ClearMind total body PET simulations with GATE

GATE meeting:
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Overview

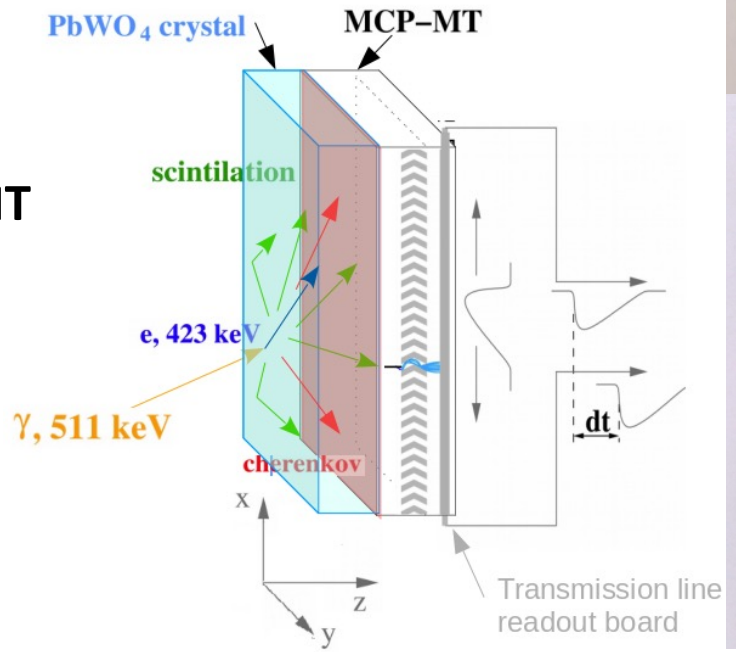
- Simulation of a ClearMind-like system
- ClearMind principles
- Experimental status
- Introduction of the AAIMME project
- Double readout with SiPM
- Geometry optimisation
- Dealing with monolithic crystals
- Introduction of a Waveform generator

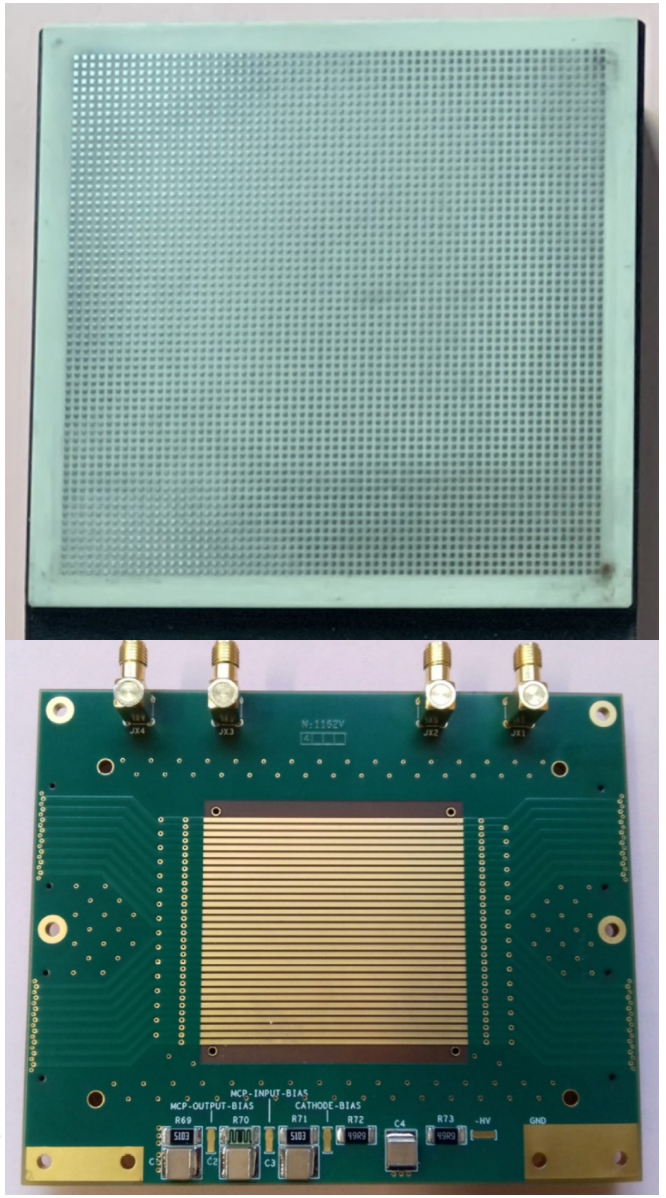
ClearMind

Aims to achieve a challenging of **ToF PET < 100 ps**:

