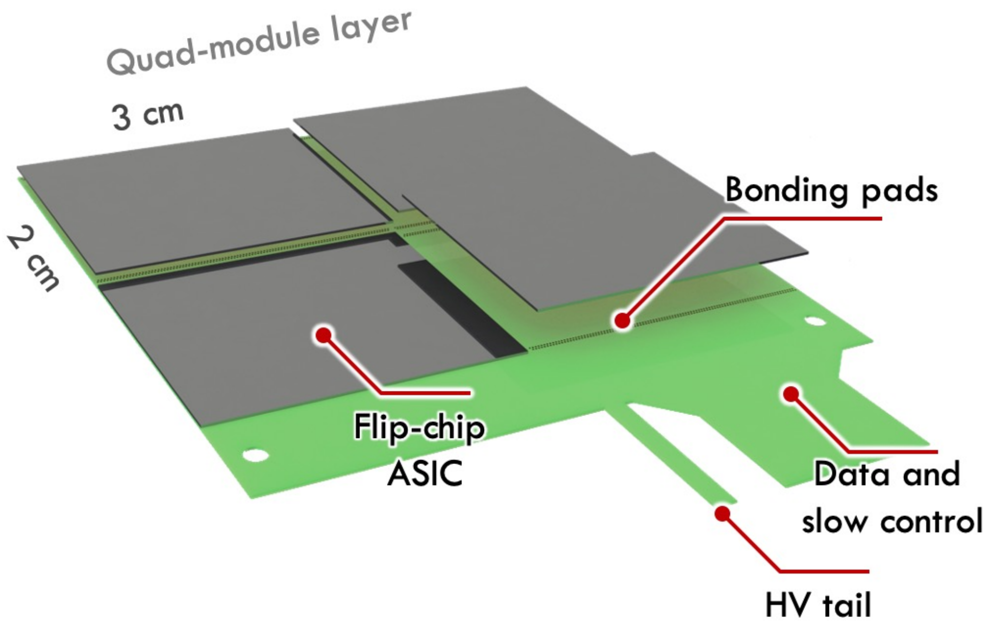
Current Format :

```
X Y Z Charge
X Y Z Charge
```

Simulated Geometries

Bismuth Geometry





- 34 mm square cavity
- 3 mm thick Al Cooling
- 4 Sectors
- 60 Layers per Sector
  - 200 μm Kapton (FPC)
  - 270 μm ASIC (250 μm depleted Si)
  - *50 μm Bismuth (31.2 vs 28.2 mm)*
- Thin FPC with 4 Flip-chip integrated ASICs
- Silicon Layer dimension : (60.2 x 44.2)mm
  - Hexagon 65 μm length (111,7 μm x 97.73 μm)

100μPET
MOLECULAR IMAGING AT ULTRA-HIGH RESOLUTION

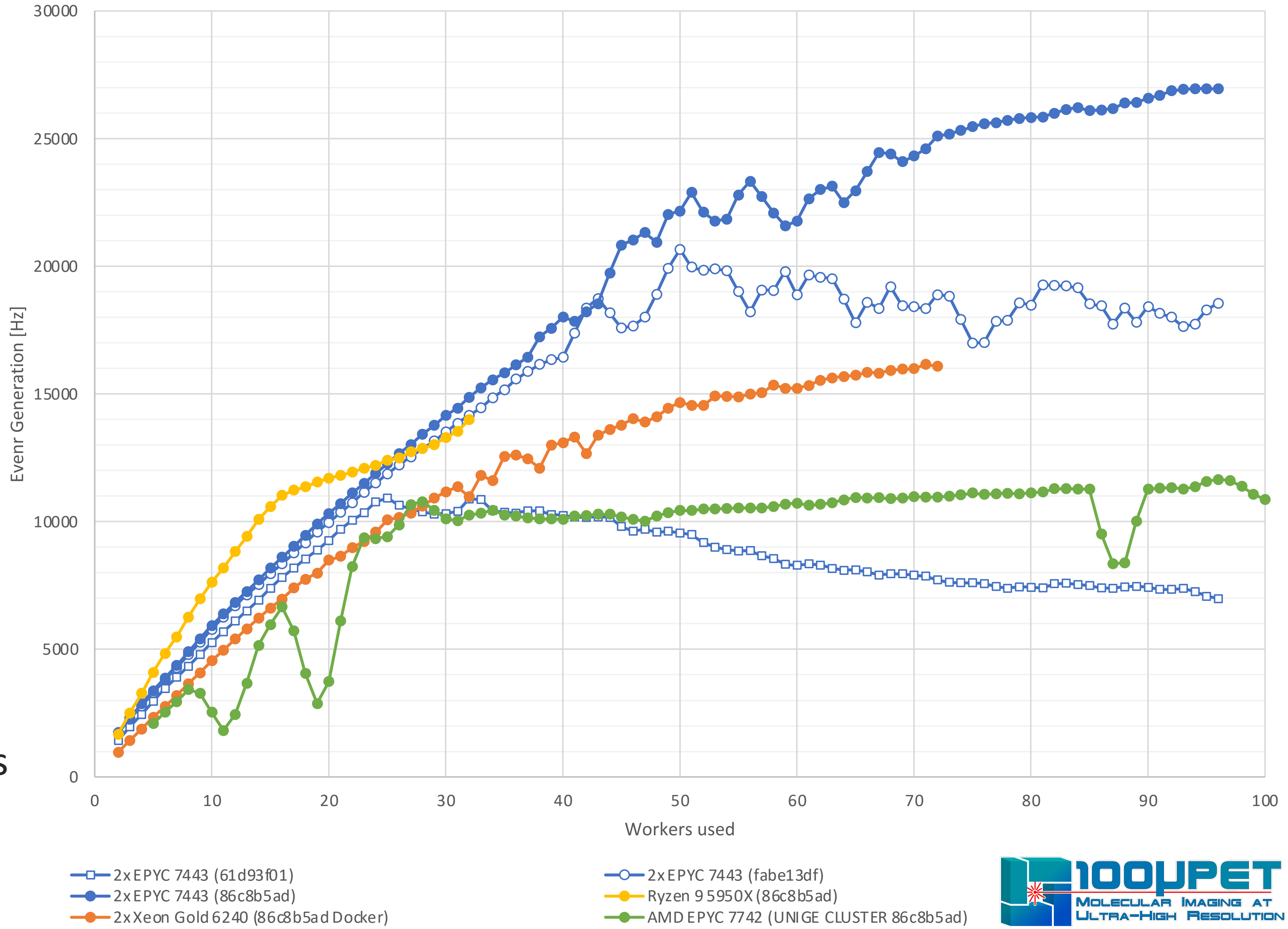
Performance Benchmark

Big Improvements from:

- Choosing right type of module
- Clever code design with root_lock

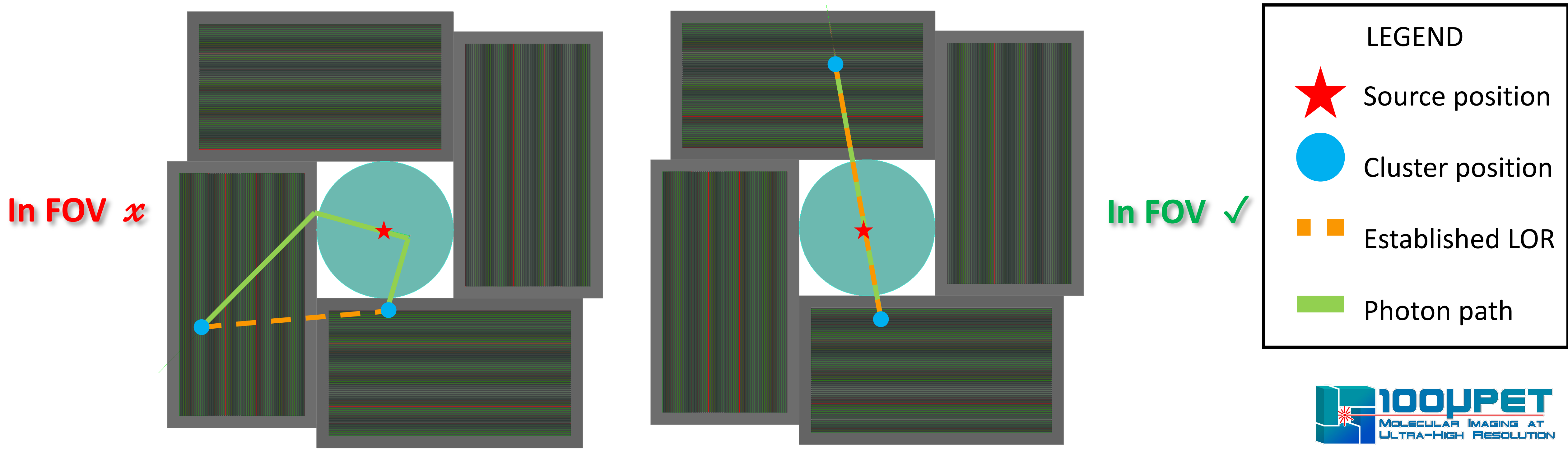
For 100µPET Project:
12 kHz + 15 kHz at the moment

ONE Real life 20 min PET scan Simulation would require 3 days of runtime ($4 \cdot 10^9$ events)



Efficiency Study

Efficient Event: has only 2 Pixel Clusters recorded in different scanner's sectors and the LOR crosses the Field of View (FOV).



Efficiency Study

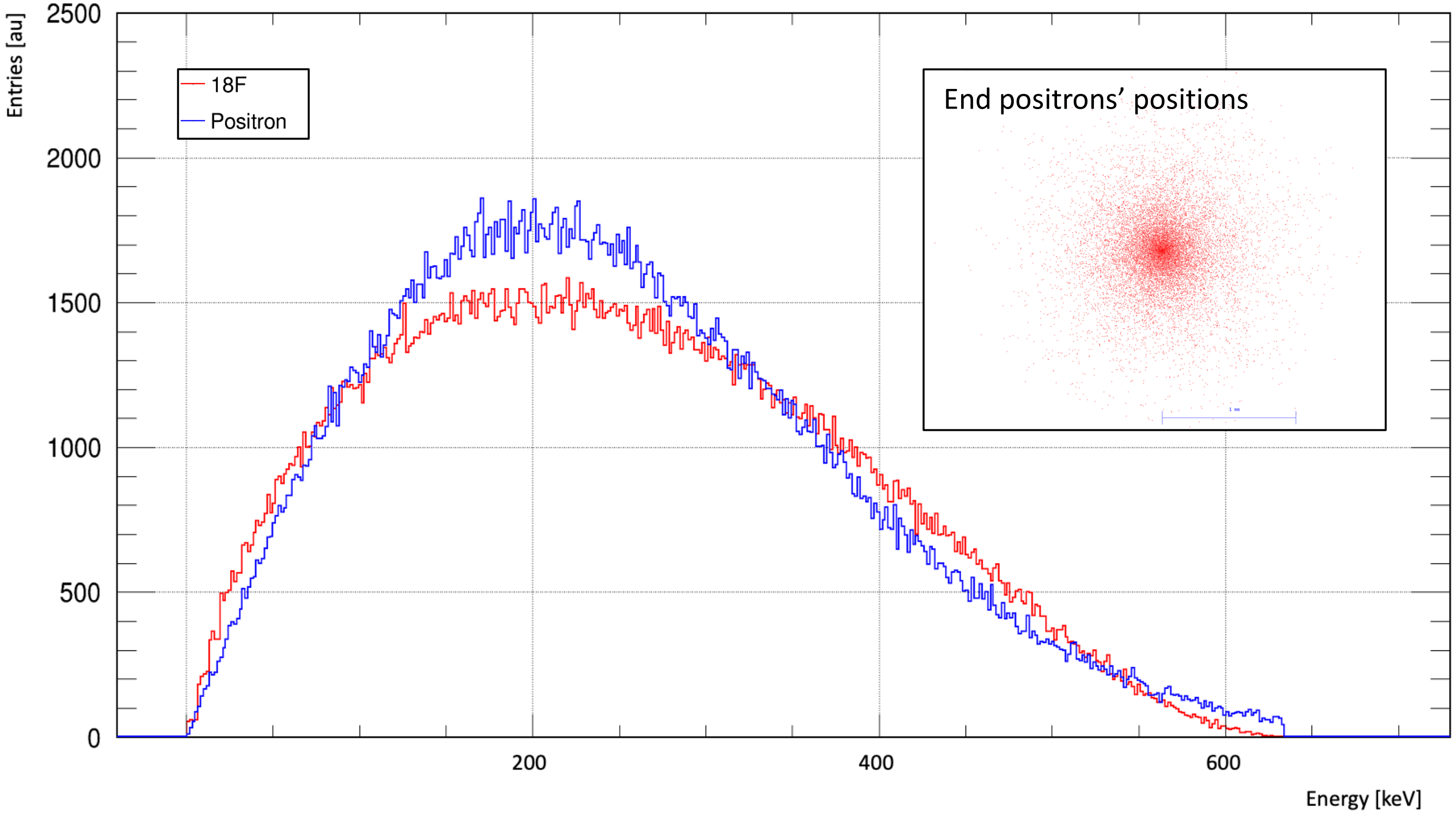
Efficient Event: has only 2 Pixel Clusters recorded in different scanner's sectors and the LOR crosses the Field of View (FOV).

