New developments in GATE 9.4 for monolithic crystal PET systems

GATE developers meeting:

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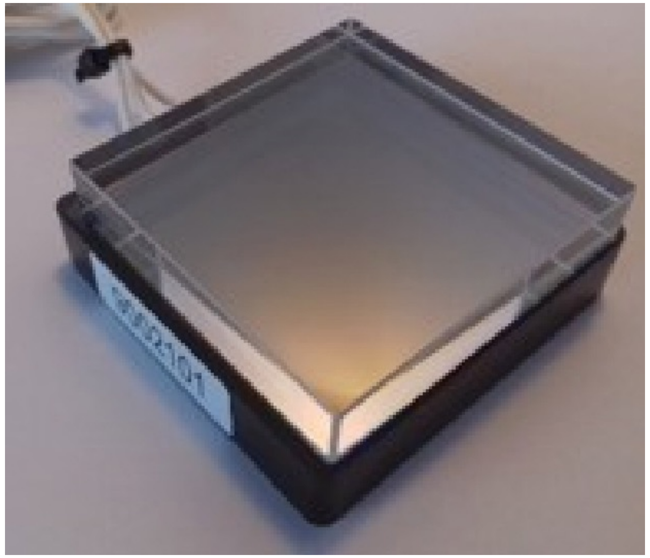
Overview

- Why do we use **monolithic crystals**?
- Understanding the needs for monolithic crystal PET scanners
  - **Position resolution** dependency of the hit position
    - With a Gate-Tool to create the input files in the right format
  - Dealing with hits at the edges and the **confined hits**.
  - **Virtual segmentation** of the monolithic crystal
    - With a Gate-Tool to create equivalent macros for **CASToR**

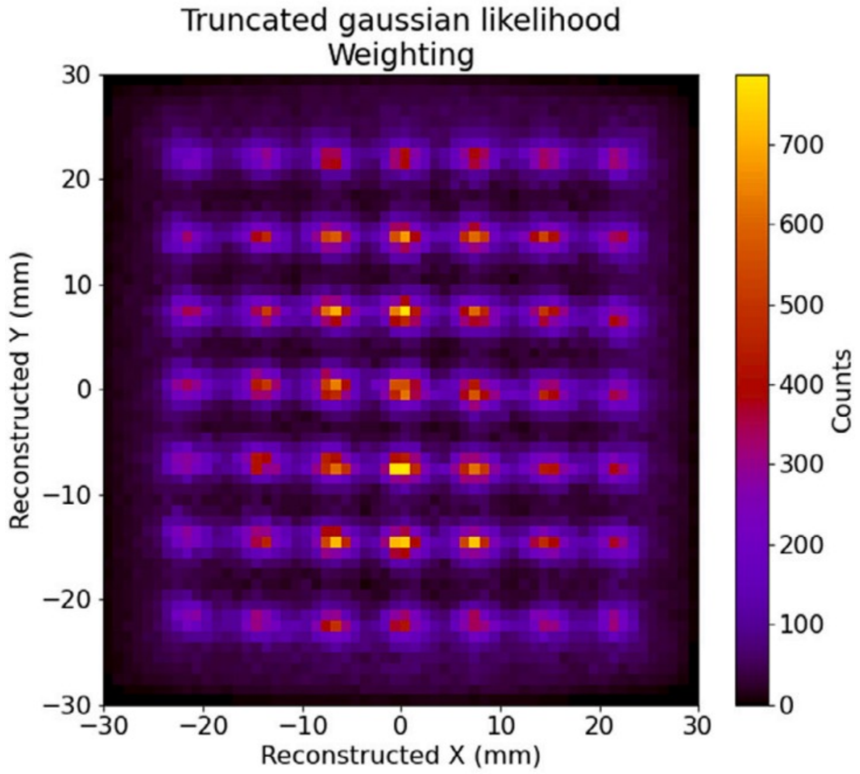
Why Monolithic crystals?

- **Monolithic crystals** appeared as a solution for **TOF PET:**
  - The increasing use of such detectors demands from a **GATE** modifications to simulate them. First tests with **ClearMind** prototype.
- Easier manufacturing process
- Increase of light collection efficiency improving **the TOF measurement** and increasing **sensitivity**
- **DOI measurement** which minimizes **parallax error**



In-crystal position reconstruction

- Within a monolithic crystal the position needs to be reconstructed.
- We worked in the context of **ClearMind** detector and ***AAIMME*** position reconstruction (right plot)
- The resolution of such reconstruction may be dependent on the interaction's position within the crystal
- The *SpatialResolution* module needs to allow a 2D distribution of the standard deviation as an input.



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: 107876.

Position dependend SR

A new module was introduced to allow 1D and 2D distributions in GATE’s spatial resolution blurring.

The module loads the distribution of the different values of standard deviation and uses the hit’s positions to find their requiered standard deviation.

