Time-of-Flight Requirements to Mitigate Blurring Induced by Annihilation Photon Acollinearity

Maxime Toussaint[1], Francis Loignon-Houle[2], Jean-Pierre Dussault[3] and Roger Lecomte[1,4]

[1]Sherbrooke Molecular Imaging Center of CRCHUS &, Department of Nuclear Medicine and Radiobiology
Université de Sherbrooke, CA
[2]Institute for Instrumentation in Molecular Imaging, i3M CSIC-UPV, Valencia, ES
[3]Department of Computer Science, Université de Sherbrooke, CA
[4]IR&T, CA

CIMS Centre d'imagerie moléculaire de Sherbrooke

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UDS Université de Sherbrooke

Spatial resolution in PET

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***Theoretical* spatial resolution limit at the center of a PET camera [Moses, 2011]**

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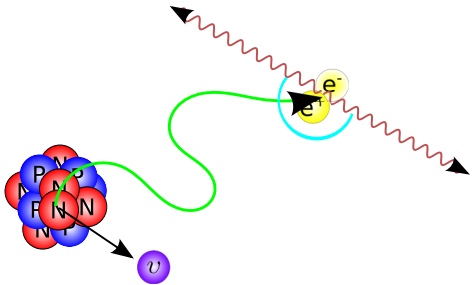

Inspired from www.depts.washington.edu/imreslab

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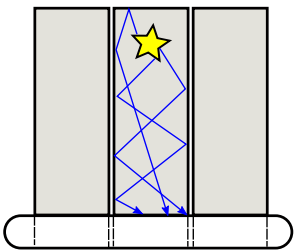

Detection module schematic

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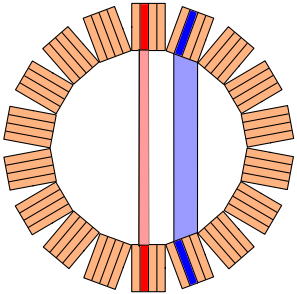

Parallax effect

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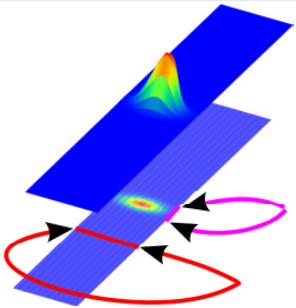
Ultimate "realistic" spatial resolution for a whole-body scanner: 2.49 mm FWHM

- $d = 3.0 \rightarrow$ 1.5 mm FWHM
- APA of 0.55° FWHM and an 80 cm diameter scanner $\rightarrow$ 1.9 mm FWHM

Mitigating the effect of detector size using ultrafast TOF



Spatial blur > TOF blur

Hot Spots simulated with 13 ps FWHM TOF [Toussaint et al., 2020b]

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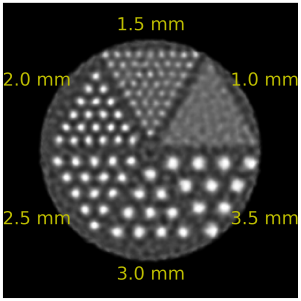
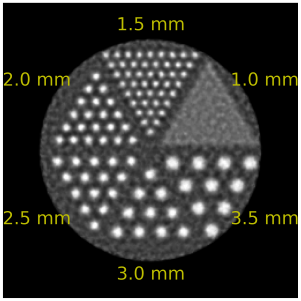
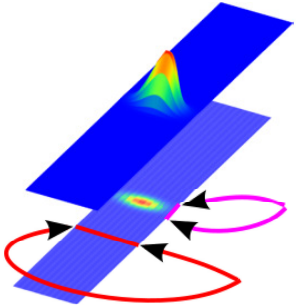


8 mm Det.



4 mm Det.