Simulated Point Source at center of the FOV with custom Energy Spectrum.

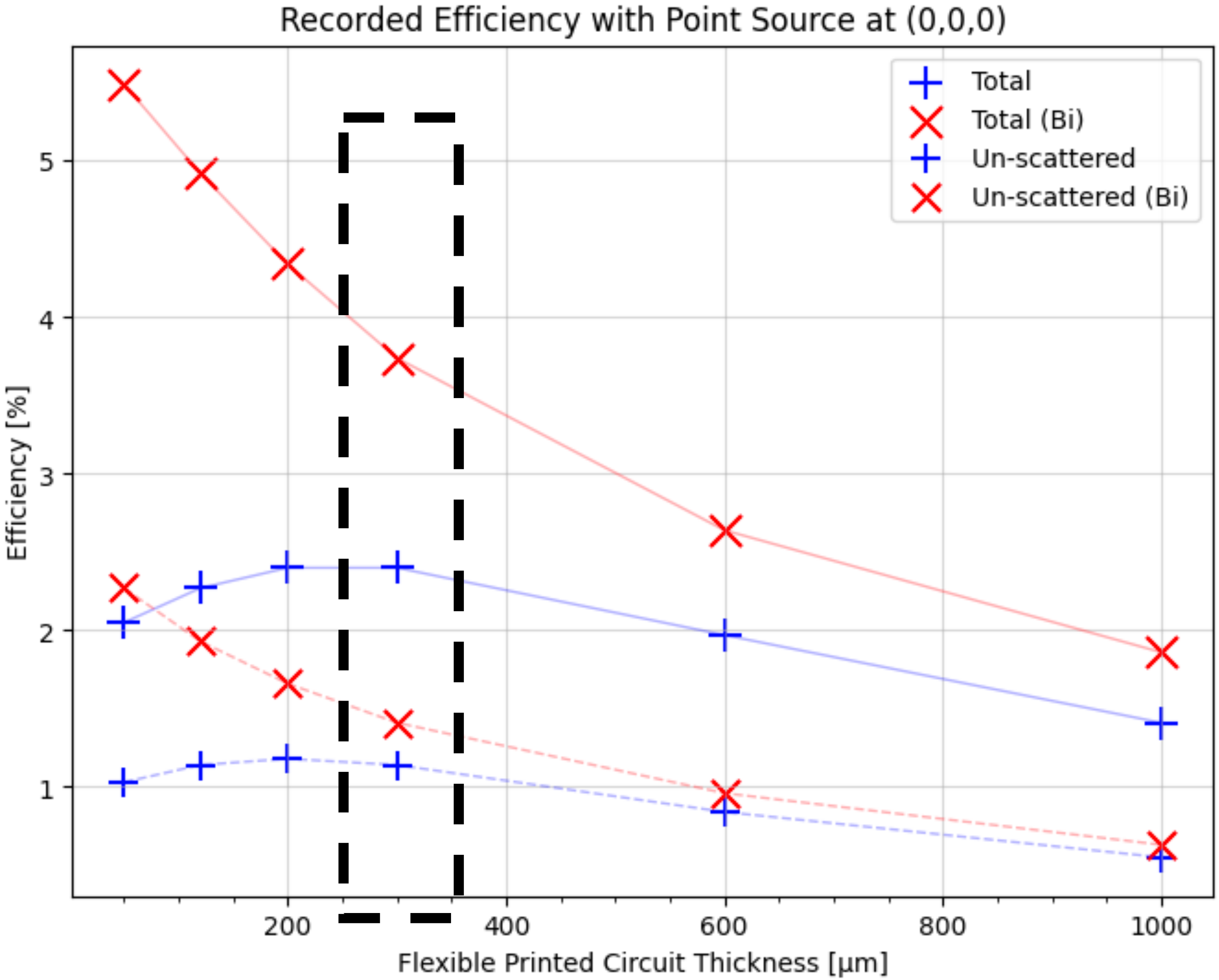
Studied the impact of different parameters on efficiency varying One Factor At the Time (OFAT) :

- Kapton Thickness
- Cooling Wall Thickness
- THR value

Energy Spectrum Comparing Positron Source and base ^{18}F Ion source



Example : Effect of Kapton Thickness



Total Events Simulated : 20 M

Un-Scattered Efficiency :
Events for which Each clusters is within 250 μm of the original photon direction

At 200μm Kapton thickness:
Higher absolute efficiency with Bi
But standard geometry has lower scattered fraction
Tradeoff between quantity and quality for reconstruction