- Current CM Prototype (CMP) [1] led crystals:
  - **Material:** $PbWO_4$
  - **Cherenkov** and scintillating
  - **Size:** 59x59x5 mm^3
  - Novel concept of crystal to **MCP-PMT direct coupling**
  - New concept for electronics

- New CMP:
  - Double side coupling with **SiPM**
  - **Size:** 59x59x10 mm^3

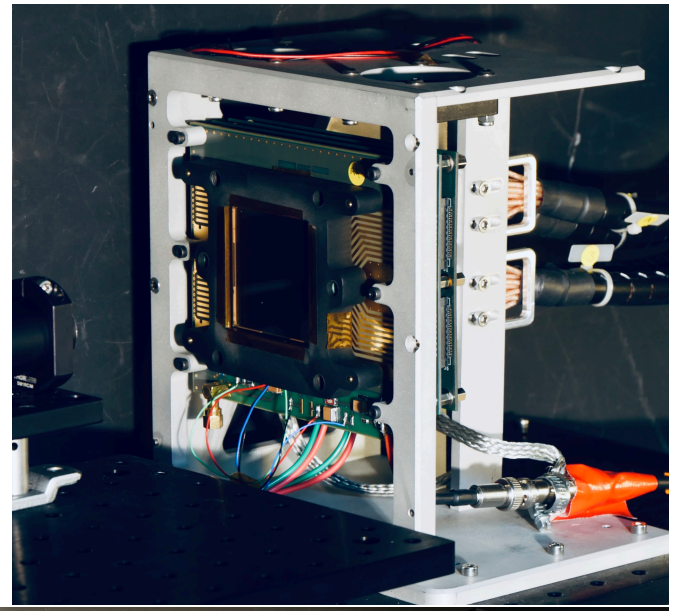


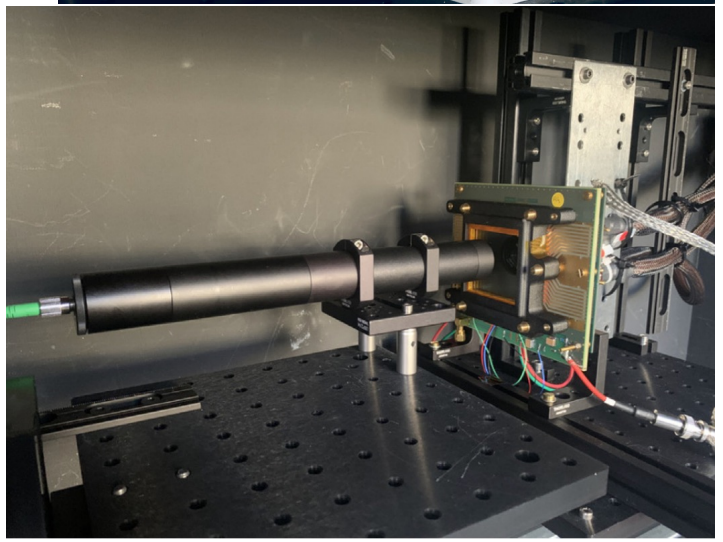


Experimental status

A ClearMind Prototype (CMP) has been tested with the MCP-PMT one side readout using:

- Lasers
- 511 KeV γ sources



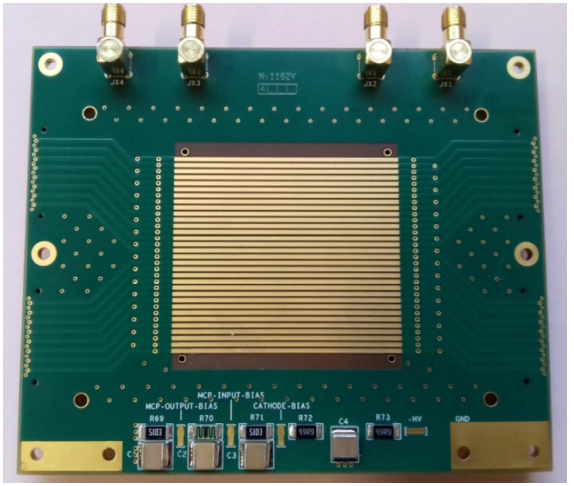


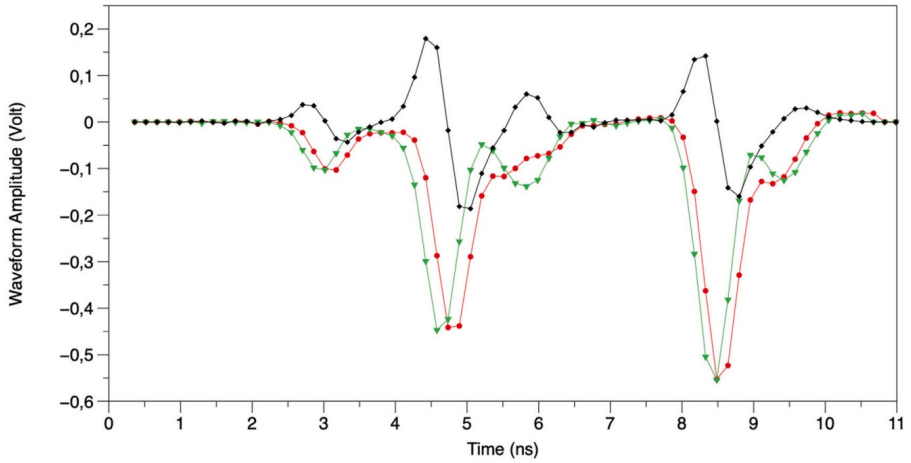
AAIMME project used AI for position interaction recontruction showing $\sigma_{x,y} = f(X, Y)$

Average of 30 photoelectrons per 511 KeV γ

Introducing AAIMME

- Position reconstruction using AI algorithms analog signal from the transmission lines [2]
- Geant4 simulations with modelled waveforms for each XY position
  - Slow simulation of optical photons
- Aim to obtain not only the position resolution but an associated error.
- Project aims to accurately compute the DOI
- Possible future introduction of a SiPM signal in the AI algorithm





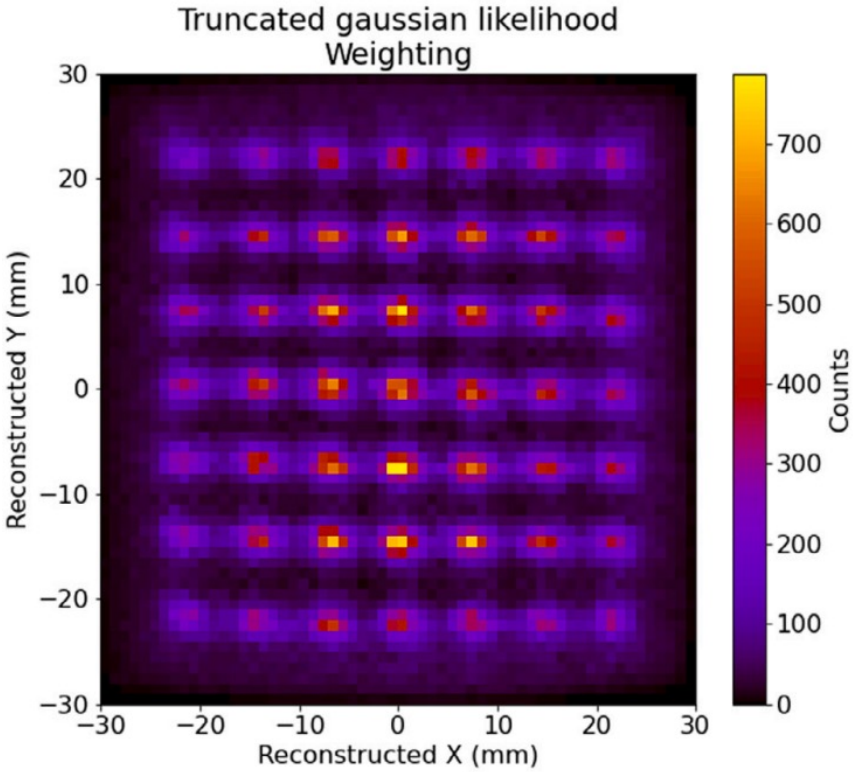
AAIMME results

- Introduction of AAIMME resolutions:
  - Resolution of x, y as a function of x and y.
    - $\sigma_{x,y} = f(X, Y)$ with:

      $\overline{\sigma_x} = 2.58\ mm$ and $\overline{\sigma_y} = 1.9\ mm$

  - Resolution for DOI still in development

Generalisation of Spatial Resolution digitizer being developed!