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Requirements:

- TOF FWHM $\approx$ detector size

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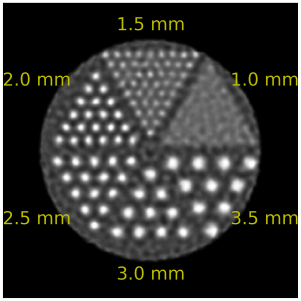

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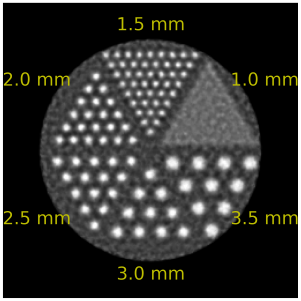

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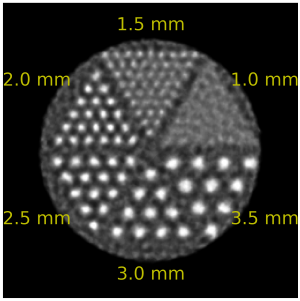

4 mm Det., $1/10^{th}$ coincidences

Hot Spots simulated with 13 ps FWHM TOF [Toussaint et al., 2020b]

Requirements:

- TOF FWHM $\approx$ detector size
- Coincidence event statistics (Inverse problem)

Ultrafast TOF on APA changes the shape of its blur

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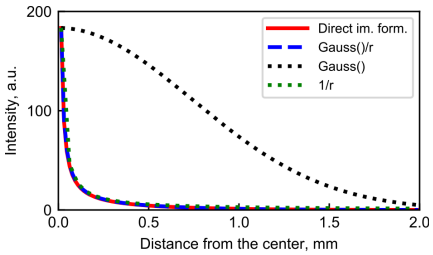
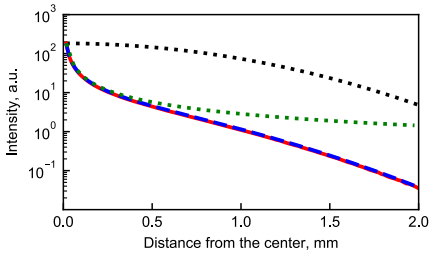


Linear-scale



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Direct image formation with perfect TOF resolution [Toussaint et al., 2020a]

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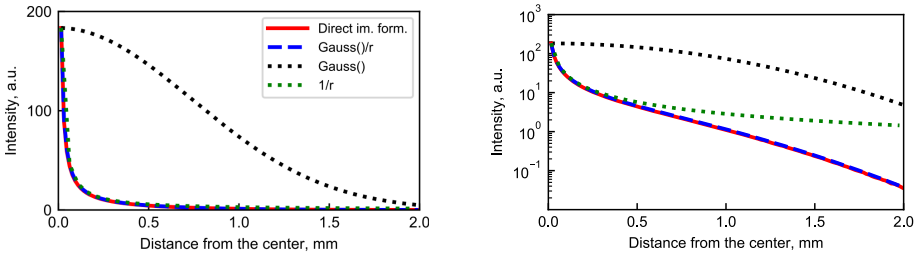
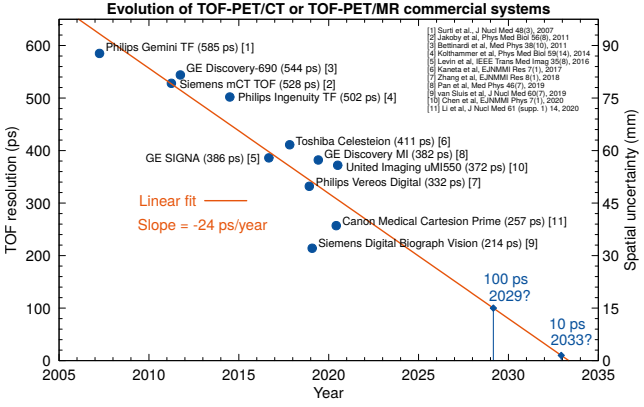


Direct image formation with perfect TOF resolution [Toussaint et al., 2020a]

Requirements:

- Only with $\leq$13 ps?
- Achievable with realistic detector size?

Ultrahigh TOF resolution: are we there yet?



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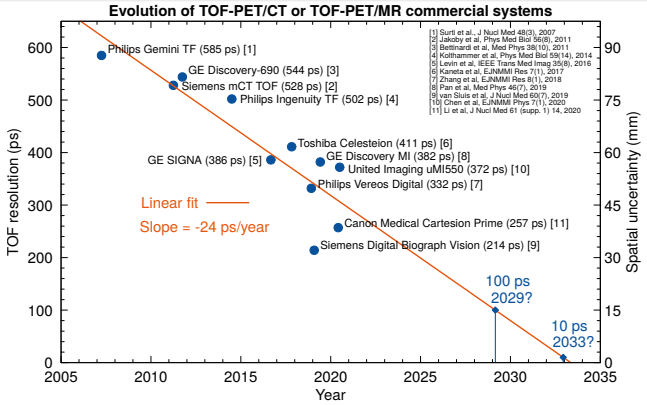

- 2033: 10 ps

Ultrahigh TOF resolution: are we there yet?

