Design of a spatially-variable-focusing collimator and impact of the forward projection model in reconstruction for small-animal SPECT

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Introduction

- SIGAHRS project (**S**ystème multi-modulaire préclinique d'**I**magerie **GA**mma **H**aute **R**ésolution et **S**ensibilité).
- Aim : Design a multi-fonctionnal preclinic scintigraphic imaging system, appropriate for 3 types of applications :
  - Oncology.
  - Neurology.
  - Cardiology.
- **Small-animal SPECT** imaging.
- High performance system with **semi-conductor** detectors (CZT).
- Original collimation system : **Spatially-Variable-Focusing Cone-Beam collimator** (SVF-CB).
- First SVF-CB collimator in small-animal SPECT.
- French TecSan ANR started in 2009, coordinated by Biospace Lab.

Project Partners

- **Biospace Lab**, Paris, marketing, automatism, systemic, software.
- **CEA-LETI**, Grenoble, gamma detection technology, electronic.
- **IMNC**, Orsay, simulations, reconstruction.
- **INSERM U877 unit** (Daniel Fagret), Grenoble : radiotracer, cardiology applications.
- **TIRO CEA-University** (Philippe Franken), Nice : radiotracer, oncology applications.
- **INSERM U930 unit** (Denis Guilloteau), Tours : radiotracer, neurology.

IMNC Aims

- Modeling the collimator and detector with GATE [1-2].
- Implementation of an appropriate iterative reconstruction :
  - Study the feasibility to reconstruct with focal lengths inside the field-of-view (FOV).
  - Develop a PSF model for this collimator.
  - Show the impact of different forward and back projector models.
- Characterize the SVF-CB collimator (sensitivity, spatial resolution) and compare to a parallel collimator.

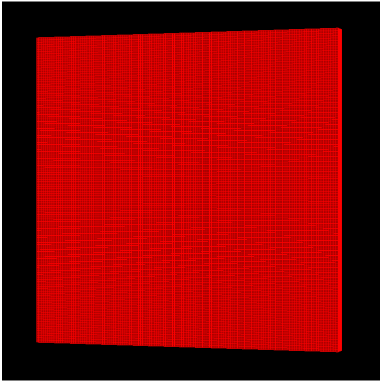
[1] Jan et al. "GATE : a simulation toolkit for PET and SPECT", Phys. Med. Biol., vol. 49, no. 19, p. 4543, 2004.

[2] Jan et al. "GATE V6 : a major enhancement of the GATE simulation platform enabling modelling of CT and radiotherapy", Phys. Med. Biol., vol. 56, pp. 881-901, 2011.

Detector

Detector simulated in GATE :

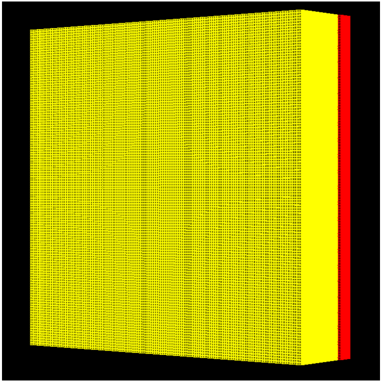
- CZT pixels.
- Pixels : $0.75 \times 0.75 \times 5.0$ mm^3.
- 131x131 pixels.

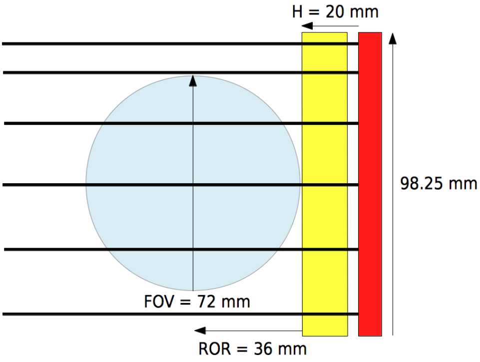


Parallel Collimator

Parallel collimator simulated in GATE :

- **Septa** in **tungsten**.
- 0.3x0.3 mm square holes.
- 0.15 mm septa width.

