Modification of image reconstruction algorithms in J-PET using time-of-flight and depth-of-interaction

Roman Shopa

National Centre for Nuclear Research,
Świerk Computing Centre, Otwock-Świerk, Poland

Outline

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  - Digital J-PET modular scanner
  - Wavelength shifters
  - Time-of-flight and sampling interval

- **Multivariate kernel density estimation**
  - Projection space
  - Image space
  - The role of DOI and multilayer geometry

- **Results**
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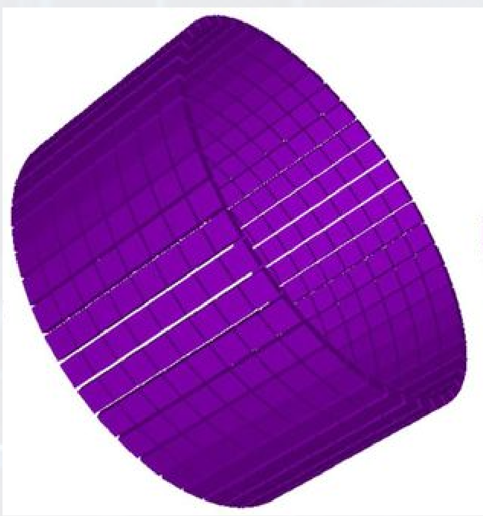
  - Image quality (NEMA IEC phantom)
  - Summary and further plans

Detectors vs strips

Traditional cylindrical PET: <u>discrete detectors</u>, voxel *i*, detector pair *j*

projection → $p_j = \sum_i a_{ij} f_i$ ← *image*

system matrix



slideplayer.com/slide/12976158/

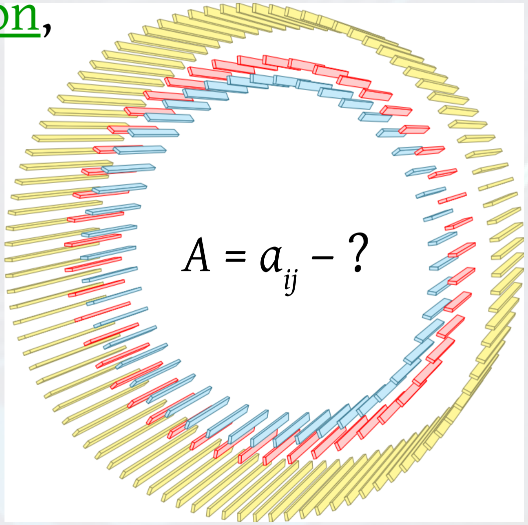
Jagiellonian PET: 3 layers of plastic scintillator strips: <u>continuous along axial direction</u>,

192 detector strips of the size:

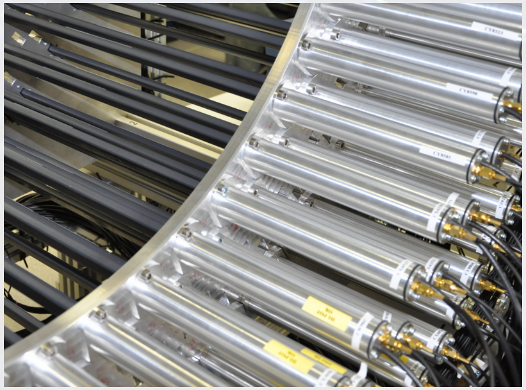
7 mm × 19 mm × 500 mm

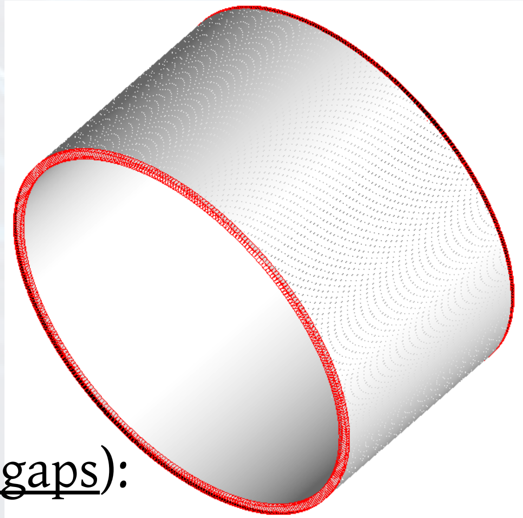
Radiuses:

- 425.0 mm (48 strips)
- 467.5 mm (48 strips)
- 575.0 mm (96 strips)



<u>Gaps between strips</u> caused by large tube PM (PMT) readouts





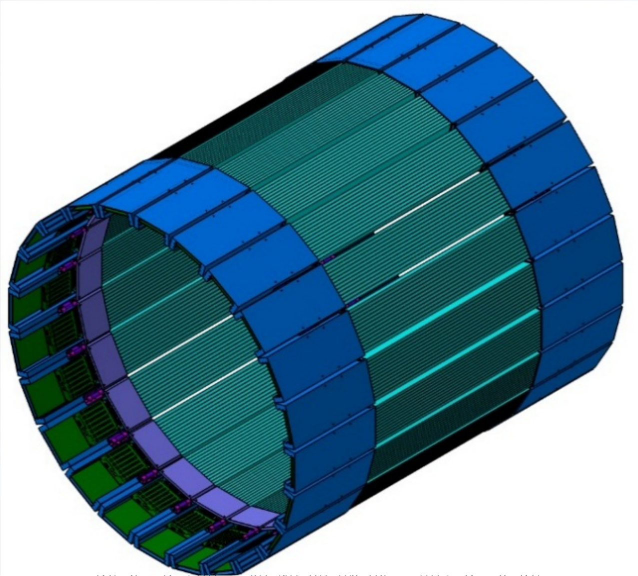
Ideal geometry (simulated, <u>no gaps</u>):