100μPET
MOLECULAR IMAGING AT ULTRA-HIGH RESOLUTION

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Point Spread Function

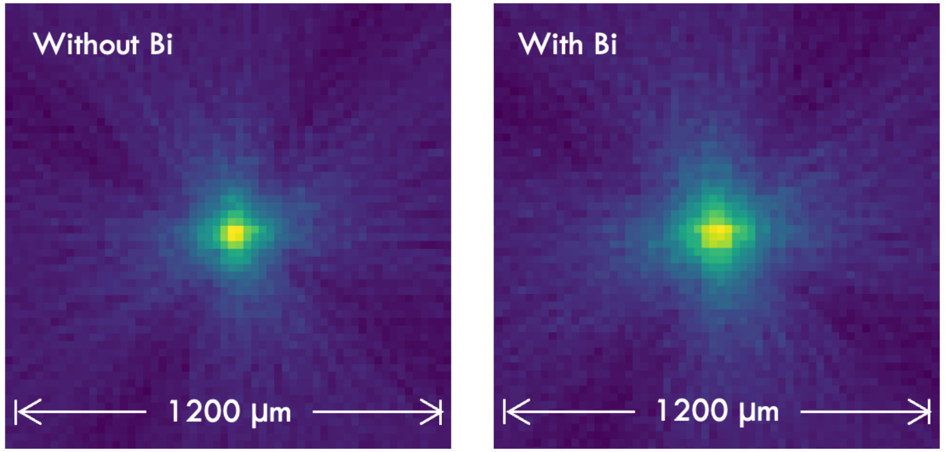
The point spread function (PSF) informs on how a point source will spread and blur after reconstruction due to physical phenomena and detector geometry.

Reconstruction with Filtered Back Projection of a point source at the centre of field of view (0,0,0) gives

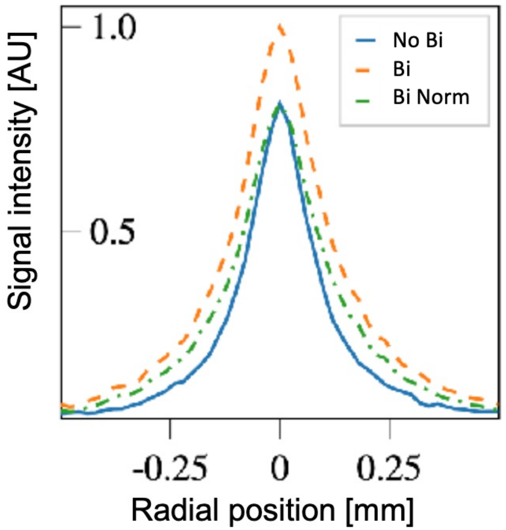
0.13±0.02 mm	without bismuth	
0.17±0.02 mm	with	bismuth