Examples of progress in coincidence time resolution:

- 30 ps FWHM (3.2 mm deep; lead glass; MCP-PMT [Ota et al., 2019])
- 123 ps FWHM (2x2x3 mm^3; BGO; FBK SiPM [Gundacker et al., 2023])
- 95 ps FWHM ($3 \times 3 \times 19$ mm^3; LYSO Ce,Ca; HF readout [Nadig et al., 2023])

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- Lower bound of the requirements to **mitigate** the blur induced by **APA** for whole-/total-body PET scanners
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  - Coincidence event statistics
- Estimate the potential gain in spatial resolution
  - Is it worth it? [Schaart et al., 2020]

Simulation configurations

GATE 9.2 simulations [Sarrut et al., 2022]

- Scanner diameter: 81 cm (Whole-body PET scanner)
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- Detectors depth: 0.1 mm (Reduce DOI-induced timing bias)
- No decoding error

Simulation configurations

TOF resolutions:

≈13, 26, 65 and 130 ps FWHM (i.e., 2, 4, 5, 20 mm FWHM)

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- "Typical" acquisition (*FullStat*)
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Coincidence event statistics

- "Typical" acquisition (*FullStat*)
  - Based on the sensitivity of the UHR scanner [Doyon et al., 2023] and converted to the simulated phantom volume
- Half of the "typical" acquisition (*HalfStat*)
- A tenth of the "typical" acquisition (*1/10thStat*)

APA image space blurring: *basicTOR* vs *obliqueTOR*

basicTOR:

Back-to-back source with 0.55° FWHM APA [Shibuya et al., 2007]

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- "Median" 3D TOR of the EXPLORER: 102 cm long [Badawi et al., 2019]

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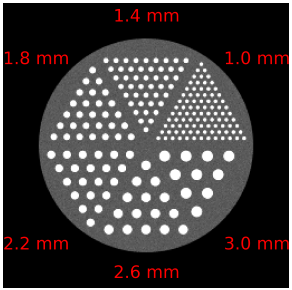
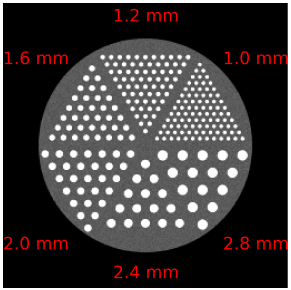
- Equivalent to 0.55° FWHM APA for a 102 cm long TOR
- Expected APA blurring: 2.4 mm FWHM
- *Theoretical* spatial resolution limit: 2.6 mm FWHM

Quantify spatial resolution gain



A Hot Spots phantom



Another Hot Spots phantom

Hot Spots phantoms parameter:

- Spots size: 1.0 mm to 3.0 mm with steps of 0.2 mm
- Number of coincidences for *FullStat*: $\approx$ 7 M
- Activity distribution: spot-to-background ratio of 4:1

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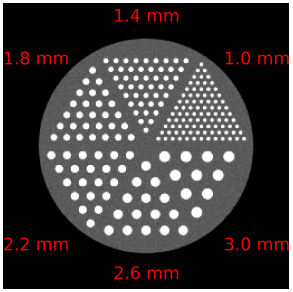

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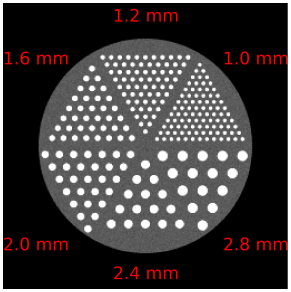

Another Hot Spots phantom

Reconstruction:

- Algorithm: TOF MLEM
- TOF discretization: uniform TOF bins and adapted to TOF resolution
- System matrix: highly accurate representation with 0.31 x 0.31 mm^2 voxels
- Stopping criteria: minimize mean squared error with ground truth

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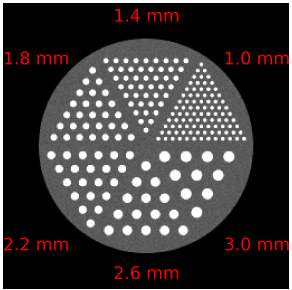