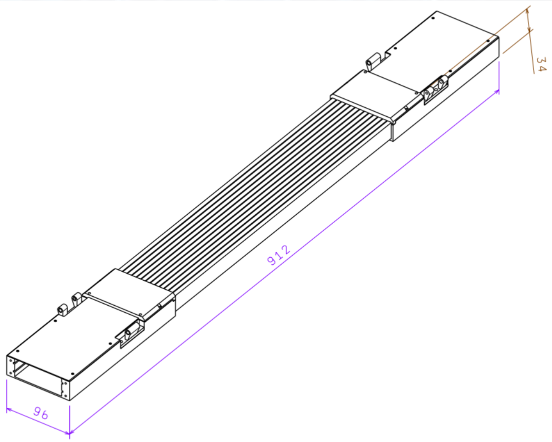
R = 437.3 mm, 384 strips

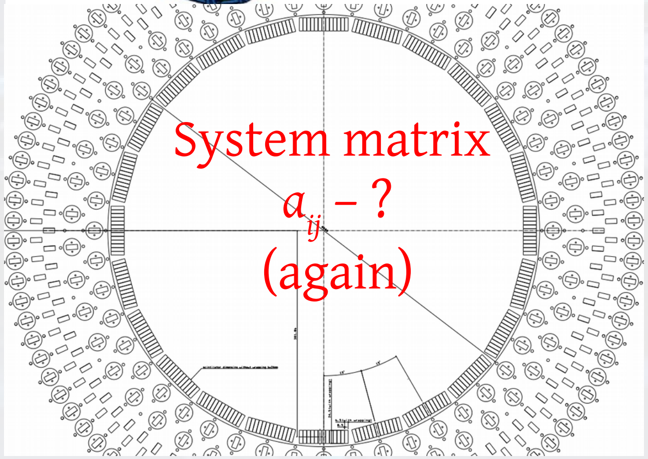
The next generation: Digital J-PET

Lightweight scanner (24 modules of 13 strips each)

– May be put inside 3-layer prototype (same L = 50 cm)
– Easily decomposed, transported and reconstructed in various shapes and sizes
– Silicon PM (SiPM) readout electronics
– FPGA based real-time data processing system
[G. Korcyl et al., arxiv.org/abs/1807.10754]



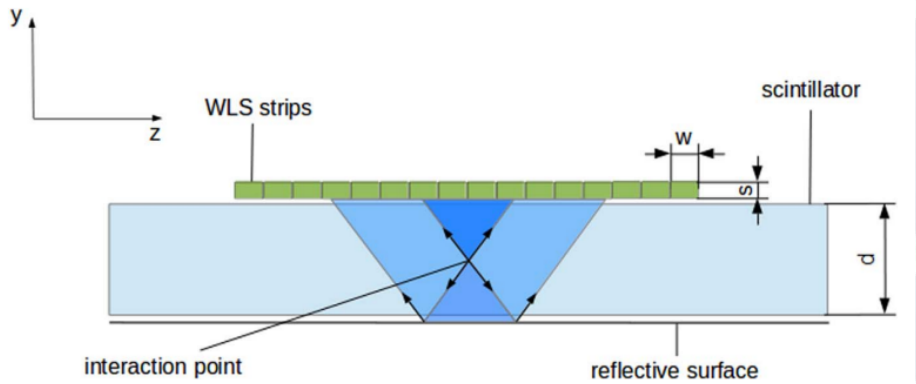


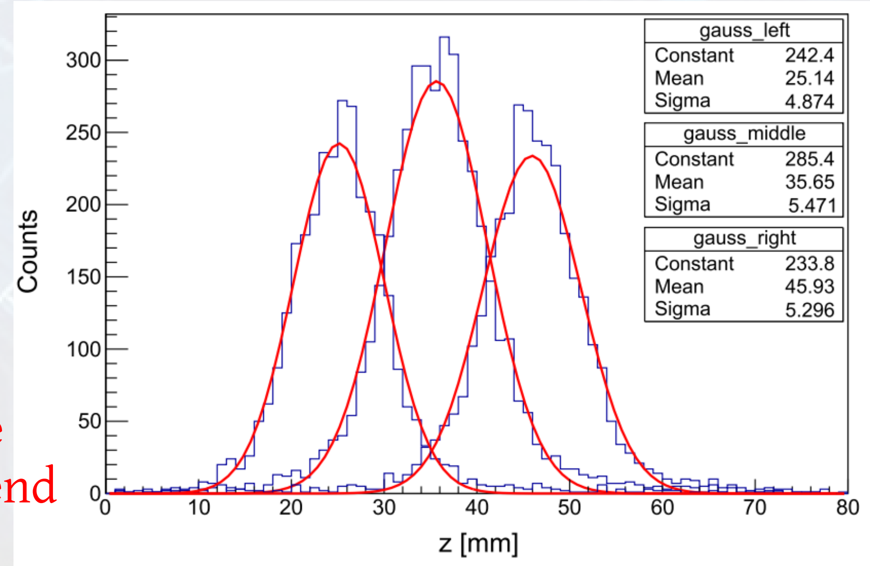


fpgafais.com/digi-pet/

Going further: wavelength shifters

Register scintillation light escaping through a side wall using an array of wavelength-shifting (WLS) strips, aligned orthogonally to the scintillator bars
[J. Smyrski et al., N. Instr. and Meth. in Phys. Res. A 851 39 (2017)]

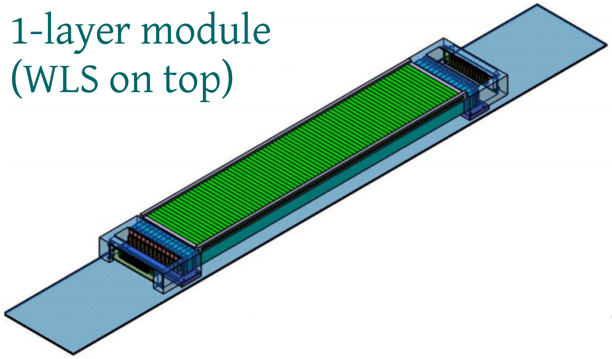




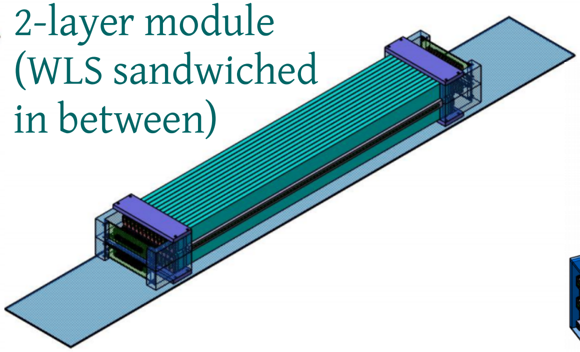
Three different positions of the ^{22}Na source