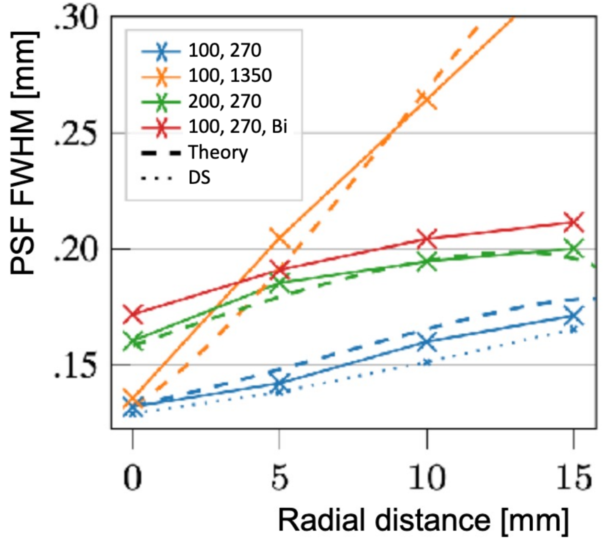
Spatial Resolution : $PSF^2 \cdot DOI$

0.0079 mm^3	without bismuth	
0.0150 mm^3	with	bismuth



Reconstructed point source
Bin size: 20 µm

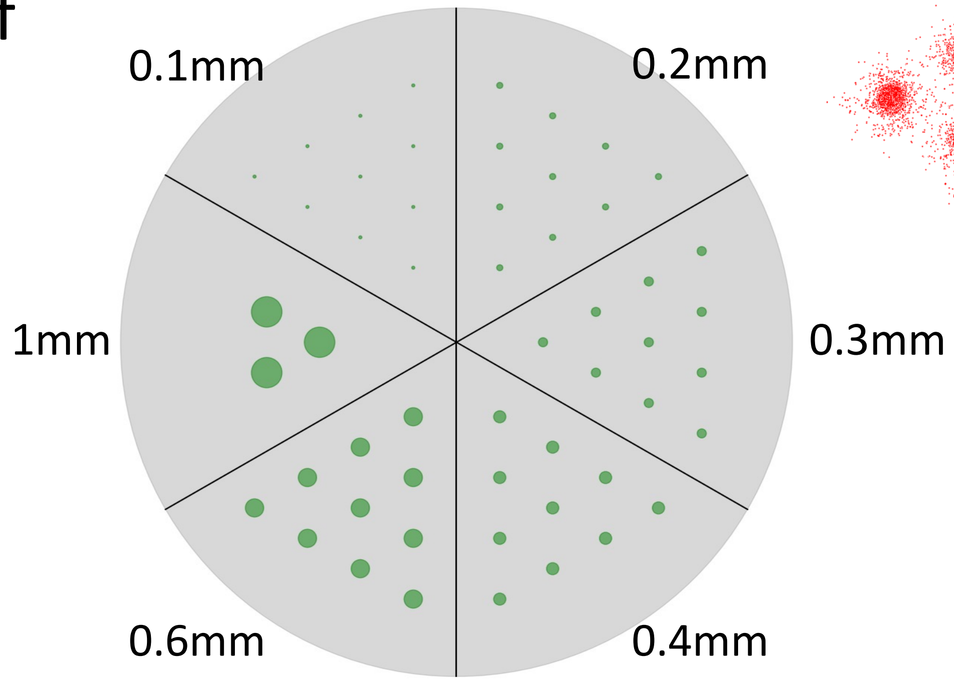


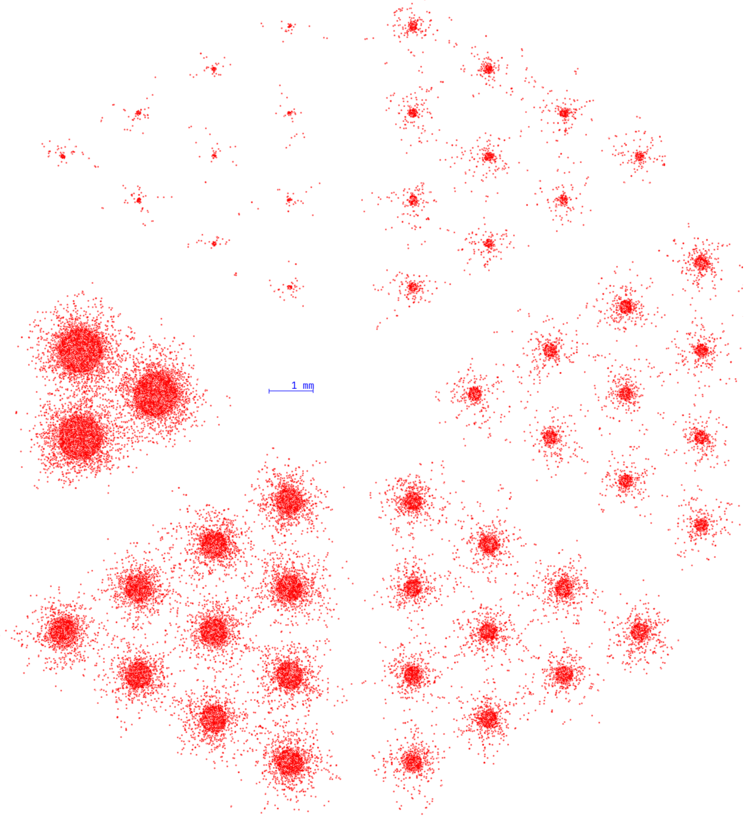


100µPET
Molecular Imaging at Ultra-High Resolution

Derenzo Phantom

- The Derenzo phantom allows for qualitative assessment of imaging with a detector
- Each Sector has rods of different diameter
- Rod spacing is fixed to 1 mm
- Available as 2D and 3D source