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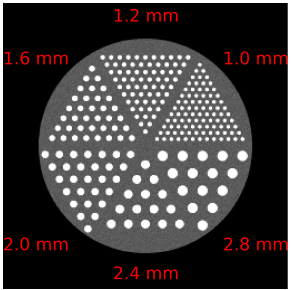

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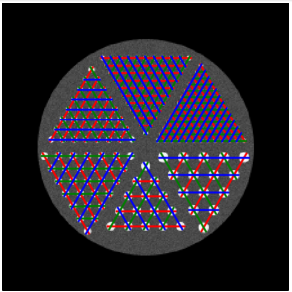


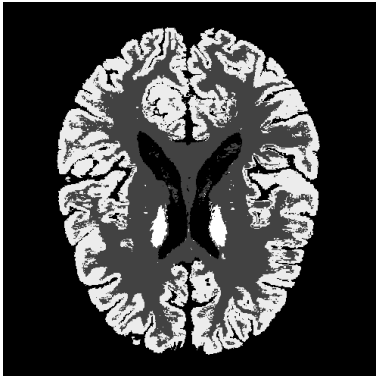
Position of the line profiles

Spots resolvability:

- Peak and valley estimation: Mean of a ROI 30% of the spot size
- Background mean was estimated and corrected prior to ratio evaluation
- Decision criterion: $\geq$90% valley-to-peaks ratio that satisfies the Rayleigh resolution criterion [Hallen et al., 2020]

In pratice?

BigBrain with FDG-like distribution



BigBrain [Amunts et al., 2013]

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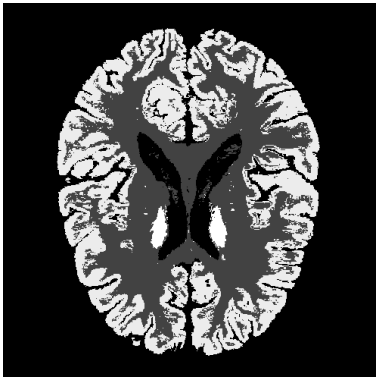
Acquisition:

- 128 replications of the 2D scanner axialy (256 mm axial FOV)
- ≈13, 26, 65 and 130 ps FWHM
- *basicTOR* vs *obliqueTOR*
- ≈100 M coincidences



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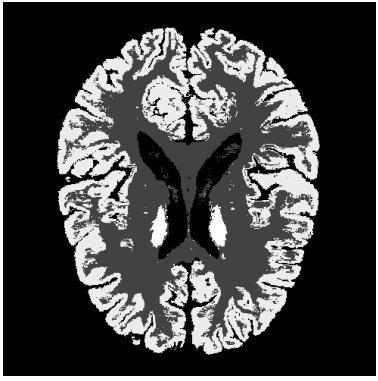
Reconstruction:

- MLEM TOF using CASToR with continuous TOF [Merlin et al., 2018]
- Projector: 25 rays multi-Siddon
- 0.4 x 0.4 x 0.4 mm^3 voxels



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Theoretical spatial resolution: **2.2 mm FWHM**. APA: **1.9 mm FWHM**.

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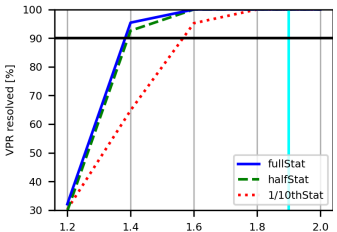

13 ps FWHM TOF

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Gains (all values are in FWHM):

- 13 ps TOF: 0.6-0.8 mm

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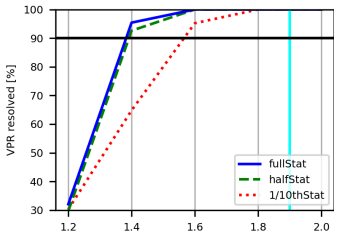

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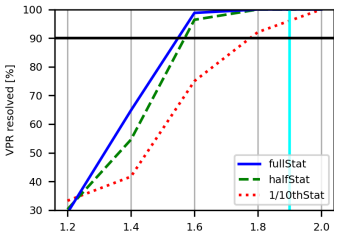

26 ps FWHM TOF

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Gains (all values are in FWHM):

- 13 ps TOF: 0.6-0.8 mm
- 26 ps TOF (i.e., $\approx 2\times$APA): 0.4 mm even with 1/10thStat