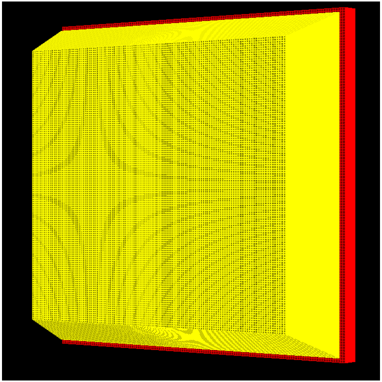


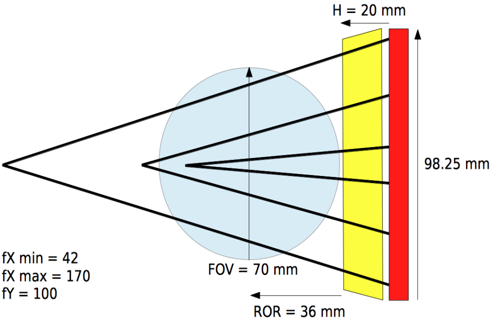


SVF-CB In Collimator

SVF-CB In collimator simulated in GATE :

- **Focals in field of view** (FOV).
- Septa in tungsten.
- 0.3x0.3 mm square holes at the surface of detector.
- 0.15 mm septa width.

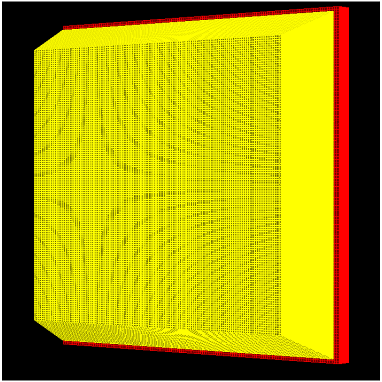


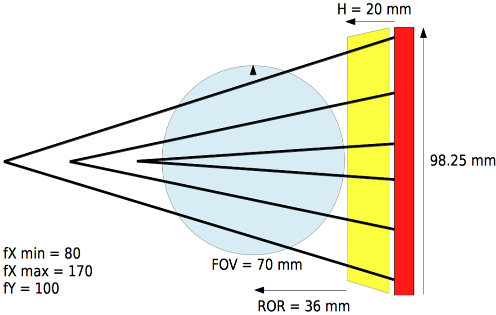


SVF-CB Out Collimator

SVF-CB Out collimator simulated in GATE :

- **Focals out field of view** (FOV).
- 0.3x0.3 mm square holes at the surface of detector.
- Septa in tungsten.
- 0.15 mm septa width.

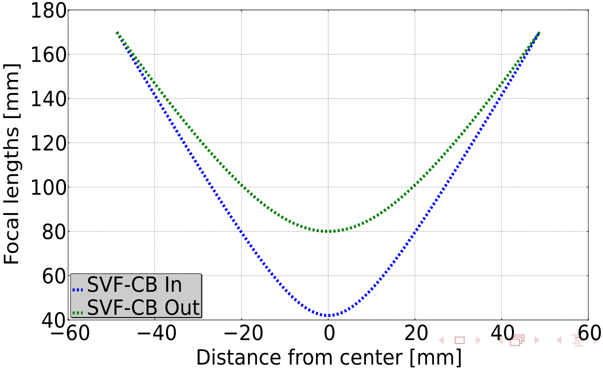




Focal Distributions

Hyperbolic focal length distributions, in the transaxial plane, proposed by CEA-LETI :

$$f(x) = f_{min}\sqrt{\left(\frac{x}{x_{max}}\right)^2\left[\left(\frac{f_{max}}{f_{min}}\right)^2 - 1\right] + 1}$$



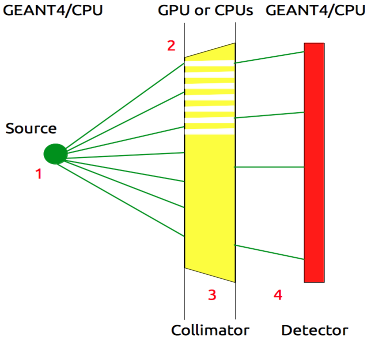
SPECT simulation in GATE : Aims

Work in collaboration with Julien Bert (LaTIM) in Brest during the first two weeks of July 2012.

- GATE/GPU and GATE/Multi-core CPUs interface for SPECT imaging.
- **Ray-tracing** technique in the collimator.
- **No interaction** modeled in the collimator (work in progress in Brest).
- Parallel and convergent **square-hole collimator** only.
- Application : small-animal SPECT ^{99m}Tc (140.5 keV).