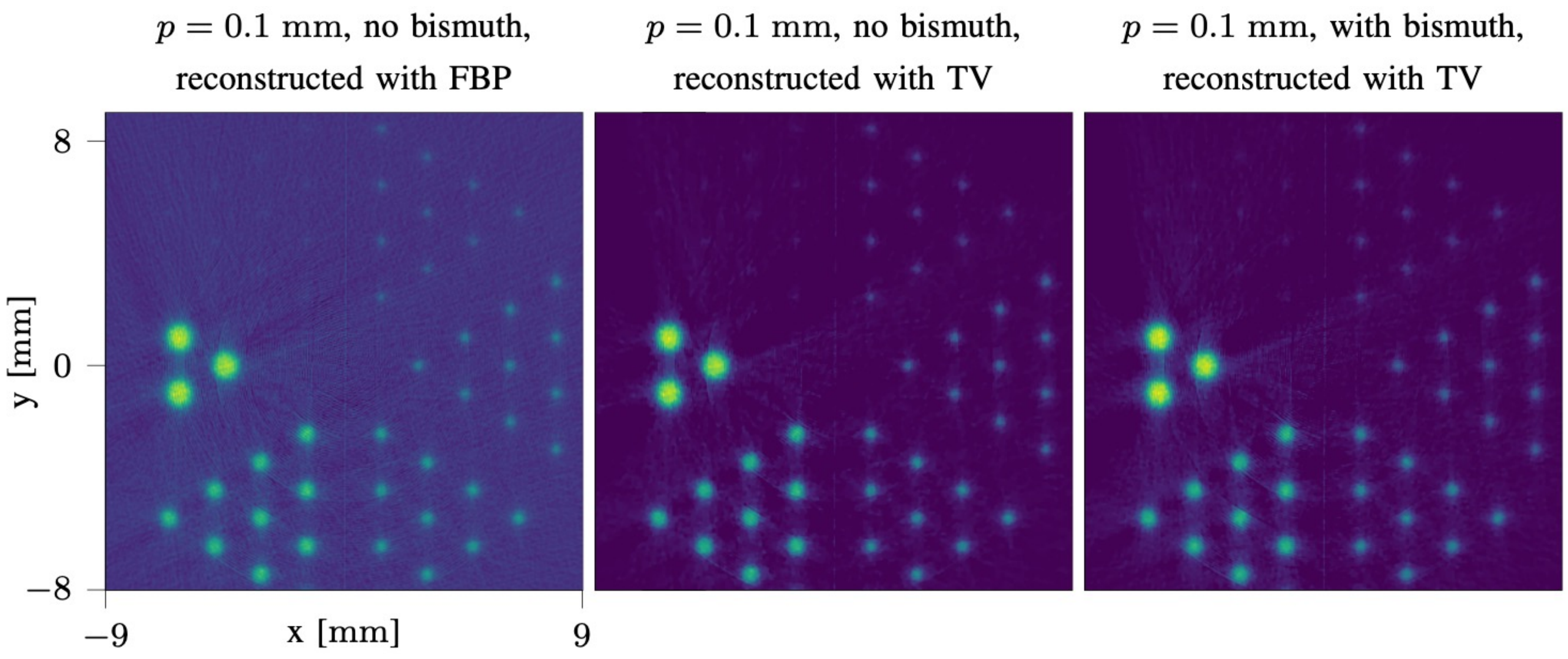




Derenzo Reconstruction Comparison

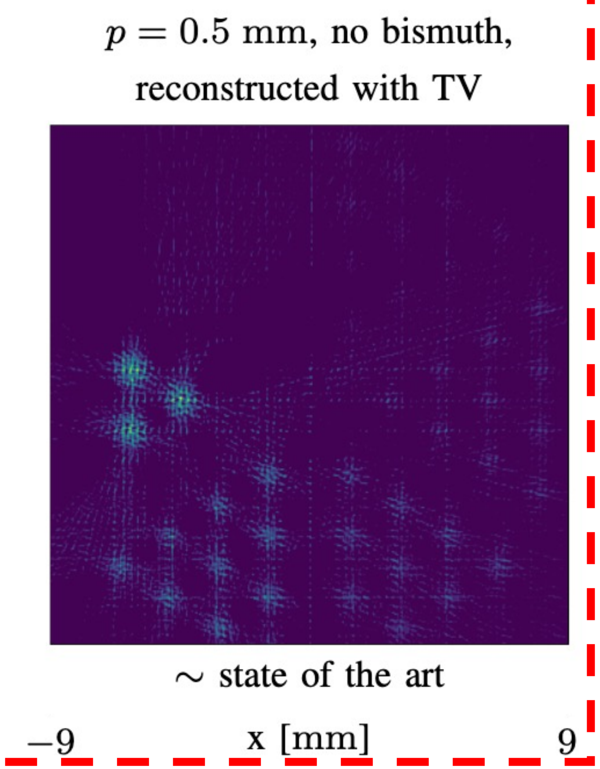
100µPET scanner

100 µm x 100µm x (470,520) µm



State of the art crystal detector

500 µm x 500 µm x 2 mm



- 100µPET clearly shows 0.2 mm rods with little artifacts

doi:10.18112/openneuro.ds002179.v1.1.0

Hi-res MRI/CT image templates

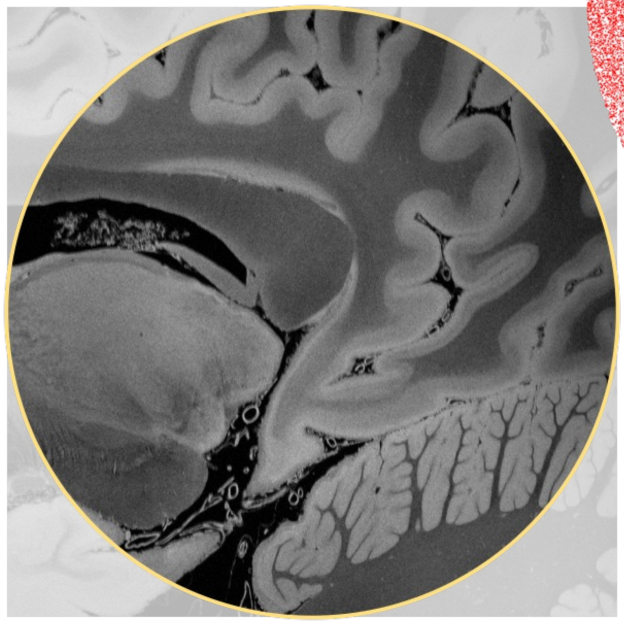
7 Tesla MRI sagittal image of brain at 100 μm used as template for source in Allpix

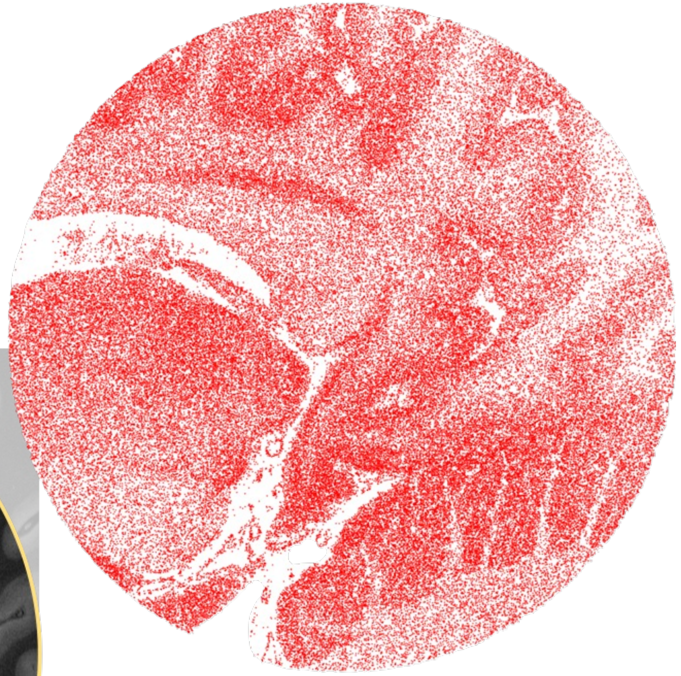
68 x 68 mm^2 resized to 34 x 34 mm^2

Images is now a collection of plane square sources of 50 μm

Activity is given by the original image grayscale

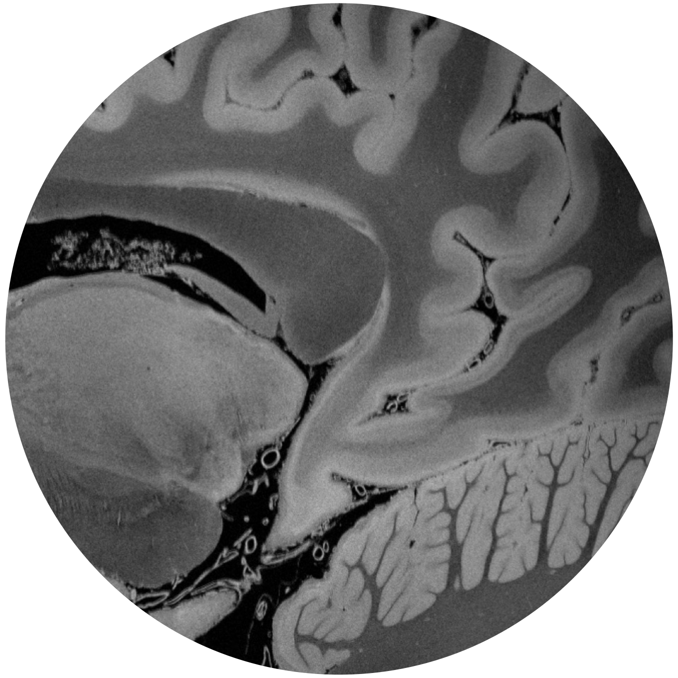
Positron mean free path is not applied here