Example of a macro’s code:

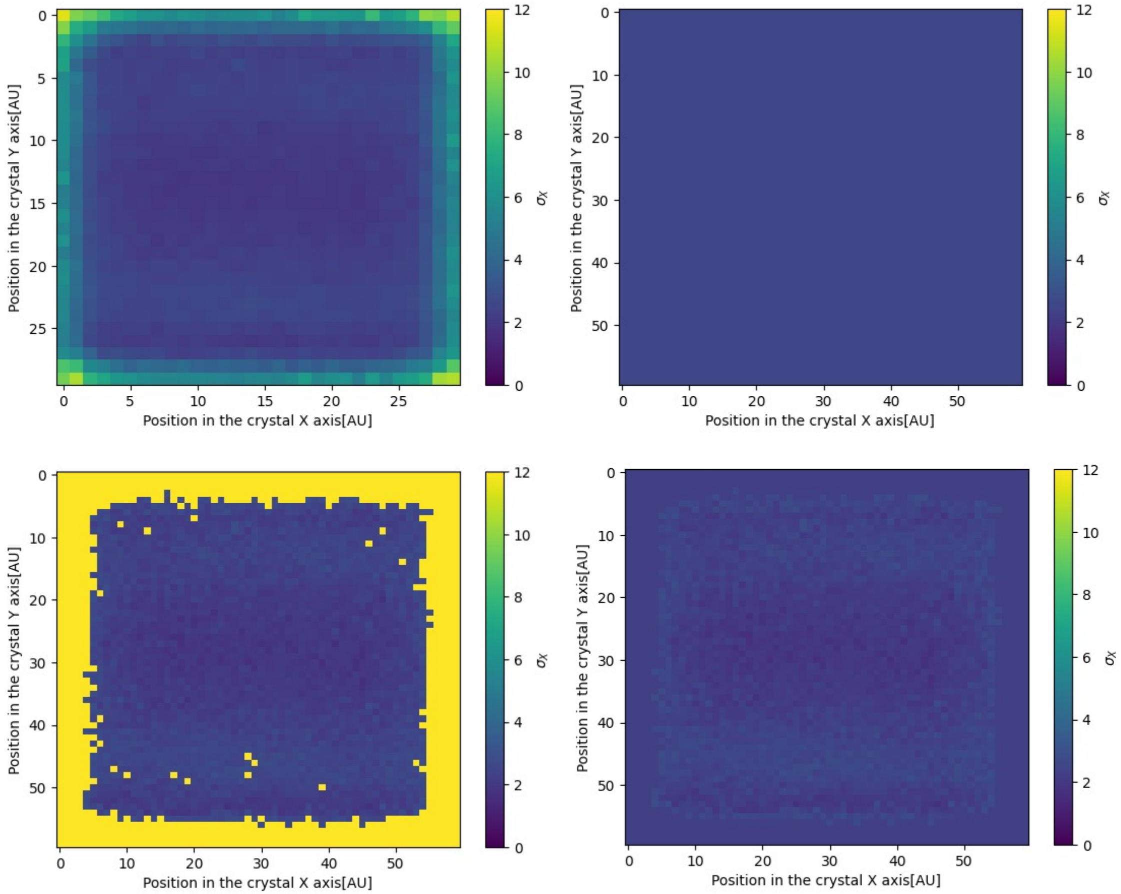
```
/gate/distributions/name my_distrib2D
/gate/distributions/insert File
/gate/distributions/my_distrib2D/setFileName data/my_stddev_distribuion_file.txt
/gate/distributions/my_distrib2D/readMatrix2d

/gate/digitizerMgr/pseudoCrystal/SinglesDigitizer/Singles/insert spatialResolution
/gate/digitizerMgr/pseudoCrystal/SinglesDigitizer/Singles/spatialResolution/nameAxis XY
/gate/digitizerMgr/pseudoCrystal/SinglesDigitizer/Singles/spatialResolution/fwhmDistrib2D my_distrib2D
```

Different distributions tested

The simulations were tested using 4 different distributions for the standard deviation within the crystal from top left to bottom right:

- The ***AAIMME*** data pooled into a 30x30 matrix
- A constant matrix of 2.55 mm standard dev.
- An exaggeration of the degradation of the standard dev on the edges by incresing it to 40 mm
- A case with zero degradation at the edges using a constant value for the external part equal to the mean of the internal



2D distribution of the FWHM

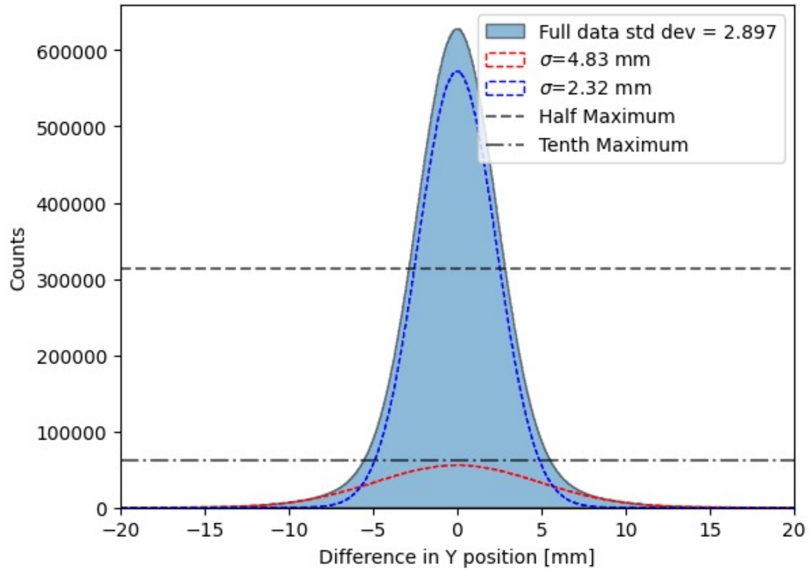
The results show a much bigger effect in the final image's noise than the measurements of the position resolution.

The effect of using a distribution has been tested and resulted to be significant, around 5% for FWHM and 16% on FWTM on the final image.

With this, dedicated algorithms could be developed to minimise the effect of the low resolution hits.