Method

1. Particles **emission** (^{99m}Tc source).
2. **Storing the particle features** at the collimator entrance (until a buffer is full).
3. When the buffer is full, we **project the particles** onto the collimator exit with the ray-tracing technique on GPU or on multi-core CPUs.
4. When the buffer content is processed, we **complete** the simulation as usual **in GATE** creating new tracks corresponding to the exiting particles.



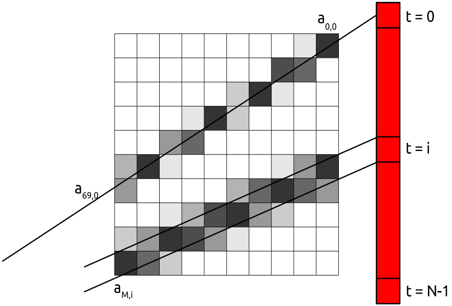
Results

- Factor 10 between GPU (580 GTX) and 1 CPU (Intel XEON) in collimator only (for a point source simulation, 1 GBq, 0.1 sec. acquisition duration, size of buffer 20000000 particles). 40 min simulation duration.
- GATE/GPU and GATE/Multi-core CPUs interface available.
- Ray-tracing limitation : no particle interaction within the collimator is modeled, so only appropriate for ^{99m}Tc.
- Future work :
  - Modeling the particle interactions within the collimator (work in progress in Brest) : scatter and septal penetration will be simulated.
  - Extending to other collimator geometry (only square-hole collimators are supported at the moment).

OS-EM-ML

Using the OS-EM-ML[3] iterative algorithm :

- **Neither scatter nor attenuation correction.**



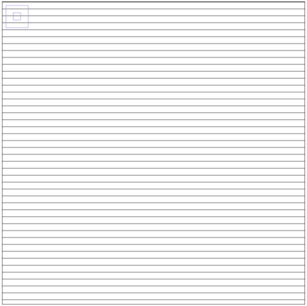
$$\lambda_j^{(k+1)} = \frac{\lambda_j^{(k)}}{\sum_{t \in S_i} \frac{\alpha_{t,j}}{N_t}} \sum_{t \in S_i} \frac{\alpha_{t,j} p_t}{\sum_{b=0}^{M} \alpha_{t,b} \lambda_b^{(k)}}$$

- k : iteration
- S_i : subset i
- λ_j : estimate voxel j
- t : element in subset
- $\alpha_{t,j}$: system matrix entry
- N_t : normalized element t
- p_t : data pixel element t
- M : voxel elements

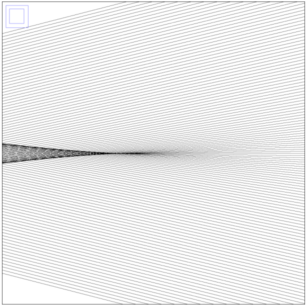
[3] *H. M. Hudson et al., "Accelerated image reconstruction using ordered subsets of projection data", IEEE Trans. Med. Imaging, vol. 13, no. 4, pp. 601-609, 1994.*

Siddon[4] Ray-Tracer (S-RT)

A projection line links the center of a detector pixel to the corresponding focal line.
Voxel : 37x750x37 μm^3



Parallel collimator

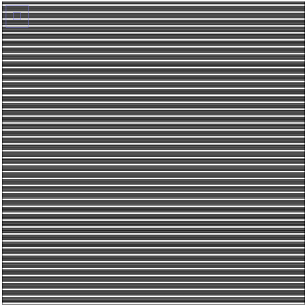


SVF-CB In collimator

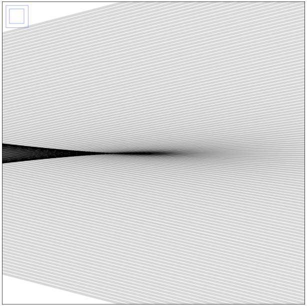
[4] R. L. Siddon, "Fast calculation of the exact radiological path for a three dimensional CT array", Med. Phys., vol. 12, no. 2, pp. 252-255, 1985.

