Implementation of acollinearity in PET Monte Carlo simulations: a subtle misinterpretation hiding in plain sight

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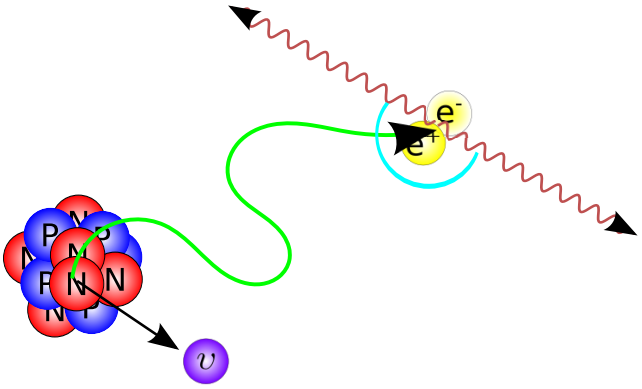
[2]Instituto de Instrumentación para Imagen Molecular (I3M), Centro Mixto CSIC - Universitat Politècnica de València, Valencia, Spain
[3]IR&T Inc., Sherbrooke, QC, Canada [4]Independent researcher, QC, Canada
[5]Department of Computer Science, Université de Sherbrooke, Sherbrooke, QC, Canada

CIMS Centre d'imagerie moléculaire de Sherbrooke

22 May 2024

UDS Université de Sherbrooke

Annihilation photon acollinearity (APA) in PET



Inspired from www.depts.washington.edu/imreslab

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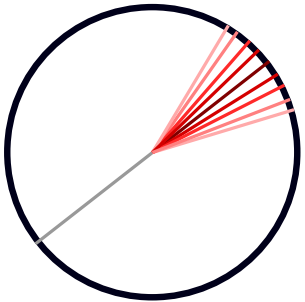

Example of APA

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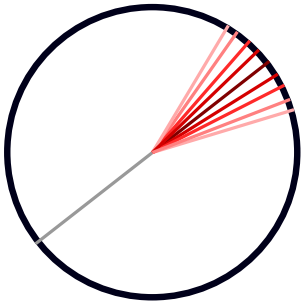

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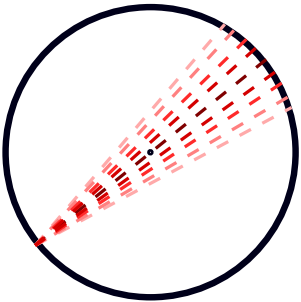

APA in projection space

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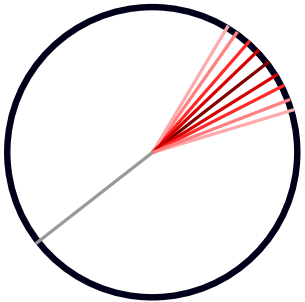

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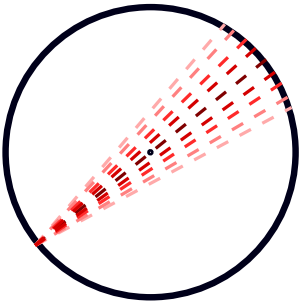

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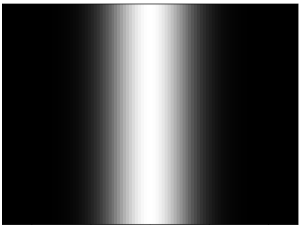

Theoretical sinogram

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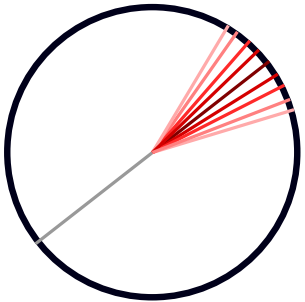

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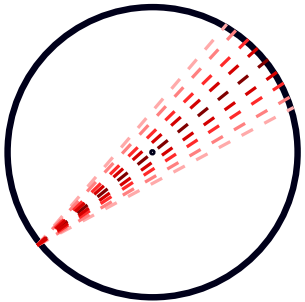

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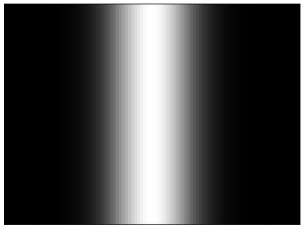


Theoretical sinogram

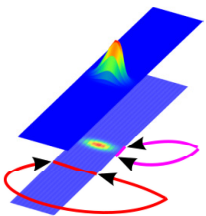
Blur induced by APA:

Isotropic 2D Gaussian for a point source at the center of a 2D scanner shaped as a perfect circle

The beginning

Goal (back in 2019):

Validate that ultrafast TOF can mitigate the blur induced by detector size



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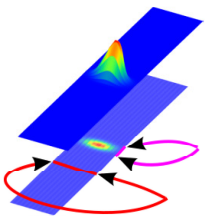
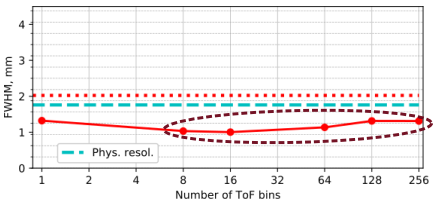


Role of APA:

Demonstrate that the results were not due to numerical artifacts

The beginning

^{18}F positron point source



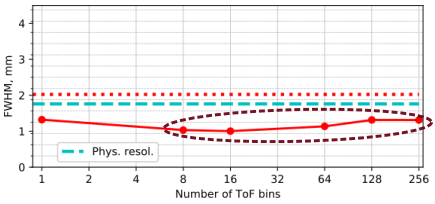
Spatial resolution achieved with 2-mm FWHM TOF

Theoretical instrumental spatial resolution limit

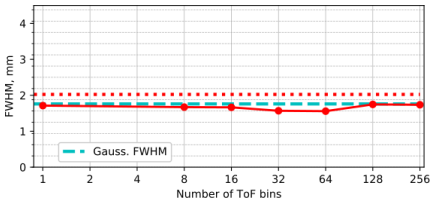
Theoretical FWHM of factors not modelized in the system matrix

The beginning

^{18}F positron point source



Gaussian-shaped source



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Sanity check: GateBenchmarks

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Repository of GATE macros built to ensure that various functionalities are working correctly

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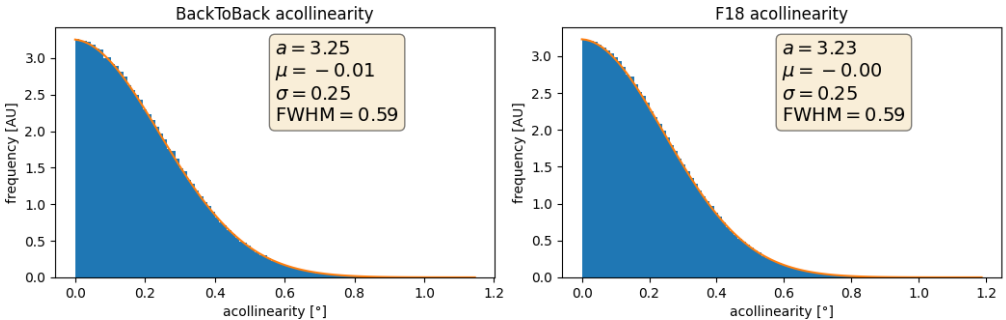
t_19acollinearity:

Test created to validate the implementation of acollinearity

Sanity check: GateBenchmarks



Result of t_19acollinearity with GATE 9.2

Understanding APA

Response function of APA:

Gaussian distribution with a $\approx 0.4^\circ$ FWHM[1]

[1] Moses, "Fundamental limits of spatial resolution in PET".

[2] Colombino, Fiscella, and Trossi, "Study of positronium in water and ice from 22 to -144 °C by annihilation quanta measurements".

Understanding APA

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Gaussian distribution with a $\approx 0.4^\circ$ FWHM[1]

Trivia:

Estimated from water at 20°C (significantly sharper at -144°C)[2]

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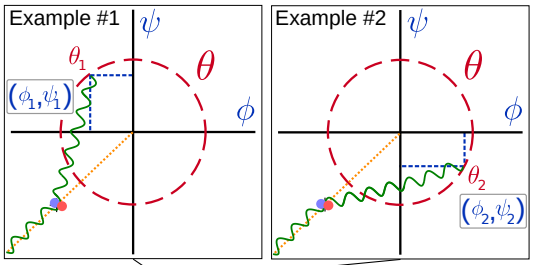