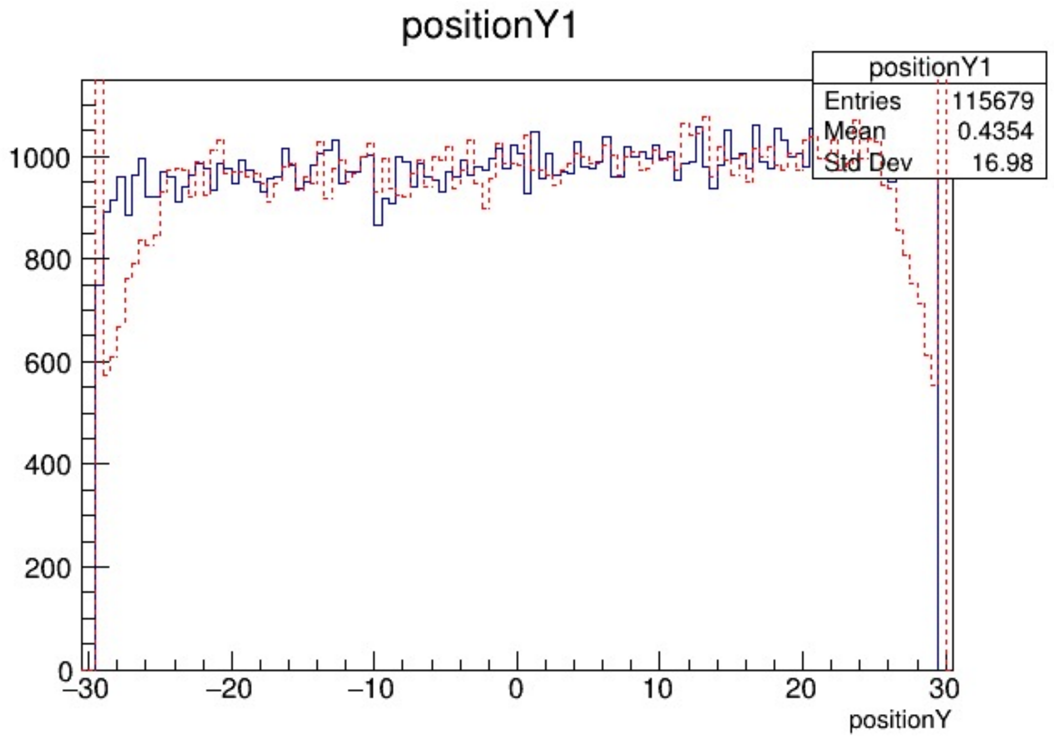
A GATE-tool has been developed to convert a .csv or .txt file into the form needed for GATE to read the files. --> Different method on the way.

Edge effect vs no edge effect

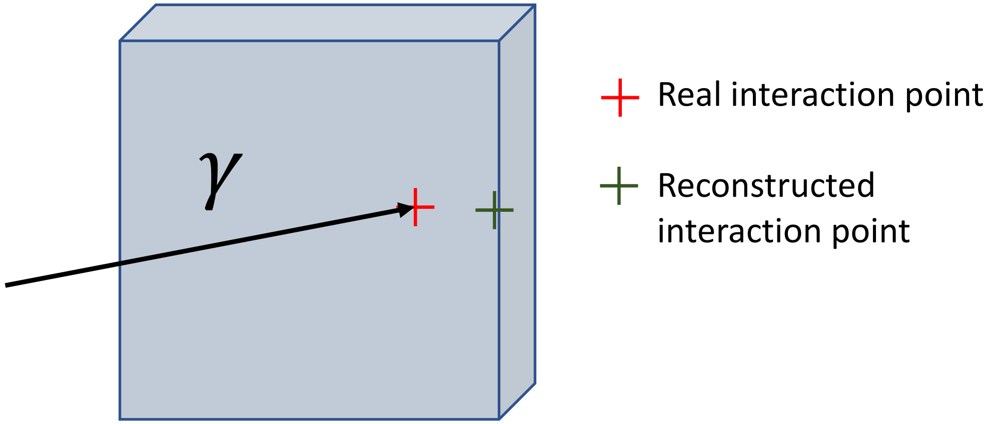


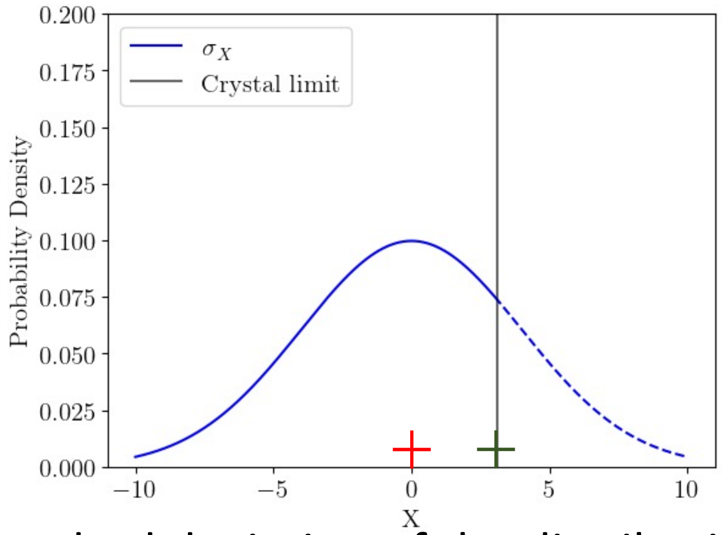
GATE edge effects

The position within the crystal is always **CONFINED!**



Original hits (blue) and reconstructed hit (red)