Siddon Ray-Tracer with Intersection Volume (S-RT-IV)

A projection line links a point randomly selected at the detector pixel surface to the corresponding focal line.
Voxel : 37x750x37 μm^3, 1024 rays



Parallel collimator

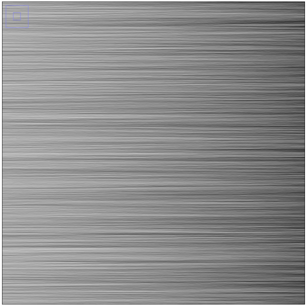


SVF-CB In collimator

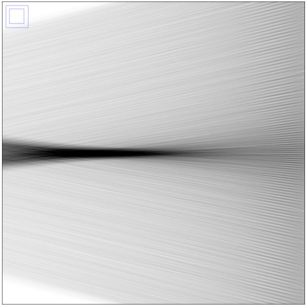
Siddon Ray-Tracer with Solid Angle (S-RT-SA)

A projection line links a point randomly selected at the detector pixel surface and a point randomly selected at the entrance of the collimator hole.

Voxel : 37x750x37 μm^3, 1024 rays



Parallel collimator

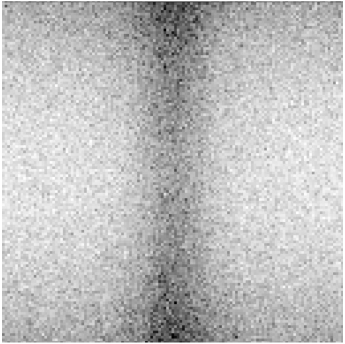


SVF-CB In collimator

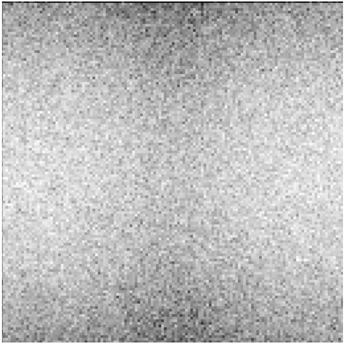
Normalization (1)

Data are normalized in order to get the same efficiency for each pixel detector elements. The normalization map was obtained by :

- Simulating a planar ^{99m}Tc source in GATE (10 mm width) close to the collimator (15 MBq, 5120 seconds acquisition duration).



GATE SVF-CB In simulation



GATE SVF-CB Out simulation

Normalization (2)

- Projecting an analytic planar source (as in GATE) with the different projectors. Storing in an array the ratio between our model (A) and the Monte Carlo (MC) model.

$$EFF_t = \frac{MC_t}{A_t}$$

- Computing the mean value of these ratios.

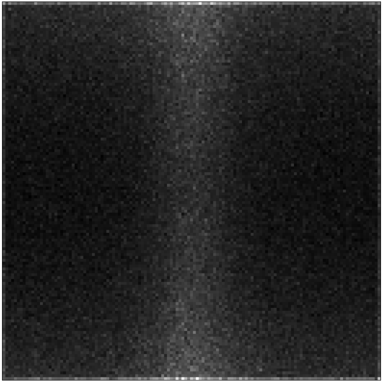
$$\overline{EFF} = \frac{\sum_{t=0}^{N-1} EFF_t}{N}$$

- Normalization :

$$Norm_t = \frac{\overline{EFF}}{EFF_t}$$

Normalization (3)

Examples of normalization maps :

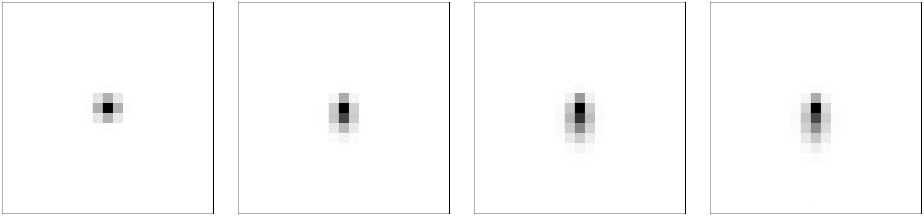


SVF-CB In normalization

PSF Model (1)

To improve the spatial resolution in the reconstructed images, we developed a PSF model for the SVF-CB collimator (non-stationary and anisotropic). For the parallel hole collimator we used an empiric stationary and isotropic PSF.