The shape and width of distributions, built from the amplitudes measured in individual WLS strips, depend on depth-of-interaction (DOI) *(yet to measure)*
[R. Marcinkowski et al., Phys. Med. Biol. 61 2196 (2016)]

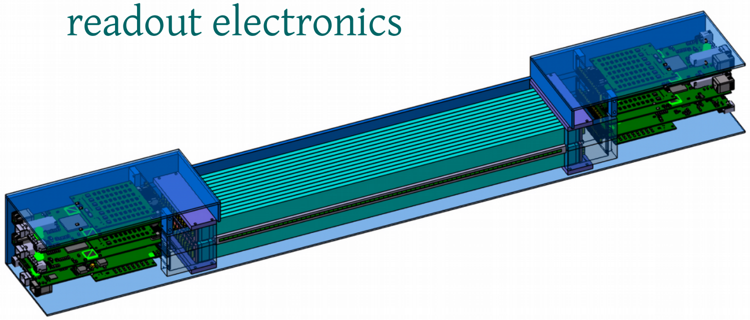
1-layer module (WLS on top)



2-layer module (WLS sandwiched in between)



Prototype module with integrated readout electronics



Time-of-flight and sampling interval

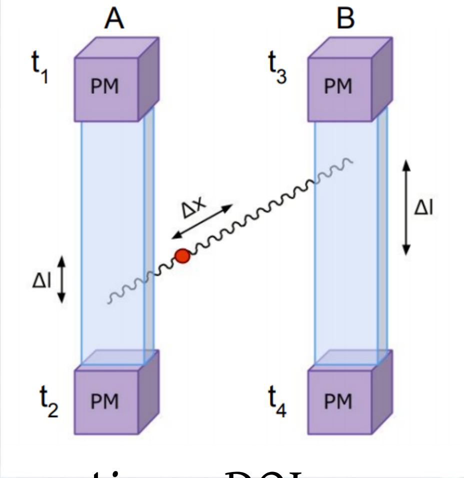
The principle of measurement – 4 times $t_{1,2,3,4}$

Time-of-flight (TOF) – estimate Δx and detect annihilation point

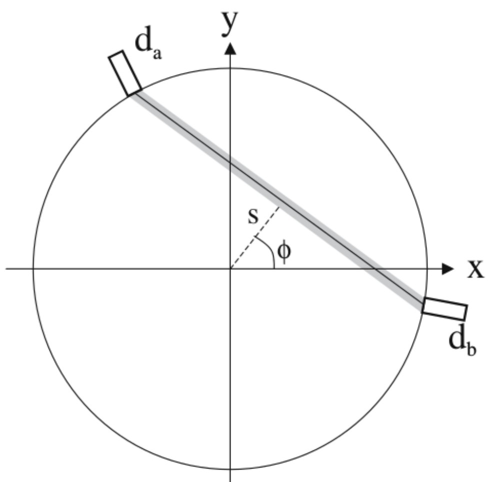
Timing resolution affect both axial coordinate and TOF:

$$\Delta l_{12} = (t_1 - t_2) \cdot v_{eff} / 2$$
$$\Delta t_{AB} = (t_1 + t_2)/2$$

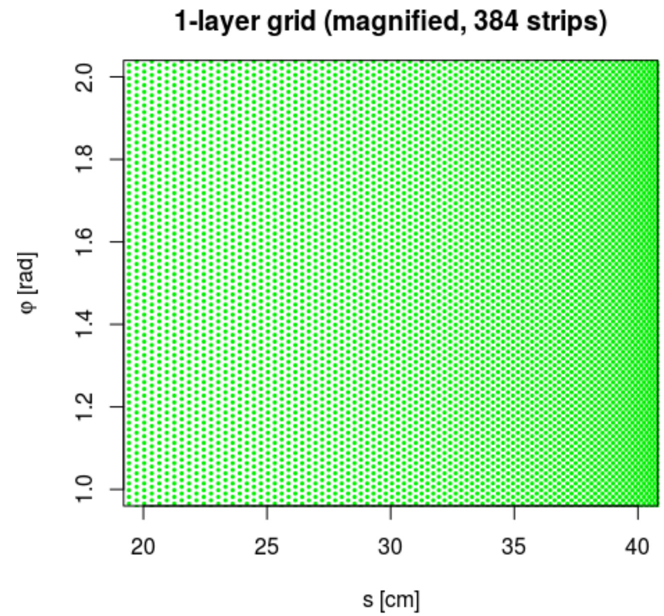
uncorrelated (separate uncertainties)

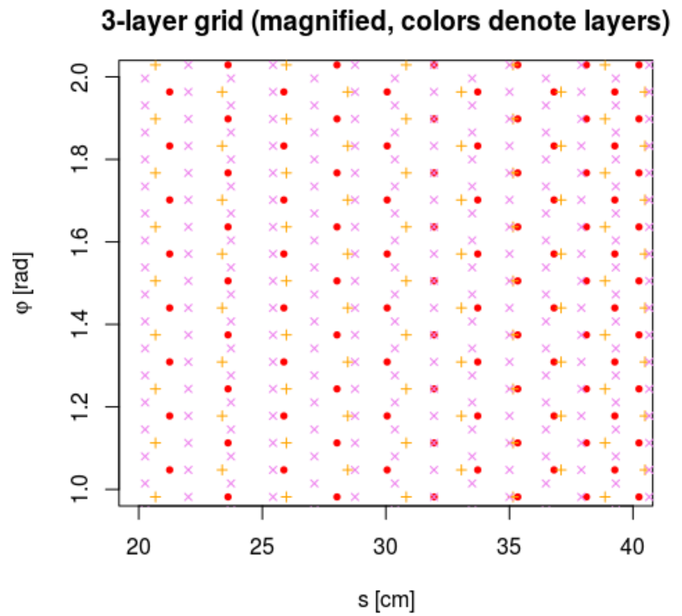


Sinogram non-uniform sampling in projection space – significant difference between 3-layer and ideal geometries. Arc correction + DOI, remapping to 1-layer, essential for some software, would lead to further distortion



[D.L. Bailey et al., "PET, Basic Sciences," London 2005, 382 p.]