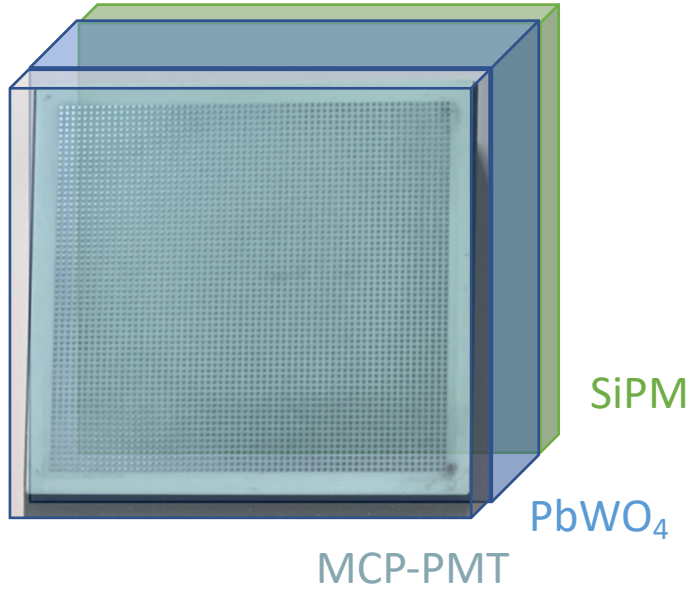


Double readout with SIPM

Expected effects of SiPM :

- Decrease in detection efficiency due to attenuation
- Improvement in energy resolution
- Improvement in spatial resolution (X,Y,DOI)
- Improvement in time resolution

What will be the effect in the final image?



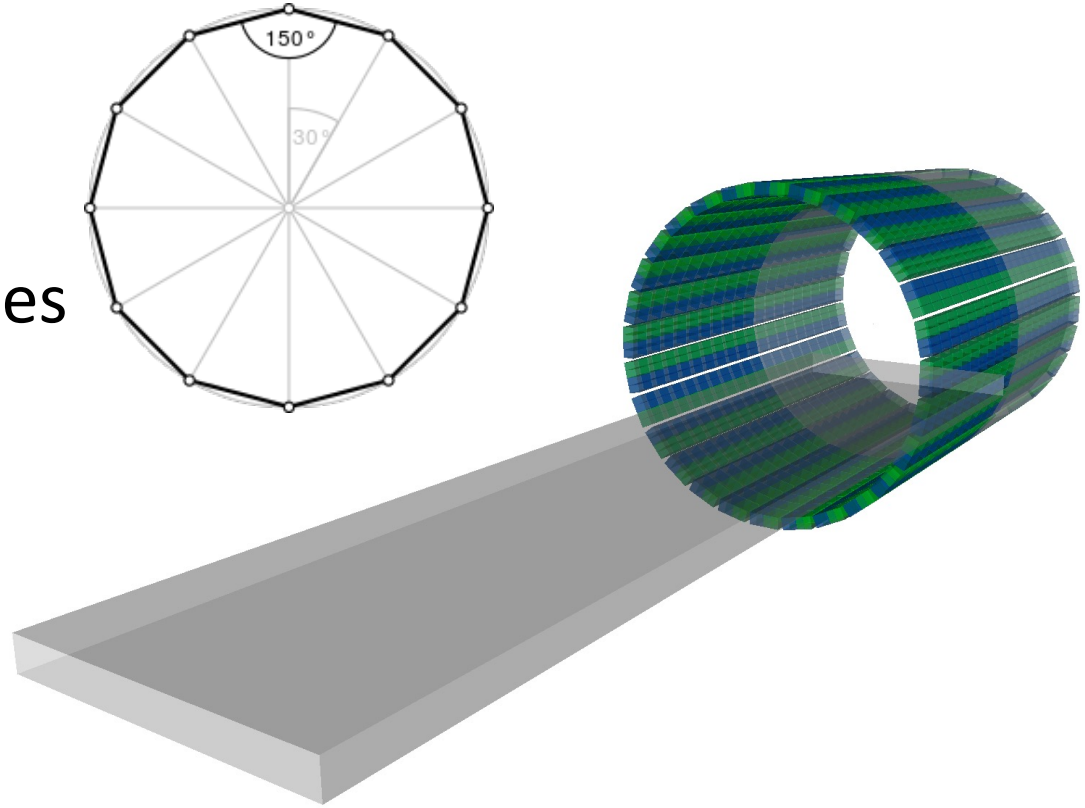
Geometry optimisation of Clear Mind with GATE