Example of few simulated points (0 mm in axial plane) reconstructed with S-RT-SA projector and SVF-CB In collimator :



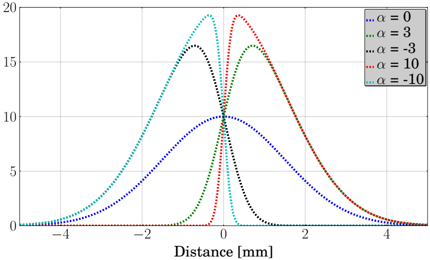
0 mm radial | 8 mm | 24 mm | 30 mm

PSF Model (2)

As in [5], we defined a kernel PSF for each voxel in the image space, and we expressed the PSF as a 1D axial function and 2D transaxial functions. The reconstructed point sources were fitted with a skew distribution :

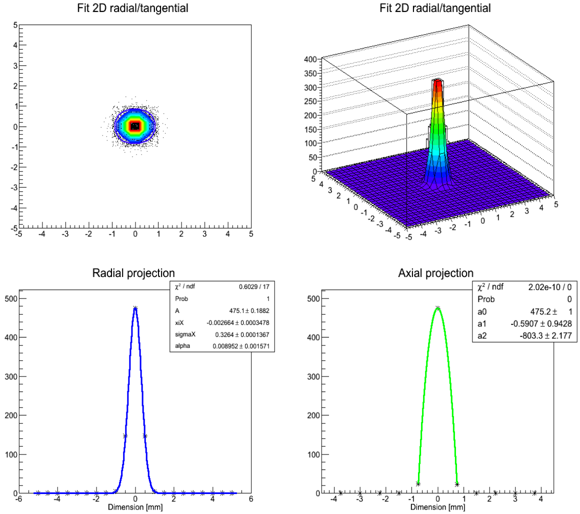
$$G(x) = Ae^{-\frac{(x-\xi_x)^2}{2\sigma_x^2}} \left[1 + erf(\alpha\frac{(x-\xi_x)}{\sigma_x\sqrt{2}})\right]$$

- ξ : location
- σ : scale
- α : shape



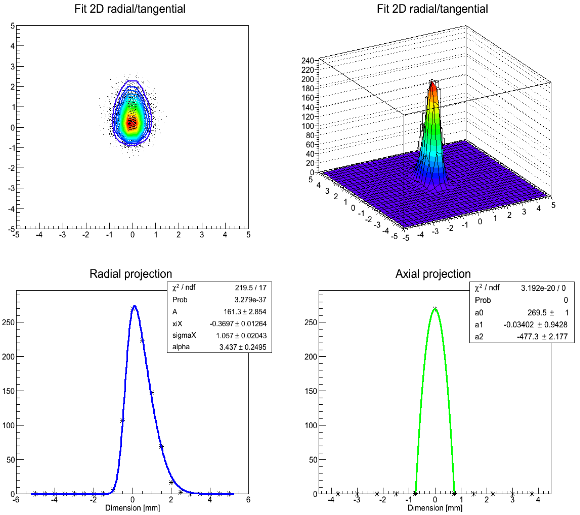
[5] C. Cloquet et al., "Non-Gaussian space-variant resolution modelling for list-mode reconstruction", Phys. Med. Biol., vol. 55 5045, 2010.

PSF Plotting example (1)



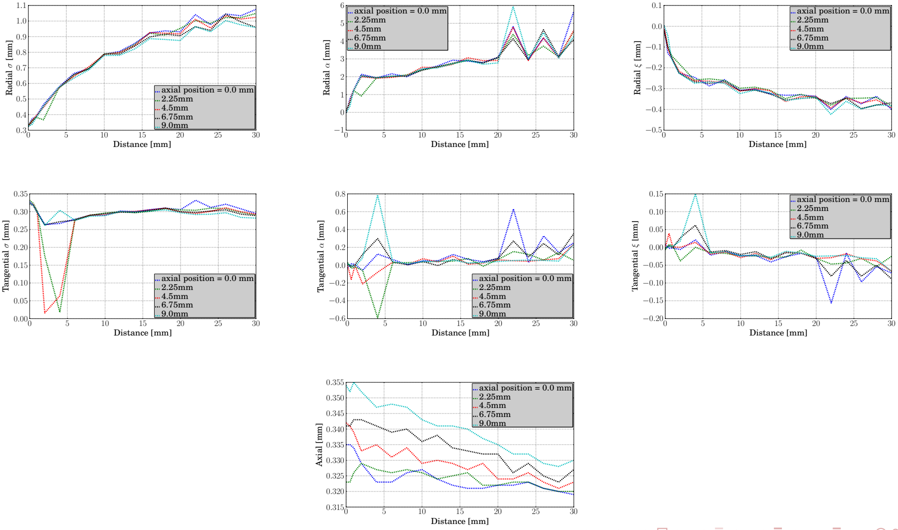
Point source : 0.0 mm in axial position and 0.0 mm in radial position