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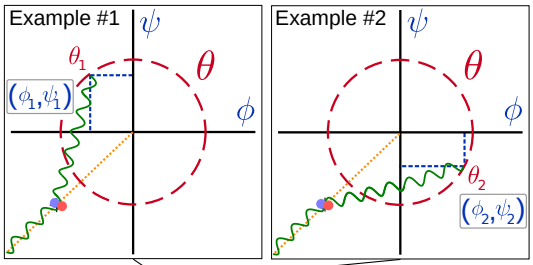
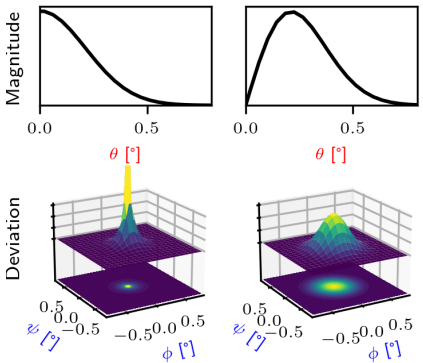


Parametrization



Acollinearity: magnitude vs deviation

So... deviation or magnitude?

Origin:

Positronium (ortho/para) vs non-zero kinetic energy vs laboratory frame

So... deviation or magnitude?

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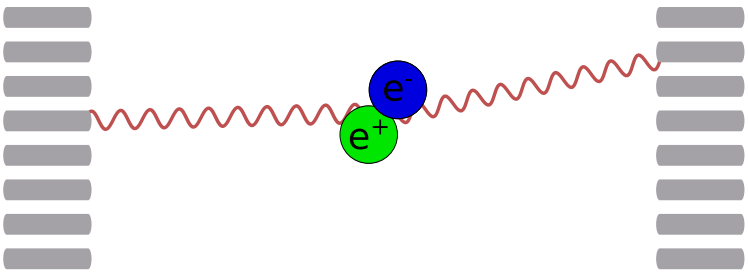
Positronium (ortho/para) vs non-zero kinetic energy vs laboratory frame

Conclusion?

Theoretical particle physics is complex

So... deviation or magnitude?



Based on distance[1]

[1] Colombino, Fiscella, and Trossi, "Study of positronium in water and ice from 22 to -144 °C by annihilation quanta measurements".

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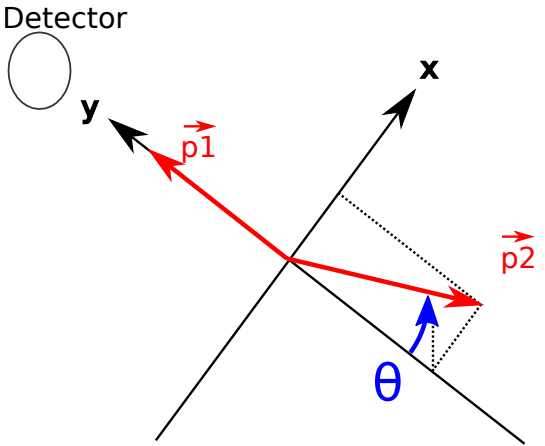
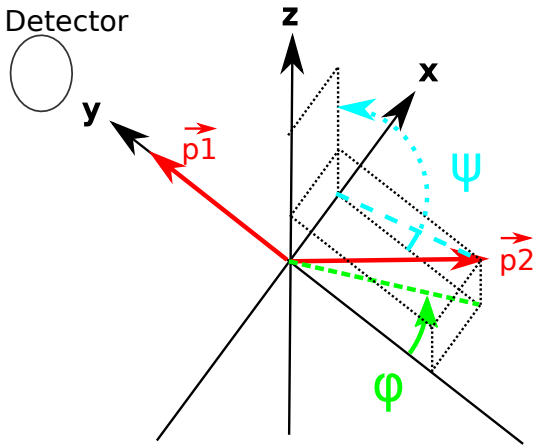


Based on ΔE of $\gamma\gamma$[1]

[1] Shibuya et al., "Annihilation photon acollinearity in PET: volunteer and phantom FDG studies".

So... deviation or magnitude?



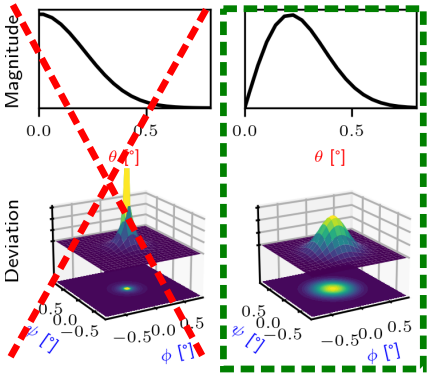
Two angles parametrization[1]

[1] Toussaint et al., A rewriting of the relation between the acolinearity of annihilation photons and their energy in the context of positron emission tomography.

So... deviation or magnitude?