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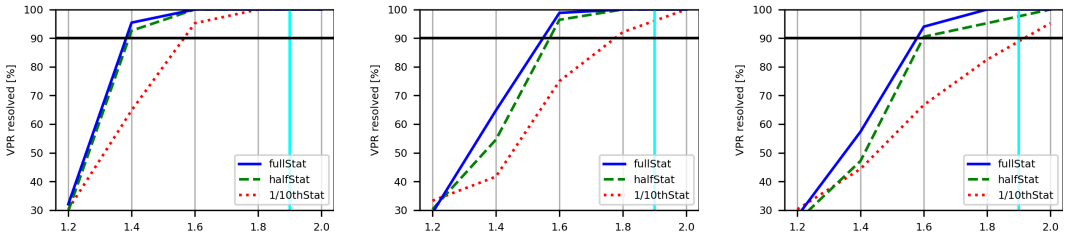

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Gains (all values are in FWHM):

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- 26 ps TOF (i.e., $\approx 2\times$APA): 0.4 mm even with 1/10thStat
- 65 ps TOF (i.e., $\approx 5\times$APA): 0.6 mm with at least HalfStat

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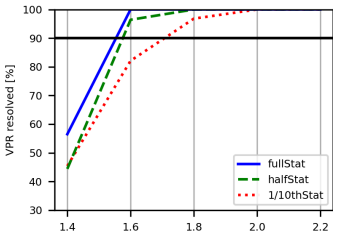
Hot Spots, *obliqueTOR*



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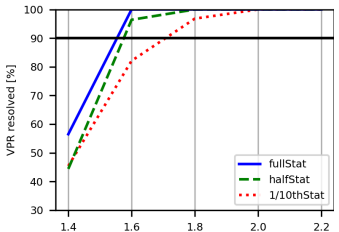

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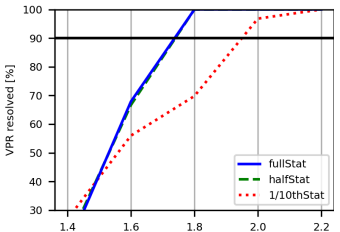

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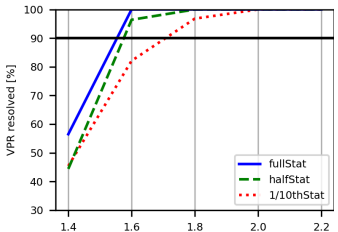
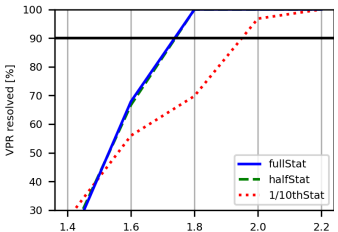
- 26 ps TOF (i.e., $\approx 1.7\times$APA): 0.6 mm even with 1/10thStat

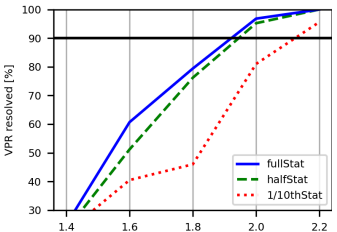
Hot Spots, *obliqueTOR*



13 ps FWHM TOF



26 ps FWHM TOF



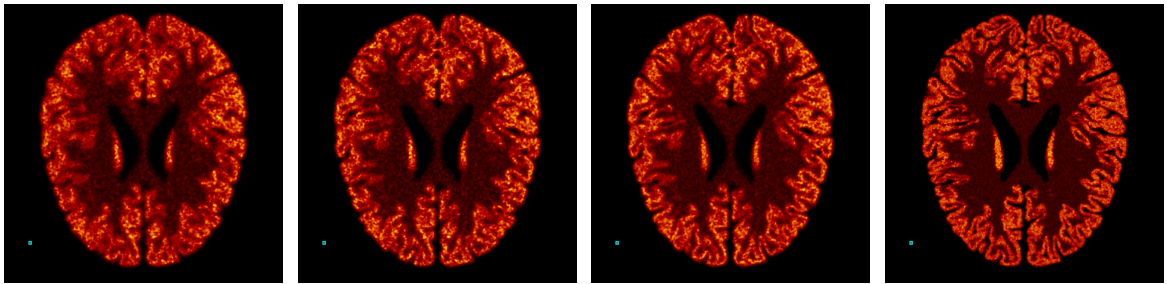
65 ps FWHM TOF

Theoretical spatial resolution: **2.6 mm FWHM**. APA: **2.4 mm FWHM**.