PSF Plotting example (2)

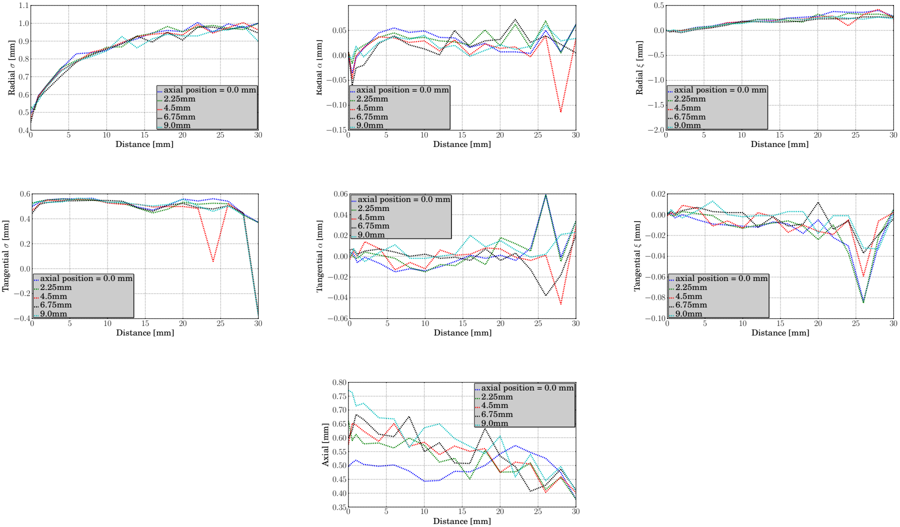


Point source : 0.0 mm in axial position and 28.0 mm in radial position

PSF evolution : S-RT-SA (voxel 500 μm, 4096 rays)

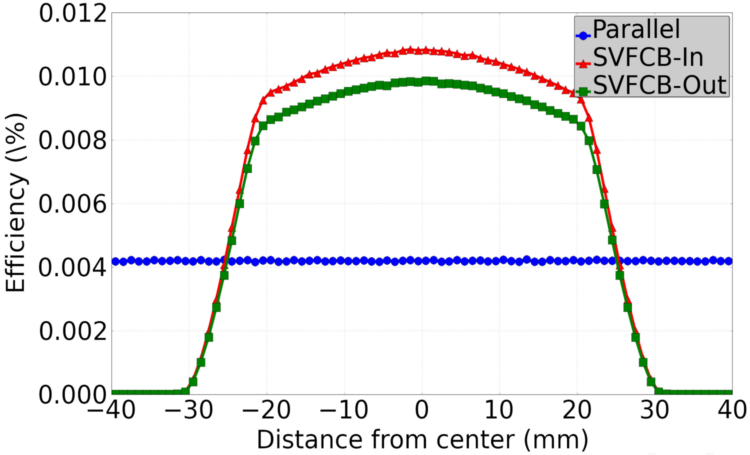


PSF evolution : S-RT-IV (voxel 500 μm, 4096 rays)