Conclusion:

APA deviation follows a 2D Gaussian



Implementation of APA in GATE: a historical review

- At the time of GATE creation, APA, in the context of PET, is not available in Geant4

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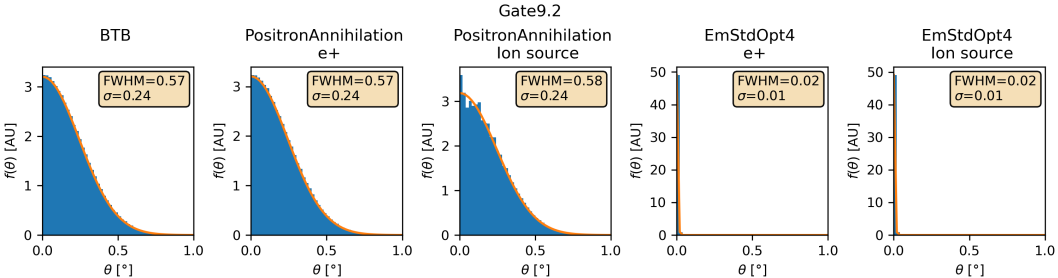
- So... end of the story? Not so fast!

Implementation of APA in GATE: a historical review



APA in GATE prior to version 10.0

Effect on PET simulation: does it matter?

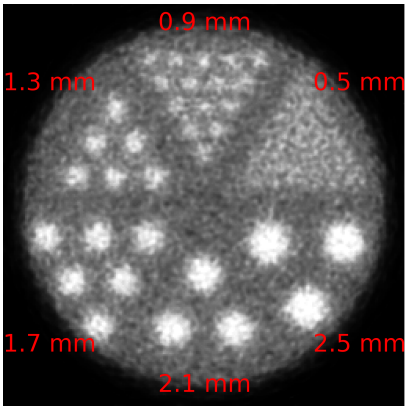
Context:

- Scanner diameter: 80 cm
- APA: 0.59° FWHM (GATE hard-coded value)
- Detector width: 0.5 mm

Theoretical instrumental spatial resolution:

2.1 mm

Effect on PET simulation: does it matter?



GaussMag, 70 it.

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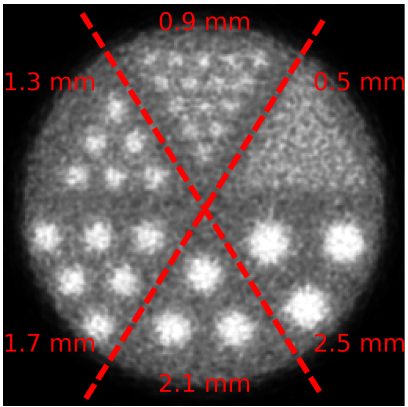

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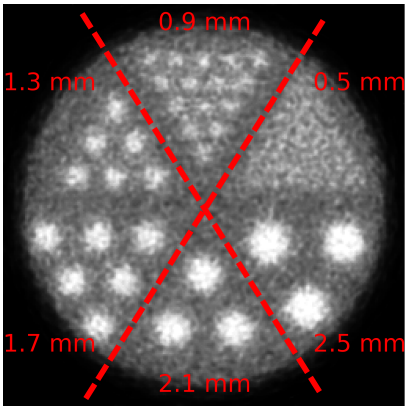

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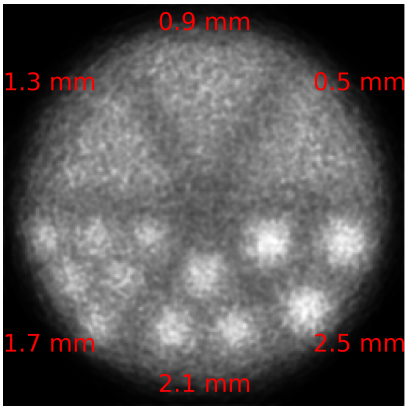

GaussDev, 40 it.