Multivariate kernel density estimation

The idea – treat the data as distributions (stochastic γ-quanta emission and scattering) DOI & TOF – as random values from (presumably Gaussian).

For a d-dimensional dataset $\mathbf{X}_1, \mathbf{X}_2, \ldots, \mathbf{X}_n$ of size n, the kernel density estimator (KDE)

$$\hat{f}_{n\boldsymbol{H}}(\boldsymbol{x}) = n^{-1} \sum_{i=1}^{n} |\boldsymbol{H}|^{-1/2} K\left[\boldsymbol{H}^{-1/2}(\boldsymbol{x} - \mathbf{X}_i)\right]$$

$\boldsymbol{x} = (x_1, x_2, \ldots, x_d)$, $K(\cdot)$ – spherically symmetric multivariate kernel (Gaussian),
$\boldsymbol{H}$ – the bandwidth matrix, symmetric and positive definite (the choice has a serious impact on the result).

Algorithms for bandwidth selection:
– asymptotic approximation mean integrated squared error (AMISE)
– plug-in bandwidth selector (multistage)
– local bandwidth selector $\boldsymbol{H} = \boldsymbol{H}(\boldsymbol{x})$ (for sparse data only)
[Chacon, J.E. & Duong, T. Test, 19, 375 (2010)]

Notation for R package “ks” (cran.r-project.org/web/packages/ks/)
“samse” = single AMISE pilot bandwidth (SAMISE)
“dscalar”, “dunconstr” – multistage algorithms for plug-in bandwidth selector PI($\boldsymbol{H}$)

Projection space example

GATE simulation of 1-mm 370 kBq spherical source (**ideal J-PET:** 1-layer, 384 strips)

$p = f(s, \varphi, \underline{\zeta, \theta}) \rightarrow f(s, \varphi, \underline{z})$ (from TOF, after smearing by σ_z, σ_t, measured experimentally)

Each transverse slice is mapped by arc correction or <u>multivariate KDE (m-KDE)</u>

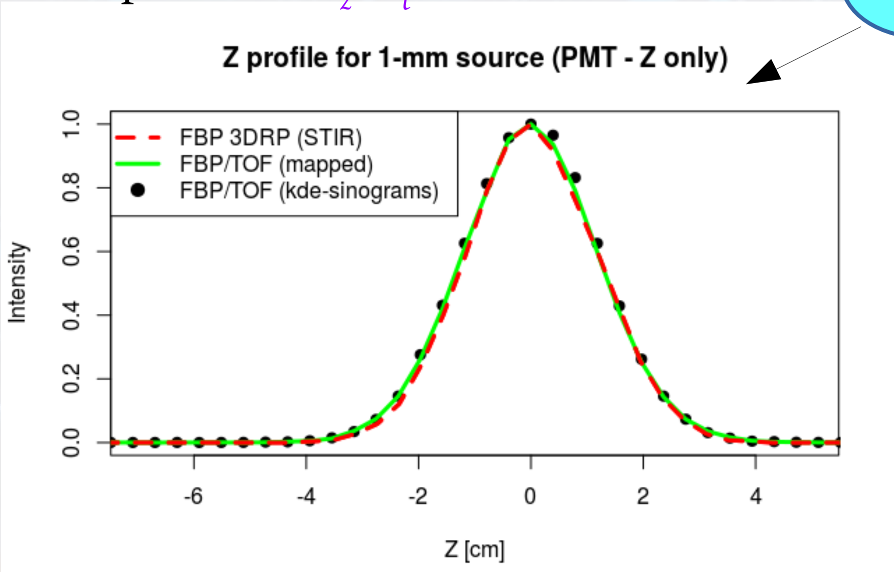
Filtered back projection (FBP):

– FBP + TOF (using R PET package)
cran.r-project.org/web/packages/PET/

– FBP 3DRP (**STIR**, stir.sourceforge.net)
(Kinahan & Rogers alg., noise & smooth)

For PMT, <u>FBP 3DRP is better</u>
(independent σ_z, σ_t?)

no σ_t!



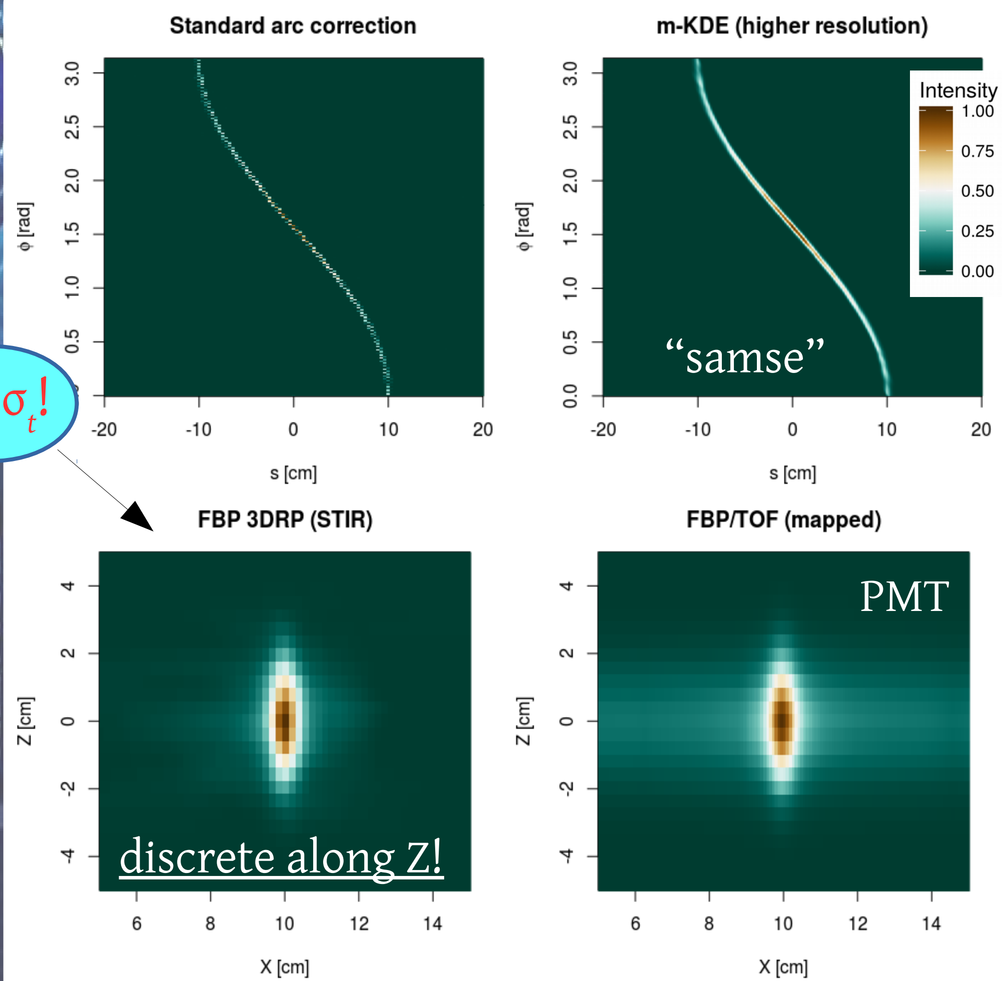
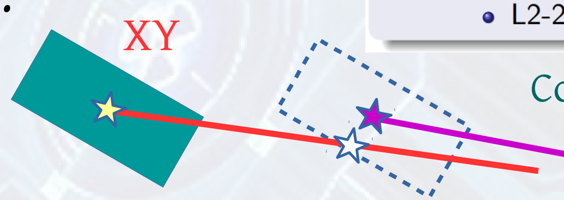