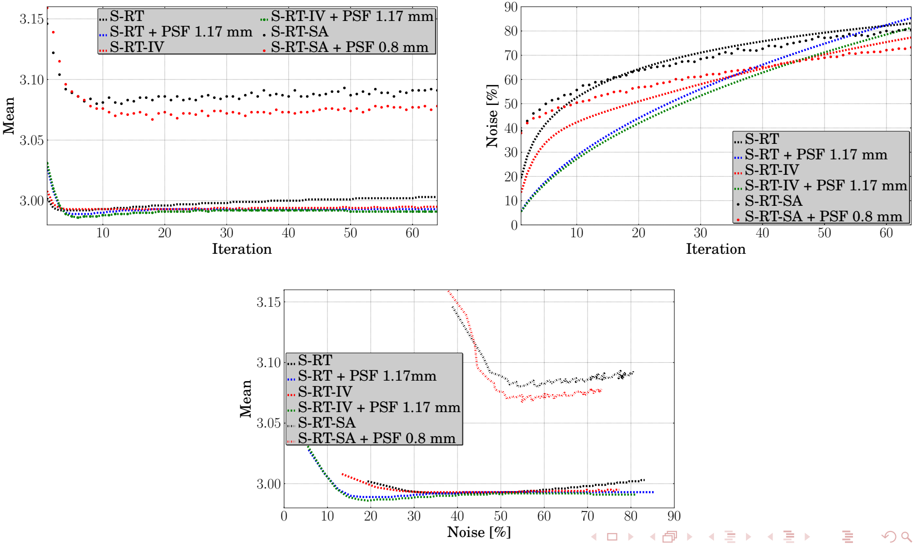


Sensitivity

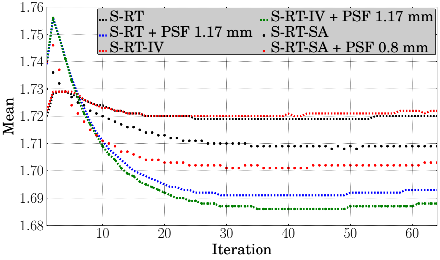
We simulated a ^{99m}Tc cylindrical source (12.5 mm radius, 90 mm height), at the center of the FOV. 60 projections (over 360°), 117 MBq and 48 seconds per projection.

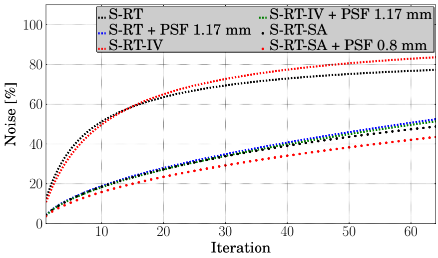


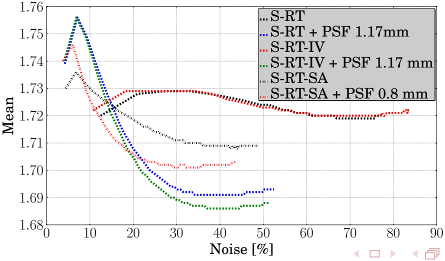
Results : Parallel-hole collimator



Results : SVF-CB In collimator

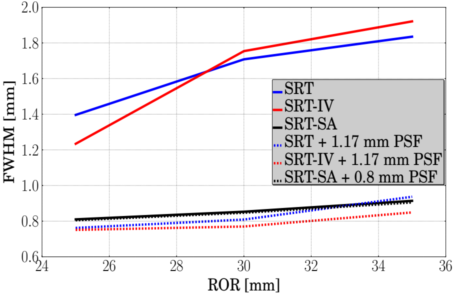




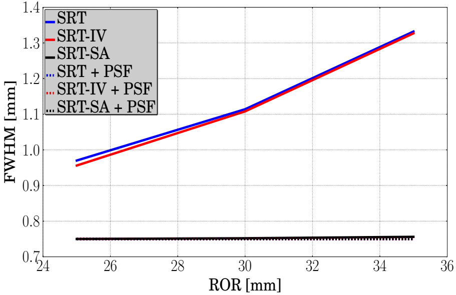


Spatial Resolution (1)

Simulations of line sources filled with ^{99m}Tc and 47,36 MBq (diameter 0.28 mm, length 90 mm) in air at 2.25 mm from the FOV center. We simulated three different ROR : 25, 30 and 35 mm, with 60 projections, 32 sec per projection.



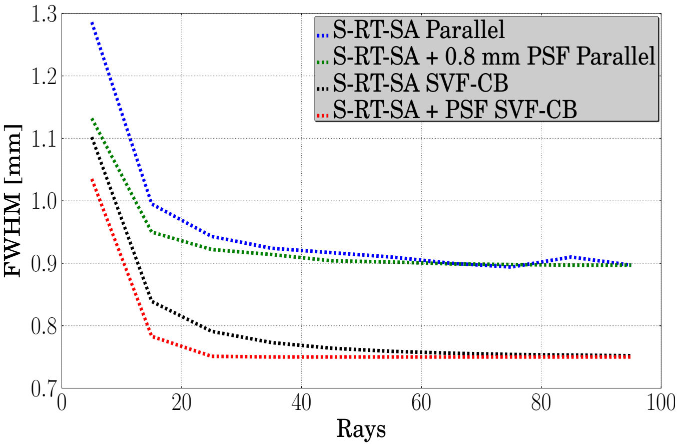
Parallel collimator



SVF-CB In collimator

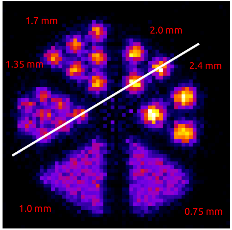
Spatial Resolution (2)

FWHM variation as a function of the number of rays for the line source with 35 mm ROR and the S-RT-SA projector.