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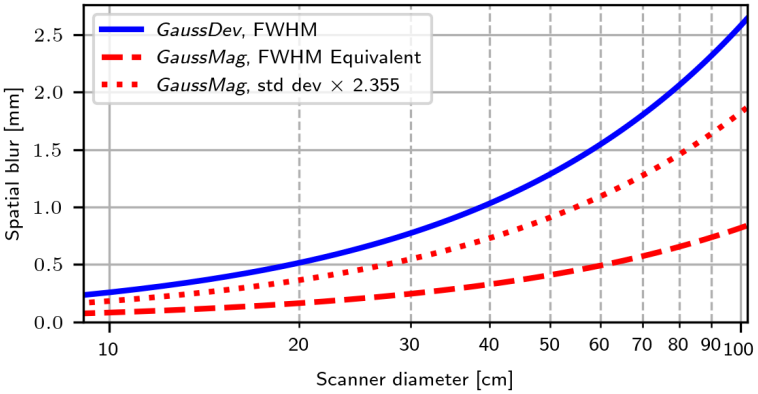

Theoretical spatial blur induced by APA at the center of a PET scanner

Current situation

[1] Thompson, Moreno-Cantu, and Picard, "PETSIM: Monte Carlo simulation of all sensitivity and resolution parameters of cylindrical positron imaging systems".

[2] España et al., "PeneloPET, a Monte Carlo PET simulation tool based on PENELOPE: features and validation".

[3] Jan et al., "GePETtoS: a Geant4 Monte Carlo simulation package for positron emission tomography".

[4] Arce et al., "Gamos: A framework to do Geant4 simulations in different physics fields with an user-friendly interface".

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[6] Toussaint et al., "On the implementation of acollinearity in PET Monte Carlo simulations".

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- Not unique to GATE; observed it in all PET simulation software I was able to access
  - e.g., PETSIM[1], PeneloPET[2], GePEToS[3], GAMOS[4] and SMART-PET[5]
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- Incorrect implementation of APA in GATE 9.4 and previous
  - If you can compile the program, two solutions are proposed in[6]
- Available soon in GATE 10
  - Geant4 implementation can be activated for ion and positron sources
  - It will be available for GenericSource soon^{TM}
    - Known as back-to-back prior to GATE 10

[1] Thompson, Moreno-Cantu, and Picard, "PETSIM: Monte Carlo simulation of all sensitivity and resolution parameters of cylindrical positron imaging systems".

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- Ensure that code refactoring and updates do not introduce any issues

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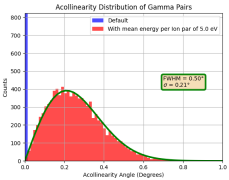
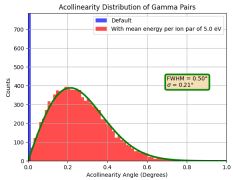
- Enable quick sanity checks
- Ensure that code refactoring and updates do not introduce any issues
- GATE 10 beta already has 80+ types of tests (Hope I am not spoiling it)

Mea culpa



BTB vs Ion, G4Material



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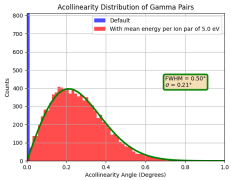
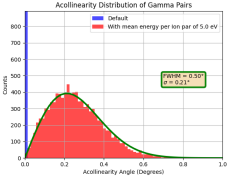
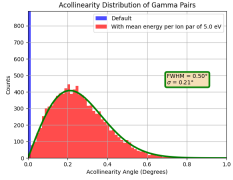


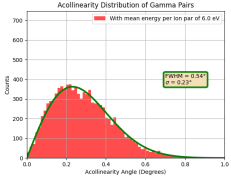
BTB vs Ion, Custom material



Ion, only one material with APA activated



e+, G4Material



Value in human subject[7]

[7] Shibuya et al., "Annihilation photon acollinearity in PET: volunteer and phantom FDG studies".

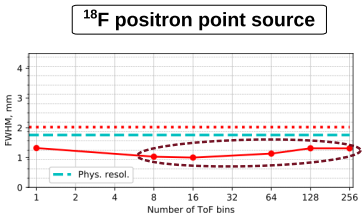
Mea culpa

The second golden rule of debugging[7]:

> When you're sure that everything you're doing is right, and your program still doesn't work, one of the things you're sure of is wrong

[7] Cooper, Oh! Pascal!

Talking about wrong assumption...



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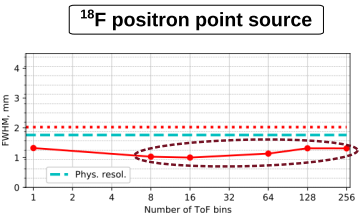

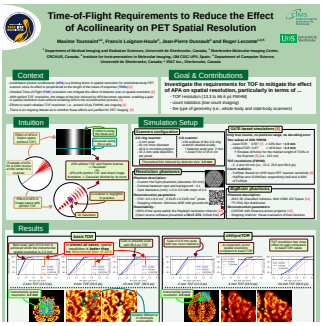

Ultrafast TOF vs acolinearity at M-08-062

Link to the poster


Fin.