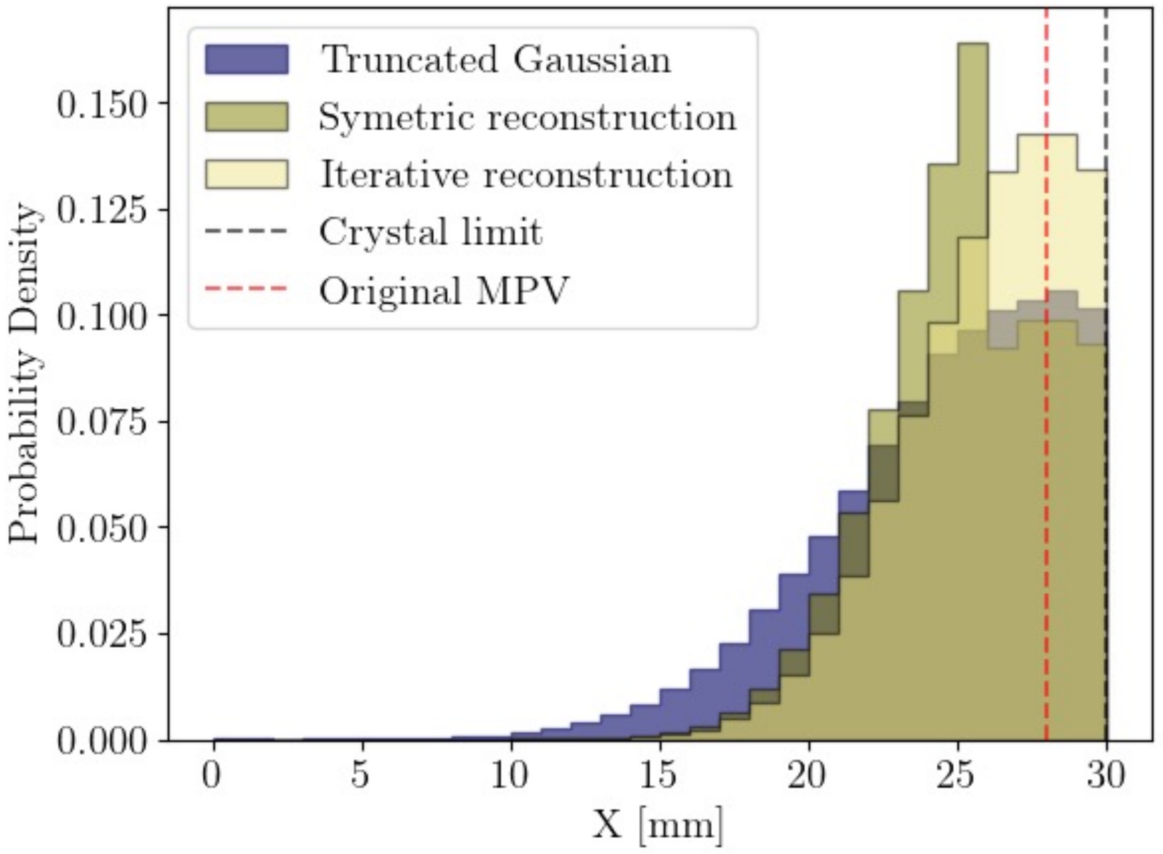




The standard deviation of the distribution is reduced and all hits that would fall out end up at the crystal's limit, closer to the original position.

Possible solutions

Values of standard deviation:
Truncated Gaussian = 4.0 mm
Symmetric reconstruction method = 2.8 mm
Iterative method = 2.8 mm



Example the possible distributions that could be used when working at the edge of the detector:

- **Symetric reconstruction:** if the position x_f is outside of the crystal apply: $x'_f = \mu - (x_f - x_0)$
- **Iterative reconstruction:** if the hit is reconstructed outside of the crystal it is randomly scattered again until it is reconstructed within the cristal
- **Trucnated Gaussian:** a truncated Gaussian is defined to have the same stddev.

The only method preserving the stddev is the truncated Gaussian.