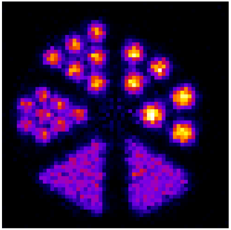


Spatial Resolution (3)

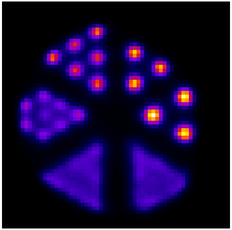
Derenzo simulations with hot inserts (2.4 mm, 2.0, 1.7, 1.35, 1.0 and 0.75). Each insert is filled with 15.9 MBq/mL ^{99m}Tc. No background activity. Derenzo at the center of the FOV, 120 projections, and 30 seconds per projection.



S-RT, parallel no PSF

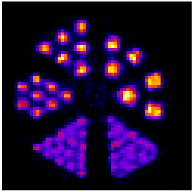


S-RT-IV

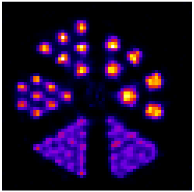


S-RT-SA

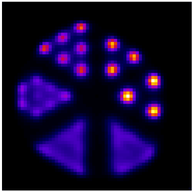
Spatial Resolution (4)



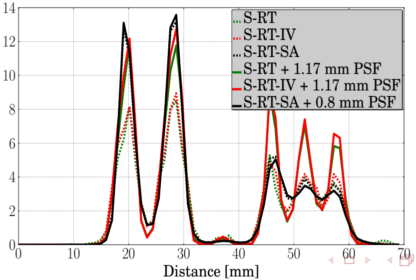
S-RT, parallel + PSF



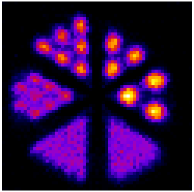
S-RT-IV



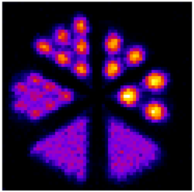
S-RT-SA



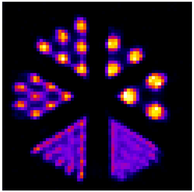
Spatial Resolution (5)



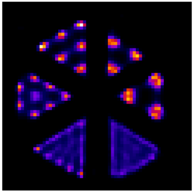
S-RT, SVF-CB In no PSF



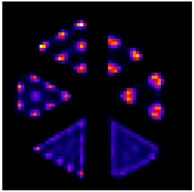
S-RT-IV



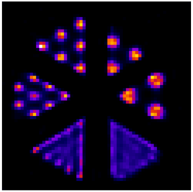
S-RT-SA



S-RT, SVF-CB In + PSF

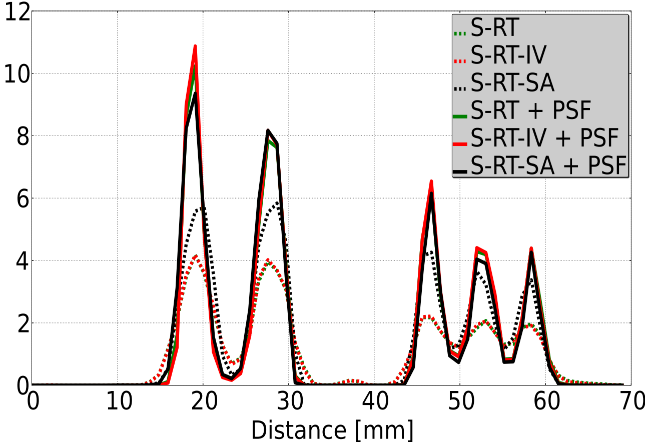


S-RT-IV



S-RT-SA

Spatial Resolution (6)



Conclusion/Perspectives

- Reconstruction for an SVF-CB collimator with focal lengths within the FOV is feasible.
- First SVF-CB collimator design for small-animal SPECT.
- Higher sensitivity of the SVF-CB collimator compared to the parallel collimator.
- S-RT-SA more accurate than S-RT because all geometric effets are included.
- The PSF model improves the spatial resolution.
- An original PSF model for an SVF-CB collimator has been developed.
- Future work :
  - Adapt the PSF model to te whole image space and improve it.
  - Compute the system matrix by Monte-Carlo simulation and compare to our PSF model for SVF-CB collimator.