Image space example (experimental)

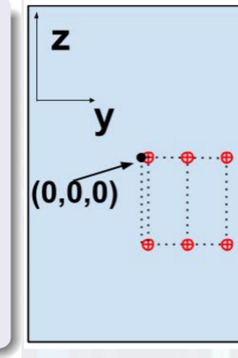
Straightforward approach: using TOF, estimate positions of annihilations (x, y, z) and apply KDE

Real J-PET 3-layer prototype, 192 strips
After preselection/calibration: ~1.7 mln. events

Other reconstruction algorithms:
– FBP 3DRP (STIR, *remapped to ideal geometry!*)
– MLEM (not shown, by Monika)

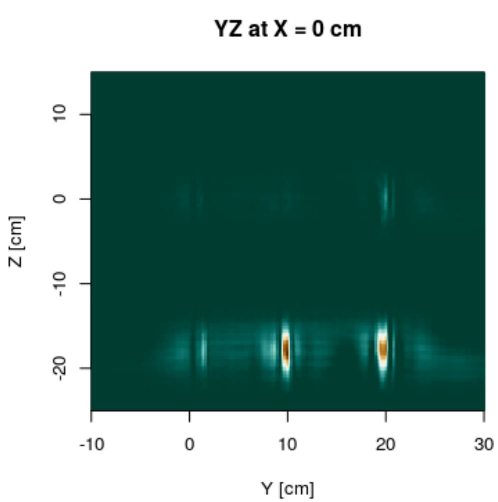


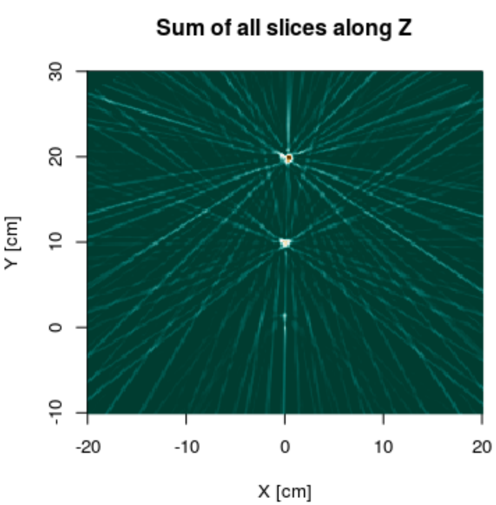
- Run 4 - data for six sources measured on 25.08.2017
- activity
  - 37/12 - 204 kBq
  - 39/12 - 207 kBq
  - UR450 - 1134 kBq
  - UR451 - 1131 kBq
  - K4-390 - 6198 kBq
  - L2-295 - 7601 kBq



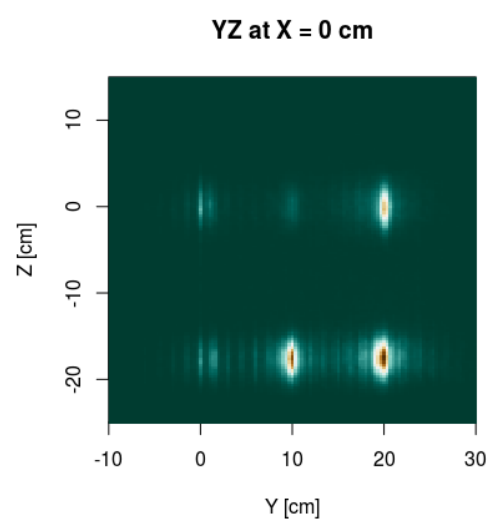
Courtesy of Monika Pawlik-Niedźwiecka

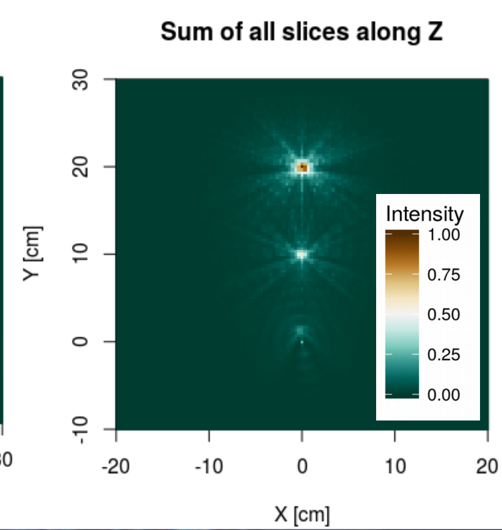
FBP 3DRP: FWHM_z = 3.6 ± 0.4 cm (mean)
y_{src} = 10 cm: FWHM_x = 1.00 ± 0.10 cm, FWHM_y = 0.79 ± 0.05 cm
y_{src} = 20 cm: FWHM_x = 1.05 ± 0.25 cm, FWHM_y = 0.80 ± 0.25 cm





m-KDE/TOF ("dscalar"): FWHM_z = 3.3 ± 0.2 cm (mean)
y_{src} = 10 cm: FWHM_x = 0.95 ± 0.27 cm, FWHM_y = 0.80 ± 0.10 cm
y_{src} = 20 cm: FWHM_x = 1.05 ± 0.10 cm, FWHM_y = 1.00 ± 0.15 cm