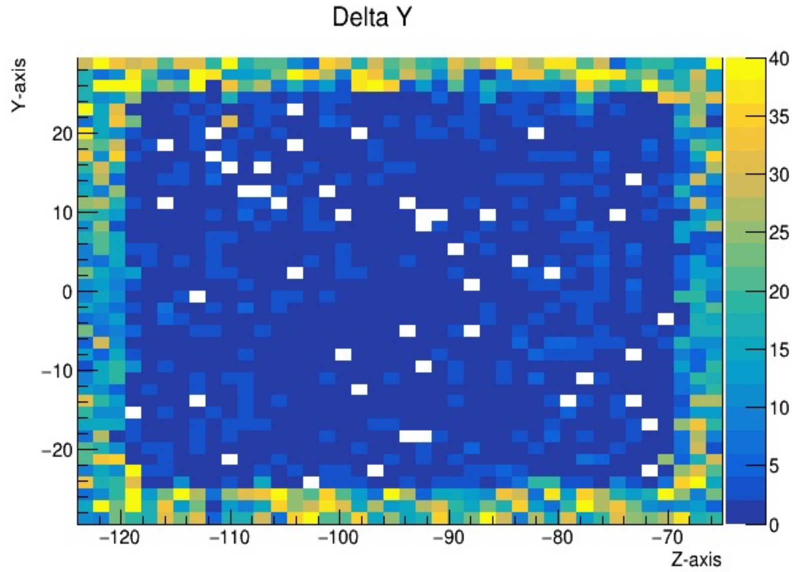
The truncated Gaussian

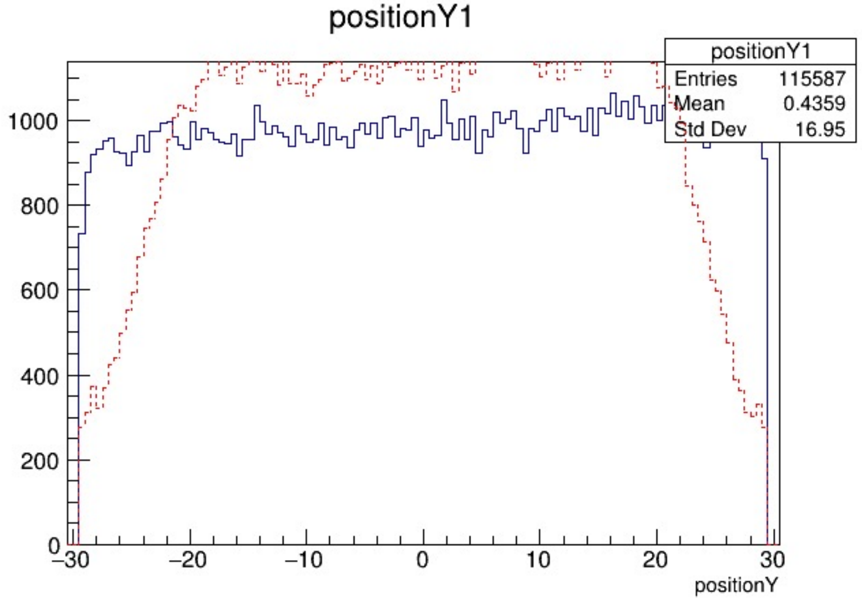
A 2D distribution with a degradation up to 40 mm at the edges of the crystal was simulated.

The plot on the top right shows the spatial blurring measured after the digitizer using the TG the bottom plot shows the befor (blue) and after (red) the truncated Gaussian blurring.

The standard deviation of the distribution is recovered when using the truncated Gaussian.

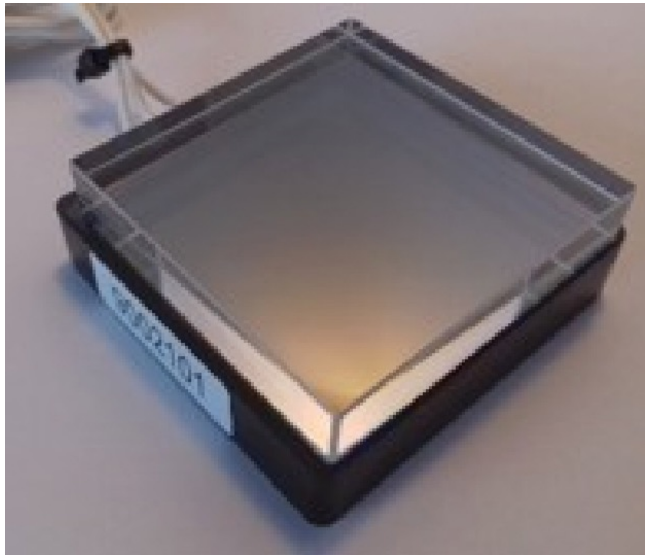
With the truncated gaussian distribution we get more realistic results for the position reconstruction within the cyrstal.





Images with monolithic crystals

- The reconstruction algorithm tools suchas **CASToR** work with crystals IDs and each crystal has an associated ID and the position is defined by it.
- Discretisation with a bin size smaller than the resolution: $\left(\frac{\sigma}{2} > Bin\right)$
  - Impossible to segment the crystals in the simulation due to high computational time.
- For monolithic crystals a tool is needed to convert **X,Y,Z** position within the crystal to a **single ID** to be equivalent to current scanners.
  - The ID is equivalent to the one associated with a linear repeater;
  - A Gate tool that converts the MC macro into an equivalent to the discretised version for **CASToR**'s look-up table creator.



ID for monolithic crystals

Using *cylindricalPET* with 3 ”empty” depths defined with the size of the monolithic crystal.

- The monolithic crystal will occupy the ***Module*** level defined with **Air** material.
- The virtual rows and columns will occupy the ***SubModule*** and ***Crystal*** levels respectively defined with Air material.
- The virtual layers will occupy ***layer0*** defined with the **real crystal's material**.

The segmentation size is defined for each axis in the Digitize in a way equivalent to *SpatialResolution*.
The *GateDigiVirtualSegmentation* module assigns a non-zero ID to these layers according to the position within the crystal.

```
# Module
/gate/cylindricalPET/daughters/name            rsector
/gate/cylindricalPET/daughters/insert          box
/gate/rsector/geometry/setXLength              10. mm
/gate/rsector/geometry/setYLength              63. mm
/gate/rsector/geometry/setZLength              26. cm


# r = 320.8 (to fit the 32 crystals) plus half width (5 mm) plus 0.5 for the Front Readout

/gate/rsector/placement/setTranslation         326.3 0. 0. mm
/gate/rsector/setMaterial                      Air

#  C R Y S T A L
/gate/rsector/daughters/name                   real-crystal
/gate/rsector/daughters/insert                 box
/gate/real-crystal/geometry/setXLength         10. mm
/gate/real-crystal/geometry/setYLength         59. mm
/gate/real-crystal/geometry/setZLength         59. mm
/gate/real-crystal/placement/setTranslation    0. 0. 0. mm
/gate/real-crystal/setMaterial                 Air

# COLUMN
/gate/real-crystal/daughters/name              column
/gate/real-crystal/daughters/insert            box
/gate/column/geometry/setXLength               10. mm
/gate/column/geometry/setYLength               59. mm
/gate/column/geometry/setZLength               59. mm
/gate/column/placement/setTranslation          0. 0. 0. mm
/gate/column/setMaterial                       Air

#ROW
/gate/column/daughters/name                    row
/gate/column/daughters/insert                  box
/gate/row/geometry/setXLength                  10. mm
/gate/row/geometry/setYLength                  59. mm
/gate/row/geometry/setZLength                  59. mm
/gate/row/placement/setTranslation             0. 0. 0. mm
/gate/row/setMaterial                          Air

#Pseudo-Crystal
/gate/row/daughters/name                       pseudoCrystal
/gate/row/daughters/insert                     box
/gate/pseudoCrystal/geometry/setXLength       10. mm
/gate/pseudoCrystal/geometry/setYLength       59. mm
/gate/pseudoCrystal/geometry/setZLength       59. mm
/gate/pseudoCrystal/placement/setTranslation  0. 0. 0. mm
/gate/pseudoCrystal/setMaterial               PWO

#Real Crystal
/gate/real-crystal/repeaters/insert                    linear
/gate/real-crystal/linear/setRepeatNumber              4
/gate/real-crystal/linear/setRepeatVector             0. 0. 63. mm
```