Size: 59x59x10 mm^3

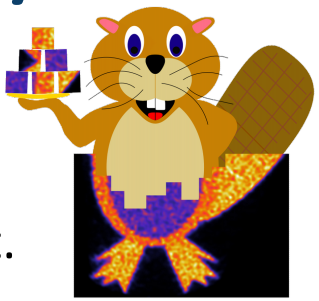
Ring Size: $\emptyset \simeq 60$ cm

Study of the effect of different gometries on total-body image:

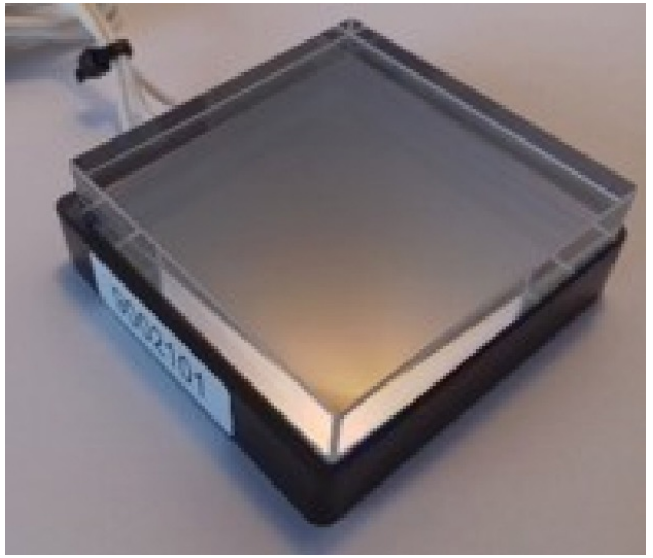
- Diameter
- Length
- Spacing between crystals
- Need for thicker crystals?



Dealing with Monolithic crystals



- The reconstruction tool CASToR works with matrix of cristals
- Each crystal has an associated ID and the position is defined by it.
- For monolithic crystals a tool to convert X,Y,Z position within the crystal to a single ID is needed
- Discretisation with a bin size smaller than the resolution: $\left(\frac{\sigma}{2} > Bin\right)$
- Need to change the macro to discretised version to use for CASToR's look-up table creator.
- With the uprise in the use of monolithic crystals this could be developed as a GATE-Tool or CASToR-Tool.



ID for monolithic crystals

X,Y position within the crystal can be converted into n_x , n_y IDs as:

$$n_x = \left(\frac{x}{bin\ size\ in\ x} + \frac{N_x}{2}\right), n_y = \left(\frac{y}{bin\ size\ in\ y} + \frac{N_y}{2}\right)$$

Where N_i is the number of bins in the ith direction

This values can be used to define a single ID for a position within a crystal with:

$$ID_{Bin} = N_y(n_x - 1) + n_y$$

Using N_s as the crystal ID in the ring, the position ID within the ring this can be used as:

$$ID_{R\ Sector} = ID_{Bin} + (n_s - 1)N_xN_y$$

With N_z as the ID of the ring within the cylinder, the position ID within the system results:

$$ID_{Pseudo-Crystal} = ID_{R\ Sector} + (n_z - 1)N_xN_yN_s$$

ID for monolithic crystals

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Where N_i is the number of bins in the ith direction

This values can be used to define a single ID for a position within a crystal with:

$$ID_{Bin} = N_y(n_x - 1) + n_y + \Delta_{Crystal}$$

Δ_{Ring} = Ring separation in numer of bins

Using N_s as the crystal ID in the ring, the position ID within the ring this can be used as:

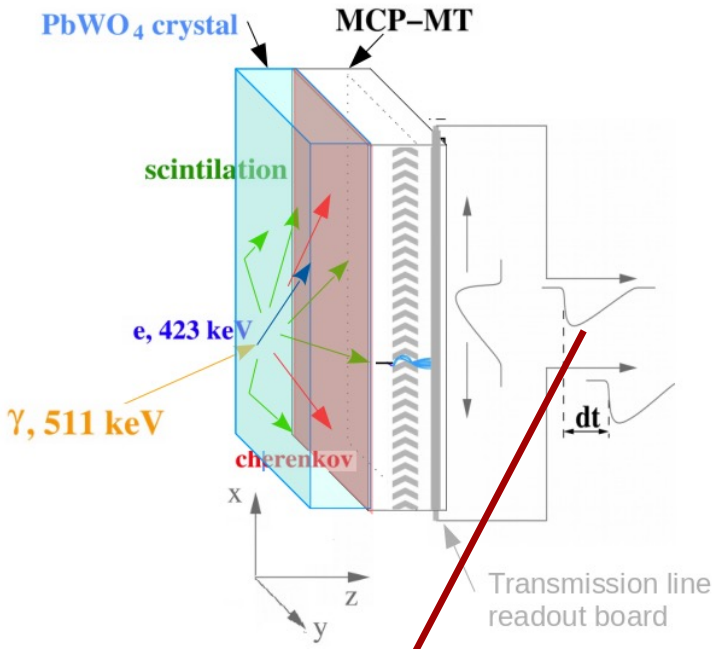
$$ID_{R\ Sector} = ID_{Bin} + (n_s - 1)N_xN_y + \Delta_{Ring}$$

$\Delta_{Crystal}$ = Crystal separation in numer of bins

With N_z as the ID of the ring within the cylinder, the position ID within the system results:

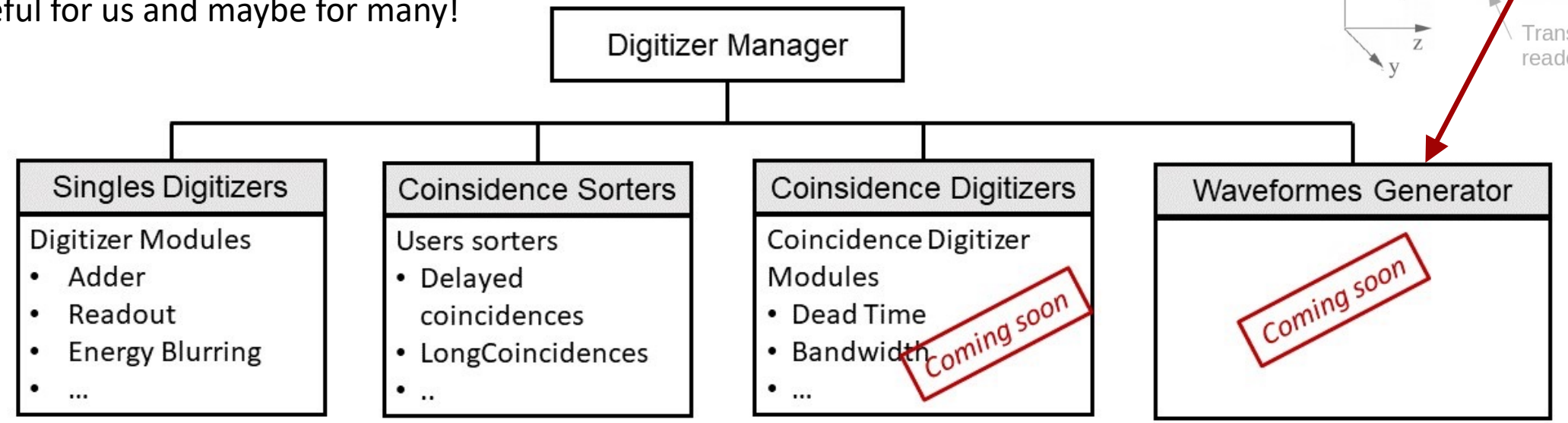
$$ID_{Pseudo-Crystal} = ID_{R\ Sector} + (n_z - 1)N_xN_yN_s$$

GATE developments



A better understanding of the analog signal can improve the whole analysis.