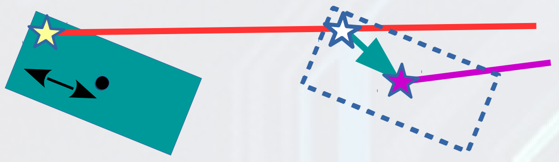


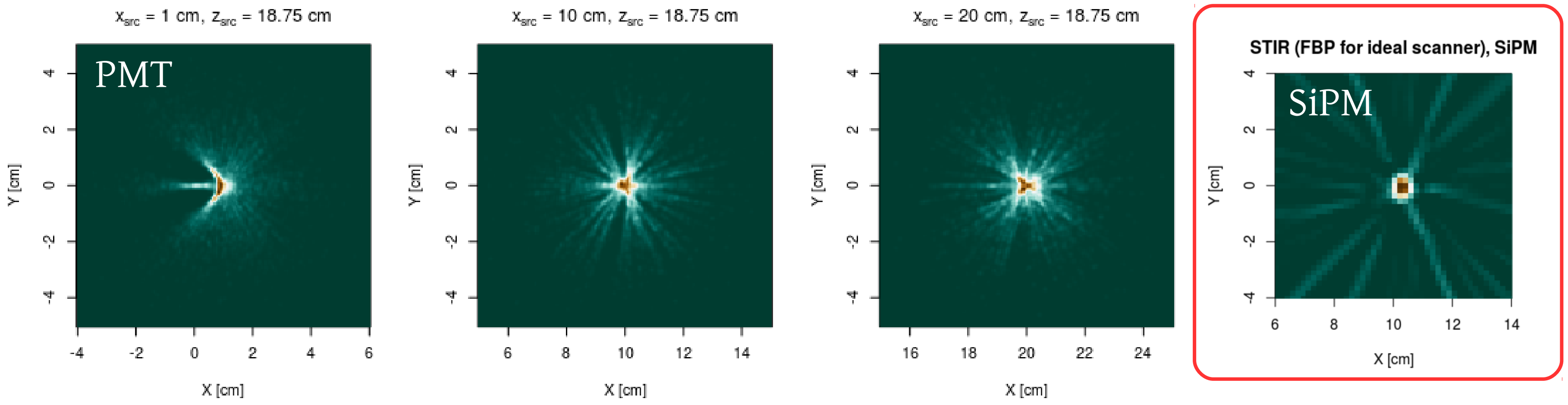


The role of DOI and multilayer geometry

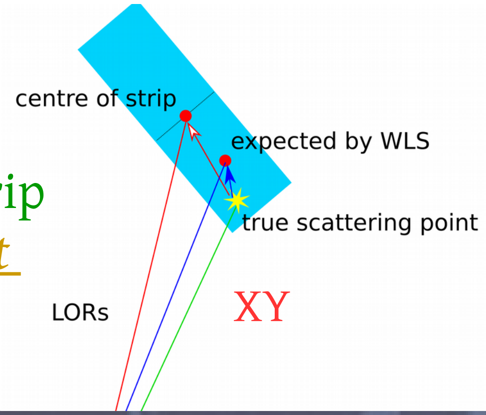
M-KDE/TOF in image space (“dscalar”), 1-mm source (370 kBq), **simulated in GATE**
3-layer geometry (192 strips), SiPM readouts, with or without WLS
100,000 events → <u>distorted image due to scanner geometry</u>

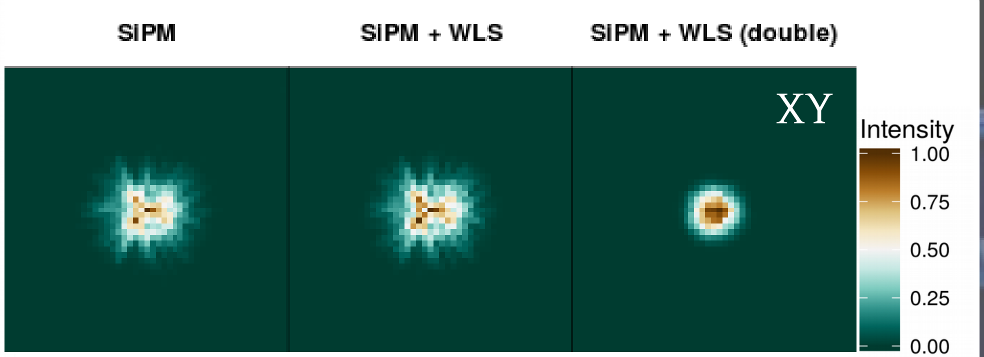
not visible if remapped to 1 layer – for STIR, the case of preserving “radial” DOI





Suppose WLS allows to detect DOI up to half-”depth” of the strip
<u>(impossible to implement in STIR software)</u>





Results: spatial resolution

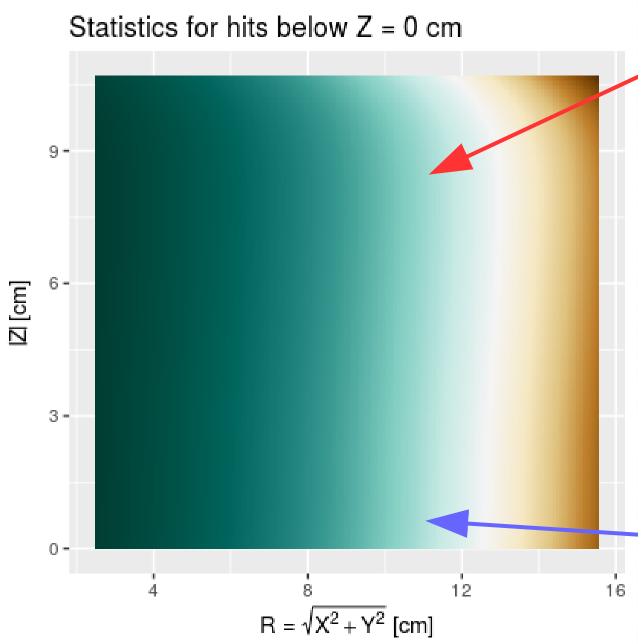
GATE simulations of 1-mm spherical source (370 kBq) – NEMA standard, 2 extreme positions, m-KDE/TOF in image space [P. Kowalski et al., PMB 63 165008 (2018)]