Gains (all values are in FWHM):

- 13 ps TOF: 0.8-1.0 mm
- 26 ps TOF (i.e., $\approx 1.7\times$APA): 0.6 mm even with 1/10thStat
- 65 ps TOF (i.e., $\approx 4\times$APA): 0.6 mm with at least HalfStat

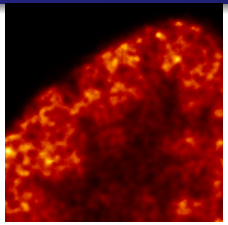
BigBrain, *basicTOR*



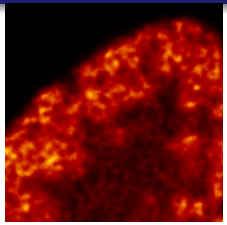
TOF: 65 ps, 12 it. TOF: 26 ps, 10 it. TOF: 13 ps, 6 it. Groundtruth

Tranverse view. Same color-scale. Similar noise in the grey matter.
Theoretical spatial resolution: 2.2 mm FWHM. APA: **1.9 mm FWHM**.

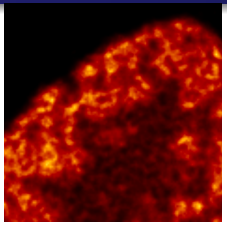
BigBrain, *basicTOR*



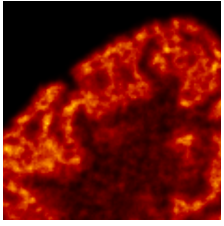
TOF: 130 ps, 16 it.



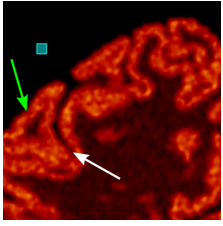
TOF: 65 ps, 12 it.



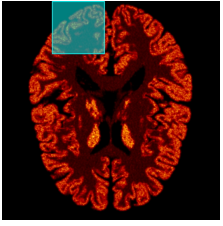
TOF: 26 ps, 10 it.



TOF: 13 ps, 6 it.



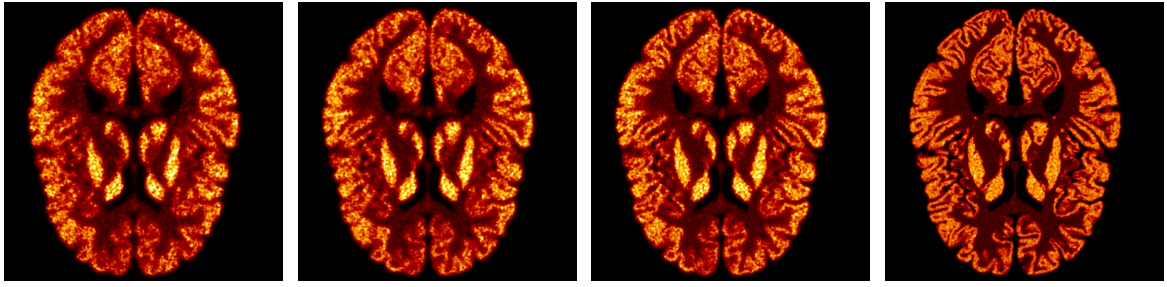
Groundtruth



ROI position

Theoretical spatial resolution: 2.2 mm FWHM

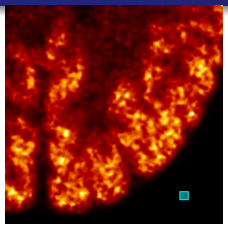
BigBrain, *obliqueTOR*



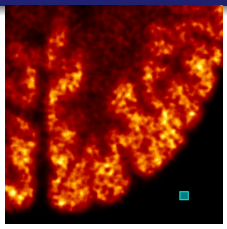
TOF: 65 ps, 12 it. TOF: 26 ps, 8 it. TOF: 13 ps, 6 it. Groundtruth

Tranverse view. Same color-scale. Similar noise in the grey matter.
Theoretical spatial resolution: 2.6 mm FWHM. APA: **2.4 mm FWHM**.