Conclusions

- The needs for PET simulations with monolithic crystals were understood and addressed.
- A new feature was introduced within the *SpatialResolution* digitizer allowing to provide a 2D distribution of the standard deviation, dependent on the hit position within the cristal, as the input for spatial resolution.
- The effect of forced confinement within a monolithic crystal was solved by introducing a truncated Guassian distribution allowing to preserve the standard deviation of the blurring close to the edges.
- A virtual segmentation digitizer was introduced in GATE to simualte monolithic crystals with the equivalent segmentations in XYZ as if they were segmented using linear repeaters
- All these new introductions have been tested and proved to work as expected and are available in the new GATE 9.4.1 version.

Thank you for your attention!

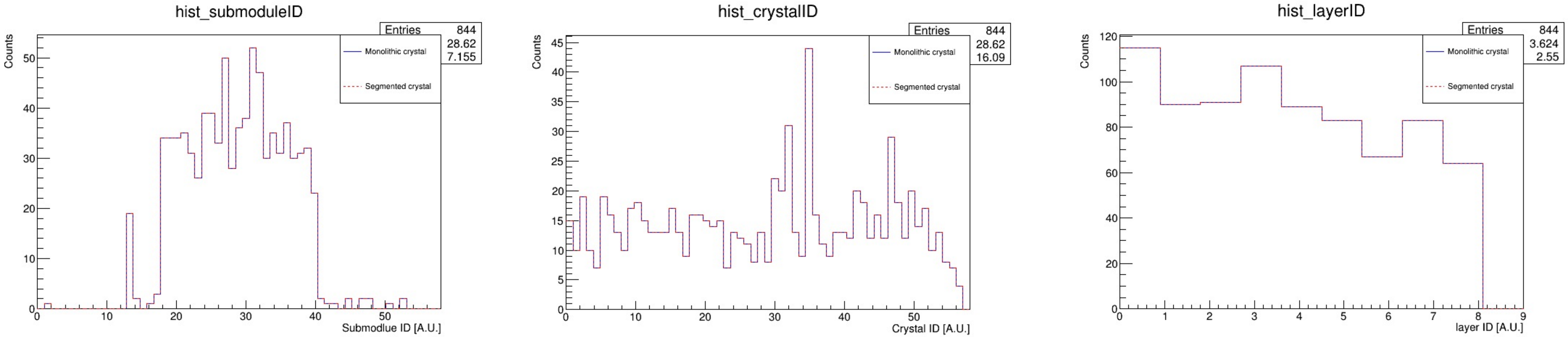
Backup

VS example of use

```
/gate/digitizerMgr/<sensitive_detector>/SinglesDigitizer/Singles/insert virtualSegmentation
/gate/digitizerMgr/<sensitive_detector>/SinglesDigitizer/Singles/virtualSegmentation/nameAxis XYZ
/gate/digitizerMgr/<sensitive_detector>/SinglesDigitizer/Singles/virtualSegmentation/pitch 1.0 mm
```

ID for monolithic crystals

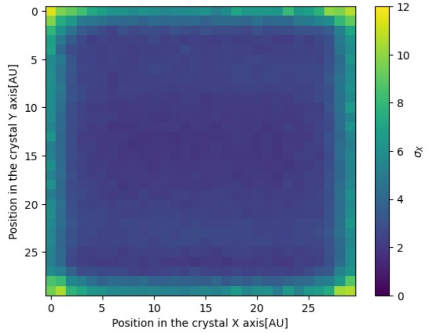
The *GateDigiVirtualSegmentation* module assigns a non-zero ID to these layers according to the position within the crystal in a way equivalent to a linear repeater.