	Readout:	SiPM			SiPM + WLS		
Source at: (y_{src} = 0 cm)	Algorithm	FWHM (in mm) along axis					
		X	Y	Z	X	Y	Z
1-layer (ideal): R = 43.56 cm, 382 strips (7 × 20 × 500 mm), 150,000 events per simulation							
x_{src} = 1 cm, z_{src} = 0 cm	FBP 3DRP	6.3	5.4	16.1	5.8	5.8	5.7
	m-KDE/TOF	7.4	6.9	15.3	6.0	5.0	4.0
	m-KDE/TOF (WLS_{DOI})	–	–	–	5.5	4.7	3.9
x_{src} = 20 cm, z_{src} = 18.75 cm	FBP 3DRP	7.2	6.7	17.0	7.2	6.7	5.7
	m-KDE/TOF	8.3	9.1	15.1	6.6	7.9	3.9
	m-KDE/TOF (WLS_{DOI})	–	–	–	6.4	5.8	4.0
3-layer (real): R = 42.5/46.75/57.5 cm, 48/48/96 strips (7 × 19 × 500 mm), 100,000 events per simulation							
x_{src} = 1 cm, z_{src} = 0 cm	FBP 3DRP	4.7	6.6	15.0	4.6	6.7	6.6
	m-KDE/TOF	7.2	4.8	14.4	5.6	3.7	4.2
	m-KDE/TOF (WLS_{DOI})	–	–	–	5.2	3.6	4.0
x_{src} = 20 cm, z_{src} = 18.75 cm	FBP 3DRP	6.6	7.7	16.3	6.4	7.8	7.0
	m-KDE/TOF	8.8	8.8	15.8	7.4	7.4	4.0
	m-KDE/TOF (WLS_{DOI})	–	–	–	6.2	5.9	3.9

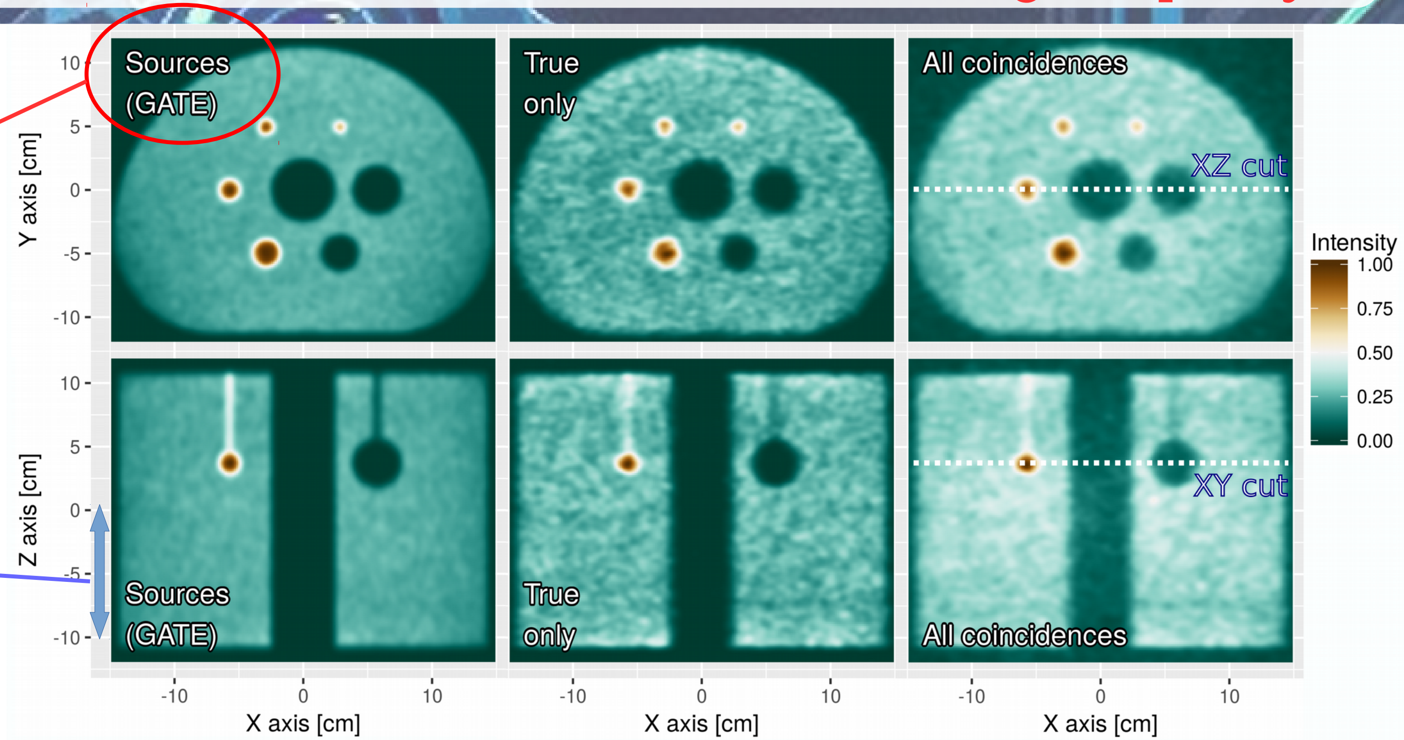
NEMA IEC phantom

GATE simulations for ideal scanner: 1-layer, 384 strips (7 × 19 × 500 mm), R = 43.73 cm
NEMA Standard NU 2-2001, no of events (coincidences) – 10 mln. ÷ 180 mln. (CIŚ)
Attenuation correction – from defined positions of sources (Lech Raczyński proposal).

Even for 1.9 mln. true events – good quality!