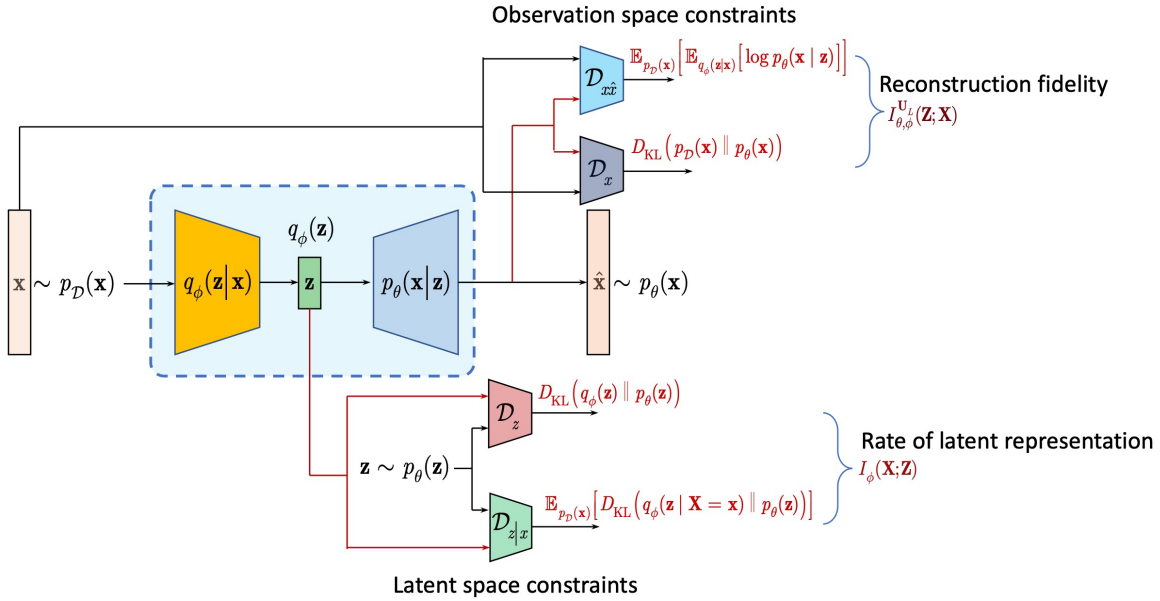
Useful for us and maybe for many!

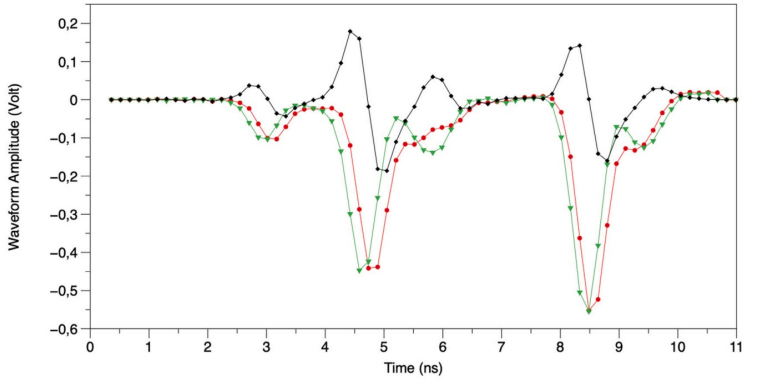


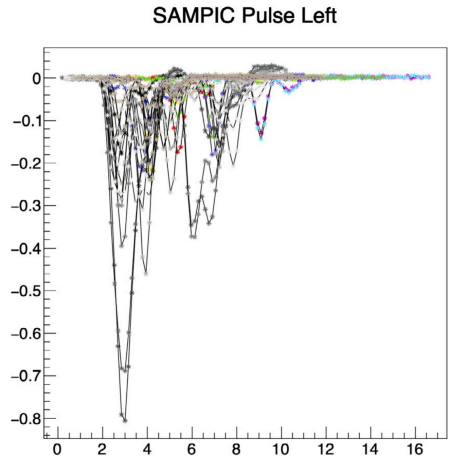
Waveform generator in GATE

Transform the energy deposition into a waveform

Possible approach: Bounded Information Rate Variational autoencoder [3] with a bottleneck with 3 dimensions (X,Y,Z)