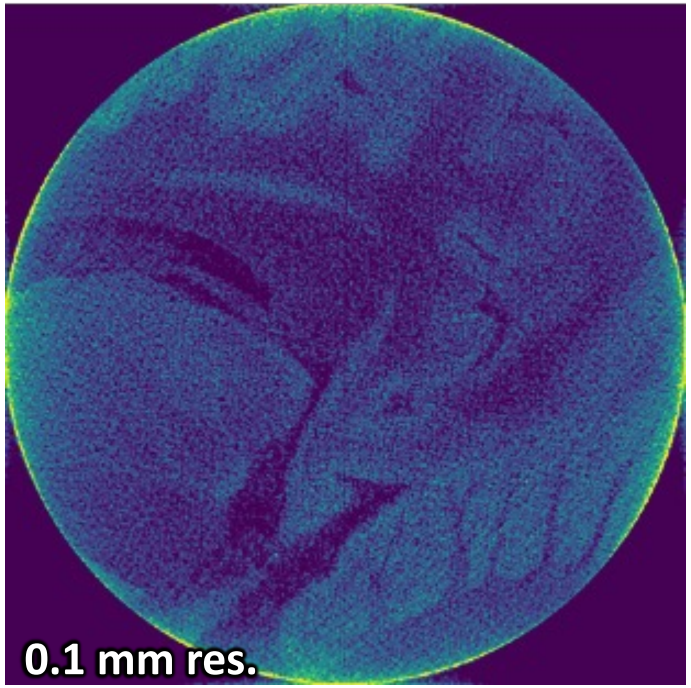




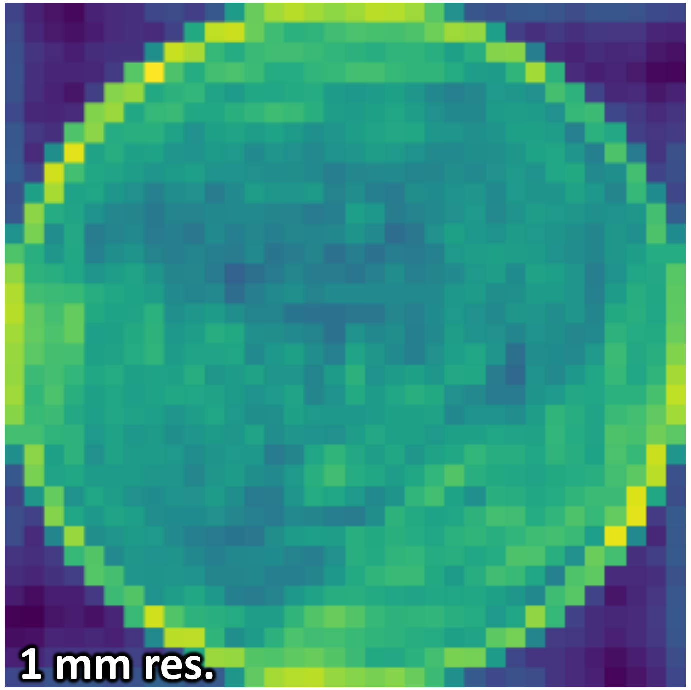
Hi-res MRI/CT image Reconstruction

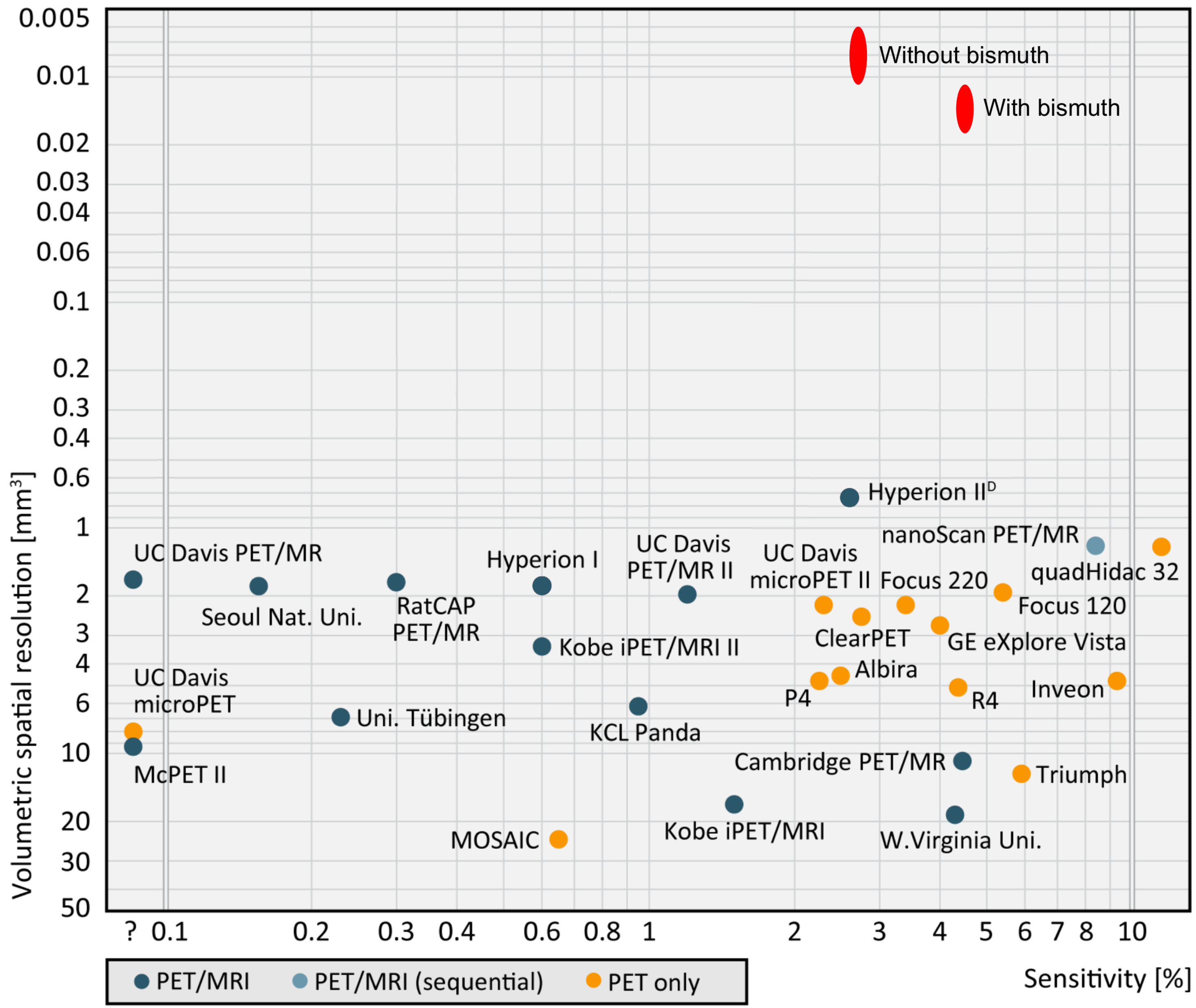
100µPET scanner
100 µm x 100µm x (470,520) µm