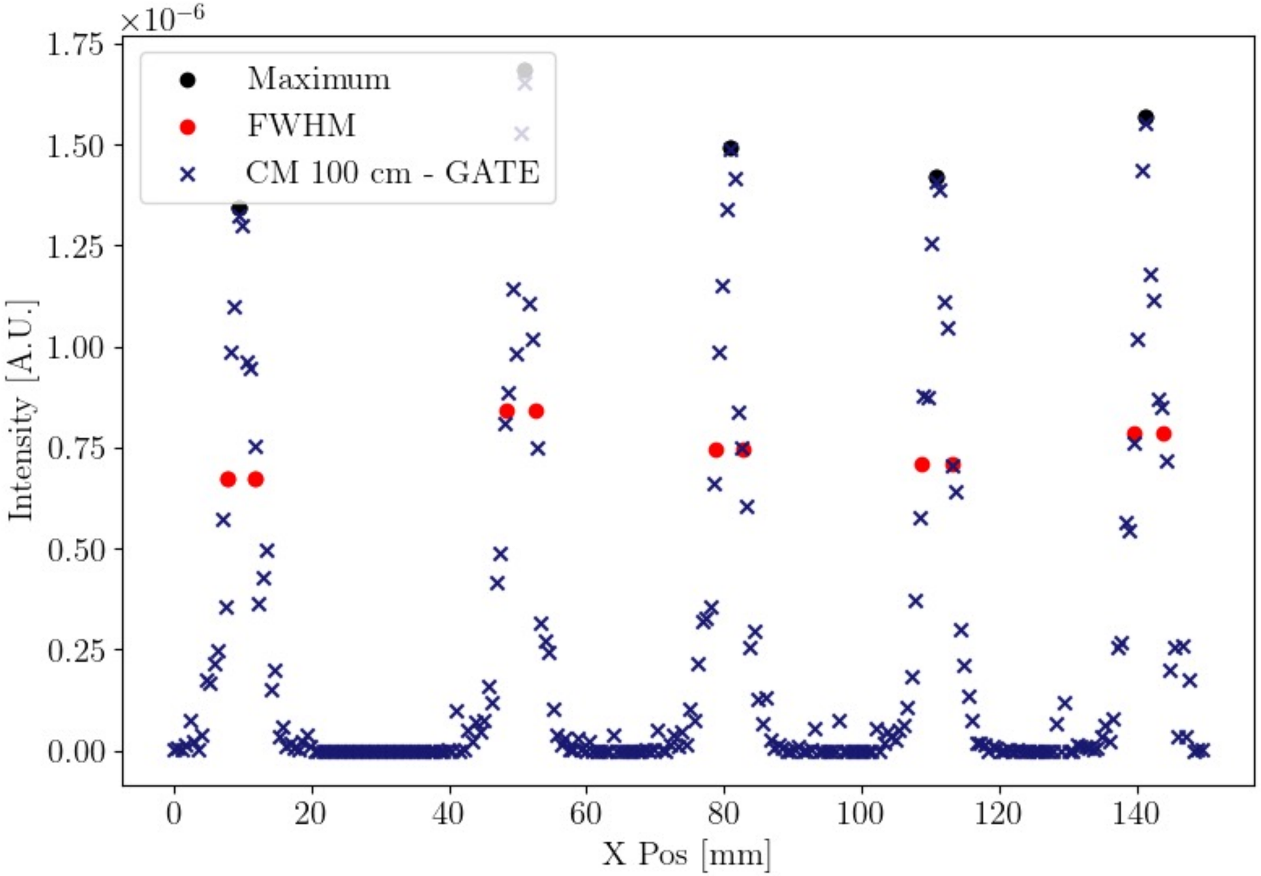


The plots above show the equivalence between a GATE simulation with a macro using a monolithic crystal with the virtual segmentation (solid blue blue) and the equivalent segmented crystal (dashed red)