Attenuation map
10 mln. events

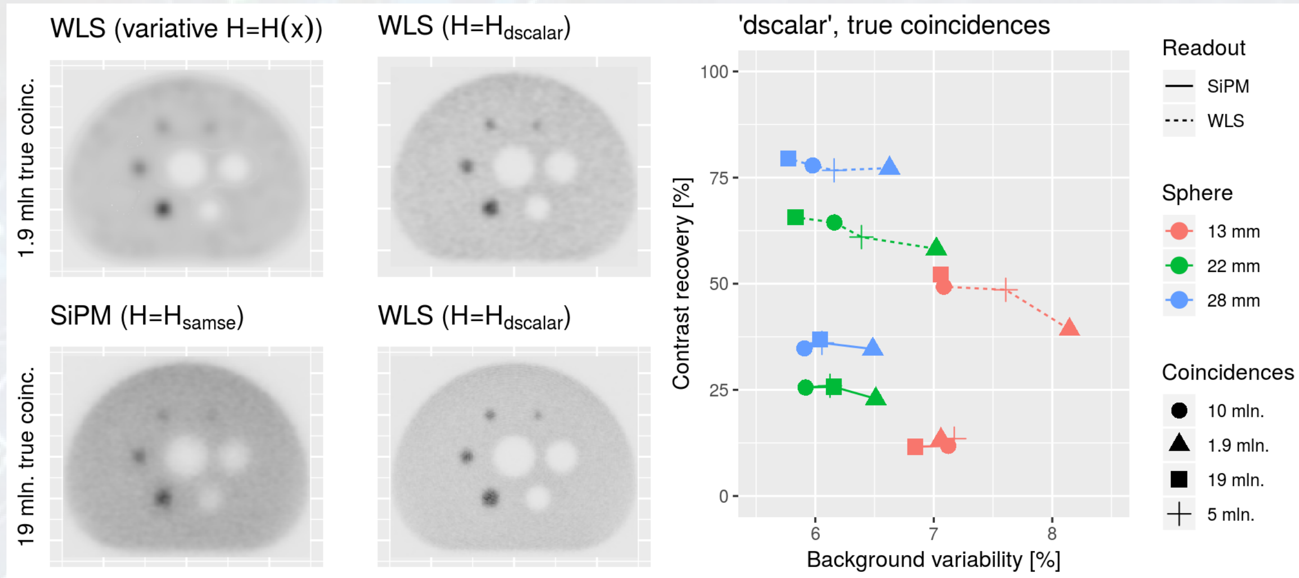


m-KDE/TOF reconstruction (no smearing of Z and t_{hit}). Left: from source positions (in GATE, 6.9 mln. events), centre: from annihilation points for true coincidences (1.9 mln.), right: for all coincidences (4.0 mln.). Elements of bandwidth matrix H < voxel size ("dscalar")

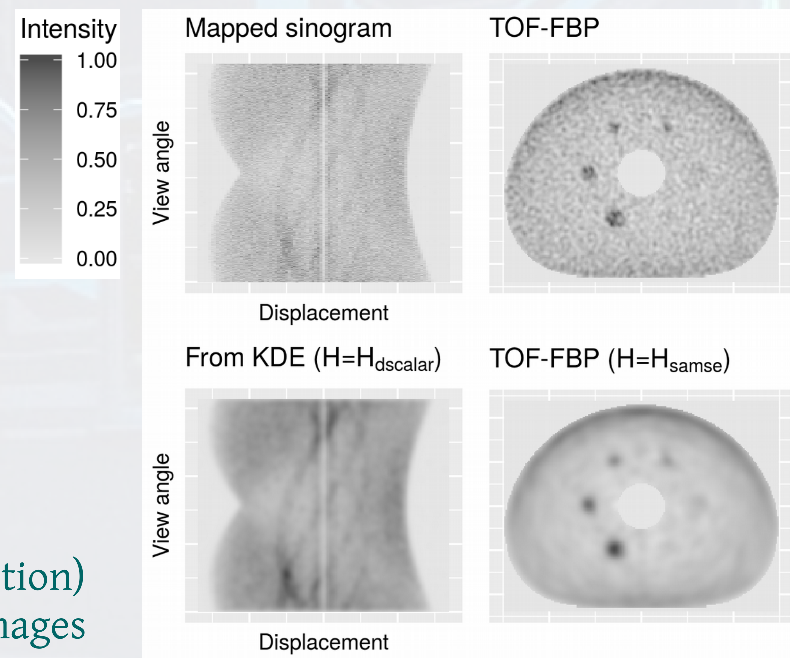
Results: image quality

Image quality (NEMA): contrast recovery vs background variability.
– No improve for local bandwidth selector.
– For SiPM, a simple filter (expander) might gain in image quality.

WLS denotes SiPM + WLS, "variative bandwidth" – kde.balloon() function from 'ks' R package, for $\boldsymbol{H} = \boldsymbol{H}(\boldsymbol{x})$



Comparison with projection space – 400,000 true coincidences, 5-mm thick slice (<u>no smearing</u>), corresponds to 50 mln. in total.
– Attenuation correction needs refinement.
– Not yet obtained a reasonable output images for STIR FBP 3DRP



2D sinograms, obtained using TOF by direct mapping (arc correction) and m-KDE, with corresponding reconstructed images

Summary and further plans

– Complex multilayer geometry of J-PET scanner with modular D-JPET optionally placed inside substantiate the need for new image reconstruction algorithms. Precise calculation of system matrix externally (analytically or using Monte Carlo) for such geometry would need a thorough software development or modification of available tools (STIR etc).

– The continuous character of strips and hence TOF and axial coordinate, along with the eventual DOI information, estimated by WLS in radial direction, motivate the usage of density estimators as a tool for the transition from discrete values to distributions.

– Uncorrelated measurements of time of hit and Z-coordinate might lower spatial resolution in transverse (m-KDE in image space) and/or axial (FBP/TOF) directions.

– The straightforward approach of m-KDE in image space would be applied to relatively small amount of data in order to obtain an acceptable image quality. However, it depends significantly on bandwidth selection and scanner imperfections, and could not be incorporated into known iterative algorithms.

Yet to resolve:
– Estimate experimentally DOI resolution for WLS.
– Implement a reliable attenuation/scatter correction method for FBP/TOF.
– Incorporate J-PET geometry, system matrix, TOF and DOI into STIR, or develop a brand-new 3D image reconstruction algorithm.
– Compare the available results with other algorithms (MLEM, TV etc).

Thank You for Your attention!