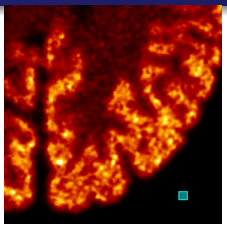
BigBrain, *obliqueTOR*



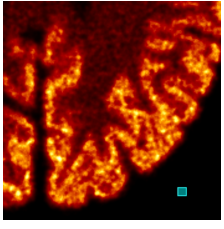
TOF: 130 ps, 16 it.



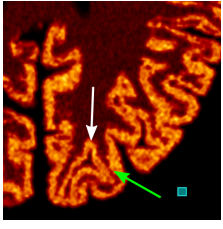
TOF: 65 ps, 12 it.



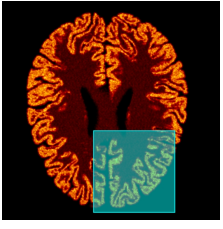
TOF: 26 ps, 8 it.



TOF: 13 ps, 6 it.



Groundtruth



ROI position

Theoretical spatial resolution: 2.6 mm FWHM

Conclusions

Main goal:

Investigate the **requirements** on TOF resolution and event statistics to **mitigate the APA**-induced blurring in the context of **whole-body and total-body PET** cameras

Conclusions

Highlights:

- Hot Spots phantom: gain achieved in all cases (**0.4 to 1.0 mm FWHM**)
- Greater gain with *obliqueTOR*

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Future works:

- Larger detectors

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- Greater gain with *obliqueTOR*
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Future works:

- Larger detectors
- Better 3D reconstructions (more iterations, better system matrix?)


Fin.

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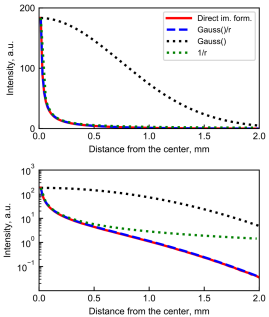
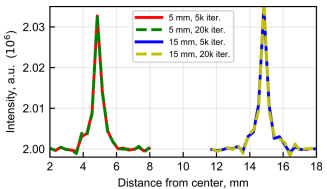
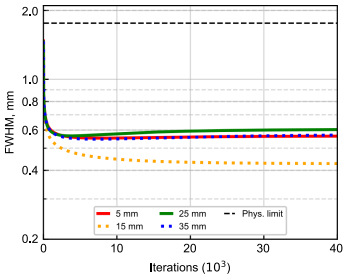
Ultrafast TOF on APA changes the shape of its blur - details



Direct image formation with perfect TOF resolution [Toussaint et al., 2020a]



Line profile of two point sources with 13 ps FWHM TOF



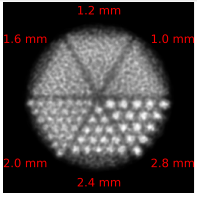
Spatial FWHM of point sources with 13 ps FWHM TOF

Requirements:

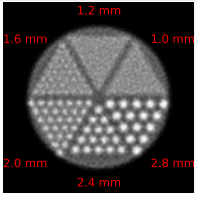
- Only with $\leq$13 ps?
- Achievable with realistic detector size?

Hot Spots, *obliqueTOR*

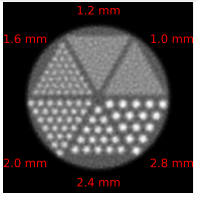
FullStat



TOF: 130 ps, 86 it.

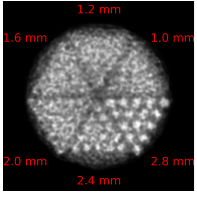


TOF: 26 ps, 30 it.

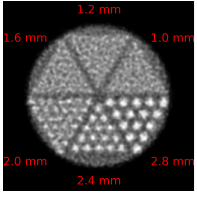


TOF: 13 ps, 18 it.

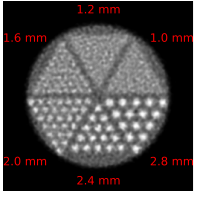
1/10thStat



TOF: 130 ps, 28 it.



TOF: 26 ps, 14 it.

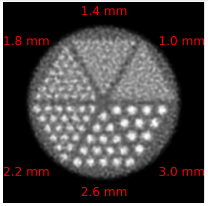


TOF: 13 ps, 8 it.