Spatial resolution with AAIMME

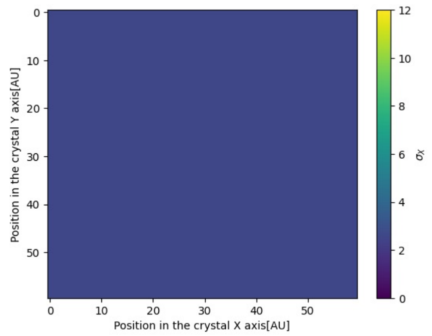
Original AAIMME

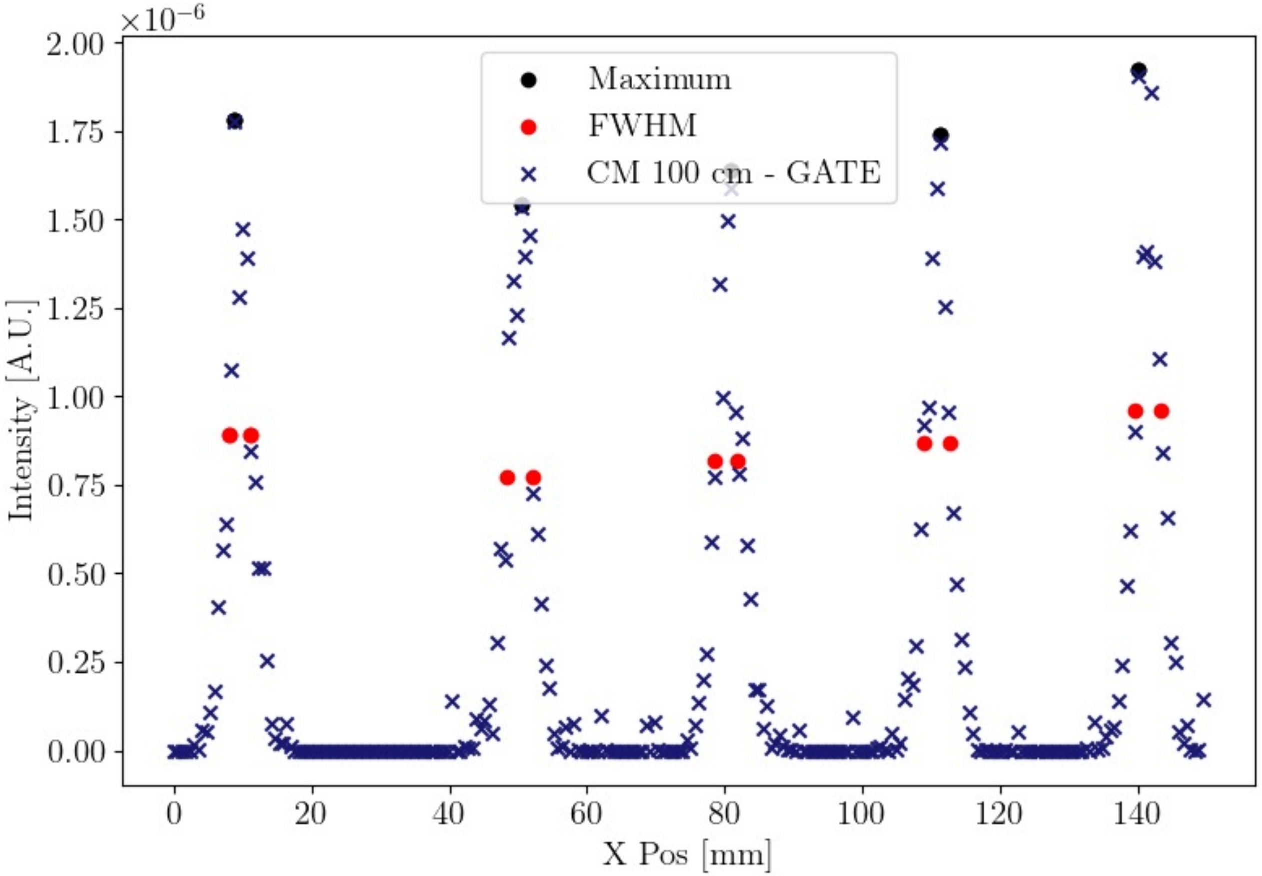




Spatial resolution with AAIMME

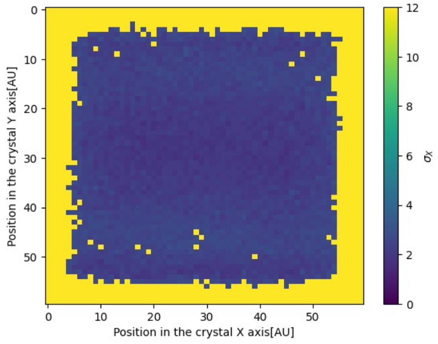
Constant at 2.55 mm

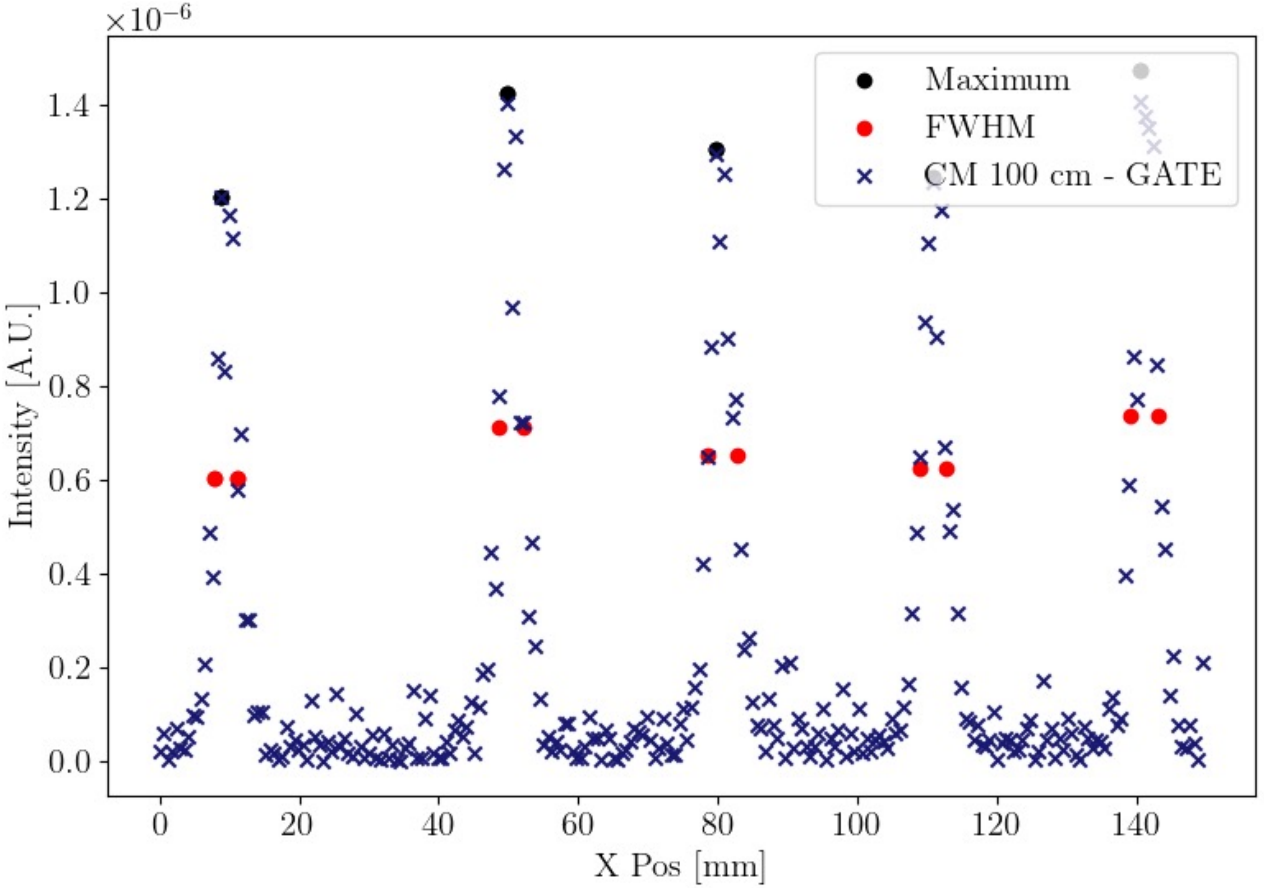




Spatial resolution with AAIMME

40 mm at edges





Spatial resolution with AAIMME

No edge effects