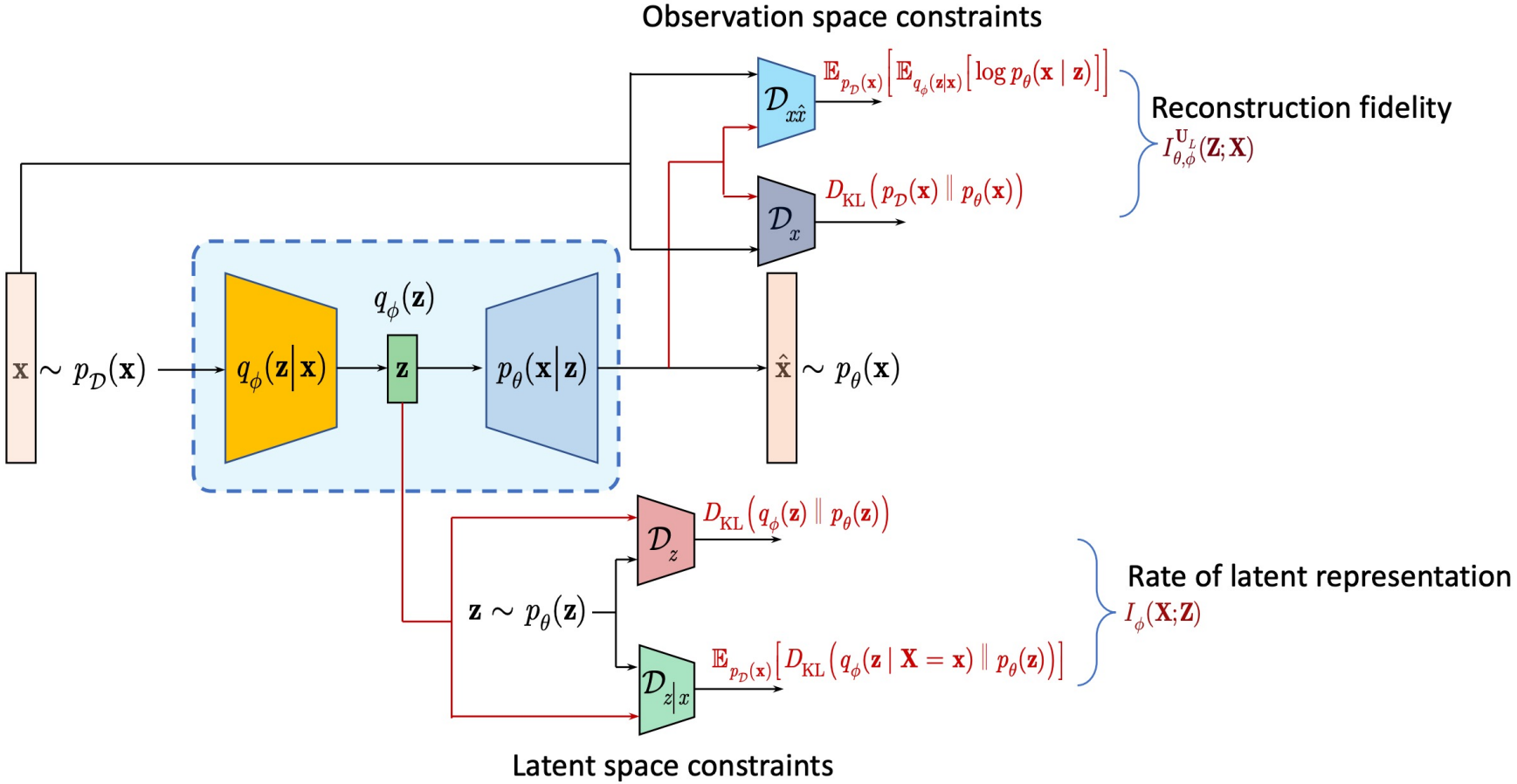




A pre-trained BIR-VAE for GATE

Aiming to create a pre-trained model with data from SiPM and MPC-PMT.

This model could be available for GATE with a tool to train it with project specific data.



Conclusions

- We want to create a full simulation of the ClearMind total-body PET system.
  - The aim is to test the effect of modifying different parameters to optimise the final image.
- The CMP developed an AI algorithm with the AAIMME project to analyse the analog signals to reconstruct the position interaction within the crystal.
- There are challenges when dealing with monolithic crystals that can be overcome with what possible could become a GATE-Tool
- The use of a SiPM for a double sided readout could improve this image reconstruction
- These studies suggest the need to create a WaveForm Generator for GATE

Thank you for your attention!

References

1. GALINDO-TELLEZ, A., et al. First ClearMind gamma detector prototype for TOF-PET imaging. *arXiv preprint arXiv:2312.13169*, 2023.

2. DANIEL, Geoffrey, et al. Deep Learning reconstruction with uncertainty estimation for γ photon interaction in fast scintillator detectors. *Engineering Applications of Artificial Intelligence*, 2024, 131: 10787.

3. BRAITHWAITE, Daniel T.; KLEIJN, W. Bastiaan. Bounded information rate variational autoencoders. *arXiv preprint arXiv:1807.07306*, 2018.