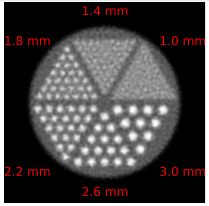
Theoretical spatial resolution: **2.6 mm FWHM**. APA: **2.4 mm FWHM**.

Hot Spots, *basicTOR*

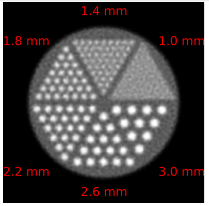
FullStat



TOF: 130 ps, 98 it.

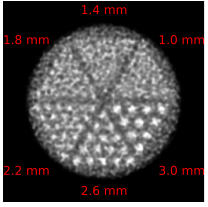


TOF: 26 ps, 36 it.

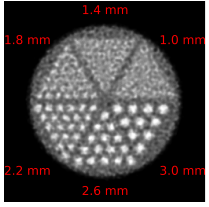


TOF: 13 ps, 22 it.

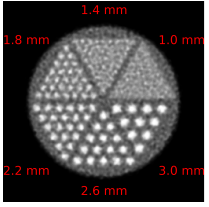
1/10thStat



TOF: 130 ps, 36 it.



TOF: 26 ps, 16 it.



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Theoretical spatial resolution: **2.2 mm FWHM**. APA: **1.9 mm FWHM**.

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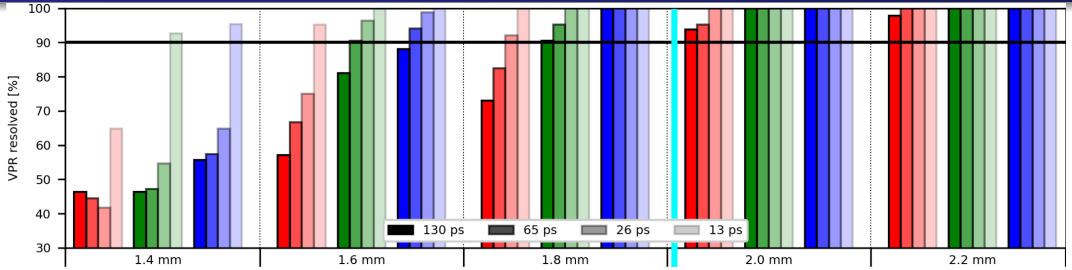
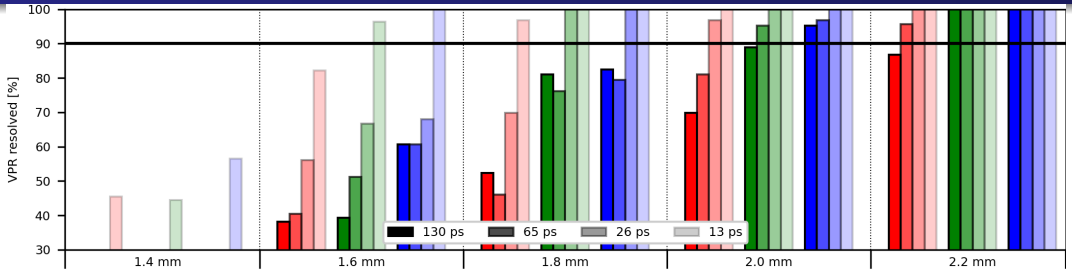


The colors refer to *1/10thStat*, *HalfStat* and *FullStat*.
Theoretical spatial resolution: **2.2 mm FWHM**. APA: **1.9 mm FWHM**.

Gains (all values are in FWHM):

- 13 ps TOF: 0.6-0.8 mm
- 26 ps TOF (i.e., $\approx 2\times$APA): 0.4 mm even with 1/10thStat
- 65 ps TOF (i.e., $\approx 5\times$APA): 0.6 mm with at least HalfStat

Hot Spots, *obliqueTOR*



The colors refer to *1/10thStat*, *HalfStat* and *FullStat*.
Theoretical spatial resolution: **2.6 mm FWHM**. APA: **2.4 mm FWHM**.

Gains (all values are in FWHM):

- 13 ps TOF: 0.8-1.0 mm
- 26 ps TOF (i.e., $\approx 1.7\times$APA): 0.6 mm even with 1/10thStat
- 65 ps TOF (i.e., $\approx 4\times$APA): 0.6 mm with at least HalfStat