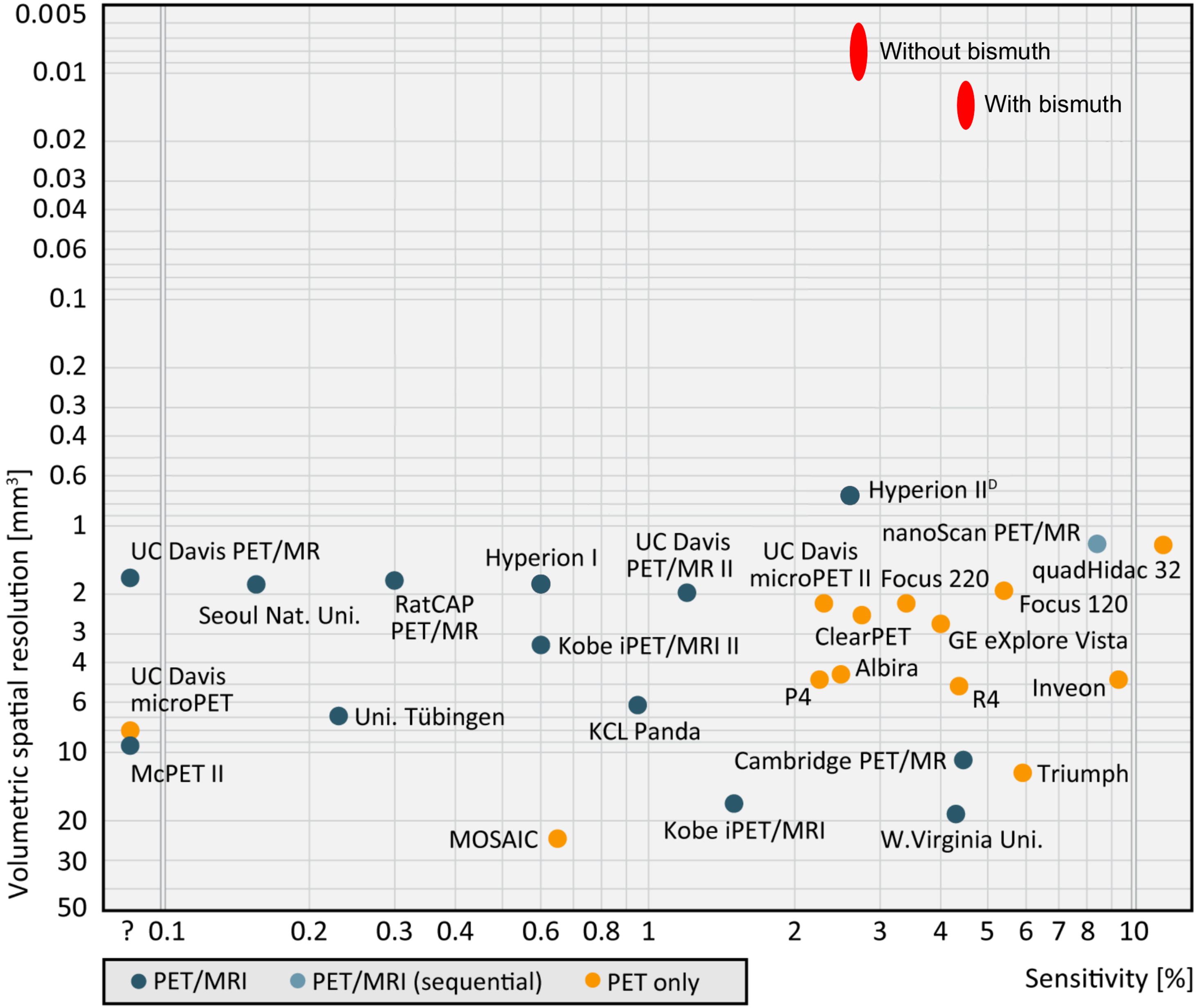
State of the art crystal detector
500 µm x 500 µm x 2 mm





Conclusions

- Detection Efficiency from 2.5 to 4.5 %
- Spatial resolutions from 0.0079 to 0.015 mm^3
- The 1000µPET Scanner is expected to be delivering unprecedented performance in the PET scanner space.



Next Steps

Simulations will be crucial for scanner design's fine tuning

- Characterize noise performance (e.g., NECR)
- Improve data acquisition

This will be possible thanks to the help of AP2 developers.

Thank you !

Thank you for the attention

Please feel free to raise any questions