3D SCANNING AND TOMOGRAPHY OF B003 DETECTOR AT IPHC

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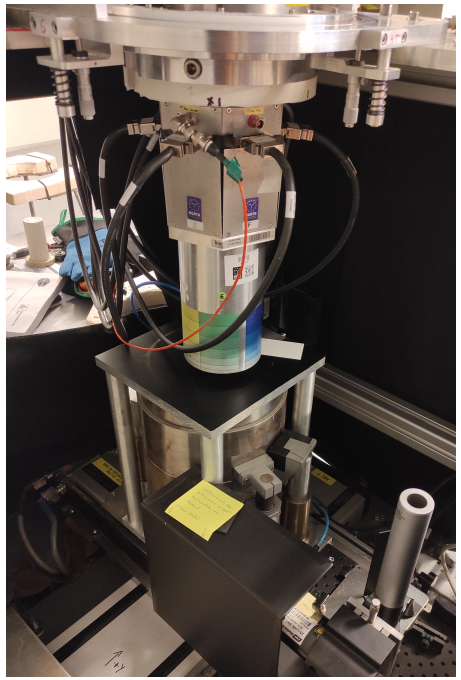
1. **3D scanning of B003 AGATA detector**
    1. Introduction
    2. 3D database

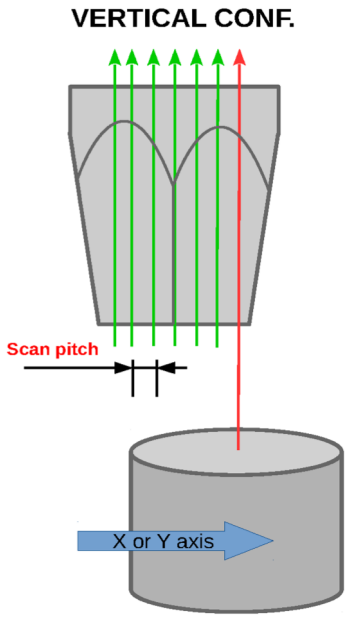
2. **Tomography of B003 AGATA detector**
    1. Measurement procedure
    2. Algorithm to reconstruct the volume
    3. Experimental results
    4. Optimisation

3D SCANNING

3D SCANNING PRINCIPLE

Objective: To **characterize a detector** by constructing an experimental database that **relates the radiation interaction position** within the crystal to its **electrical response**





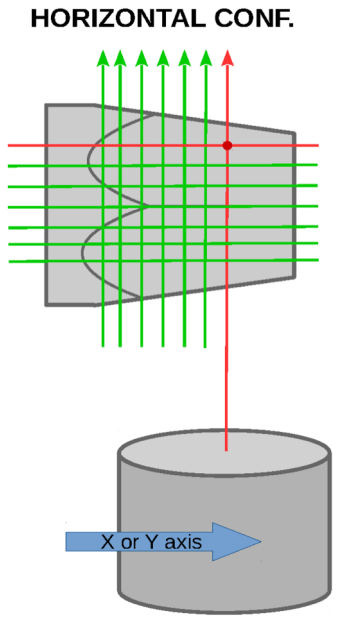
1. Vertical scan
2. Horizontal scan

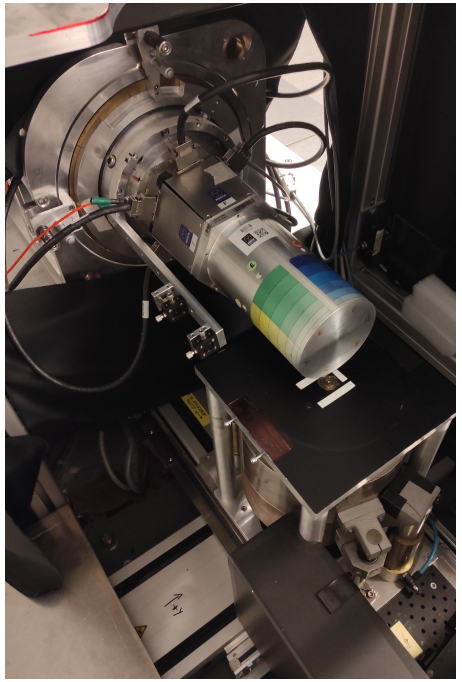
^{137}Cs (661.7 keV)

1 mm pitch

Collimator: ⌀ = 1 mm, 165 mm long

XY table position precision: 20 µm



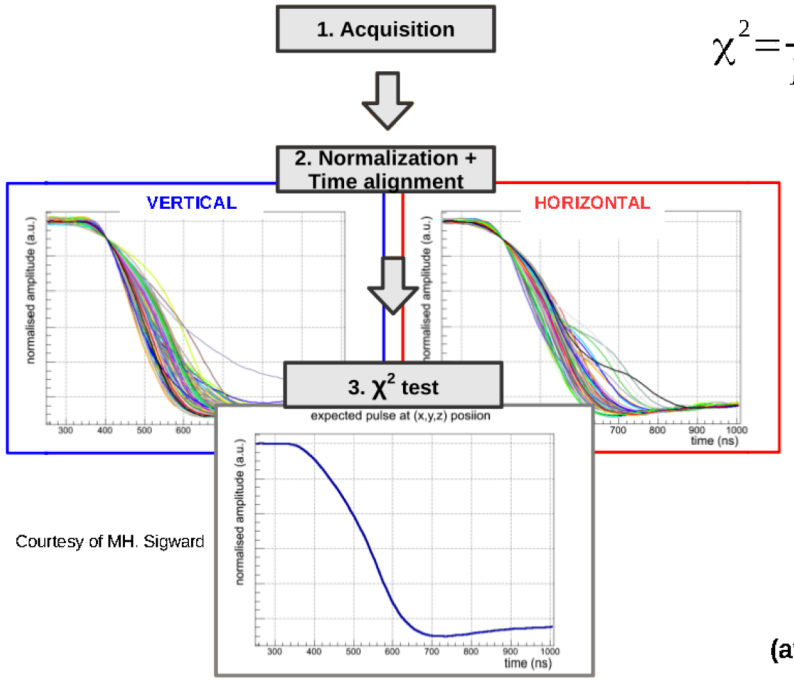


B. De Canditiis, PhD, Univ. Strasbourg, 2020

3D SCANNING PRINCIPLE

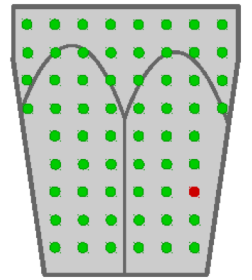
Objective: To **characterize a detector** by constructing an experimental database that **relates the radiation interaction position** within the crystal to its **electrical response**

1. Vertical scan
2. Horizontal scan
3. Fold1 selection: events with only one segment hit
4. PSCS technique: χ^2 comparison of V and H pulse shapes



Courtesy of MH. Sigward

$$\chi^2 = \frac{1}{N} \cdot \sum_{ch=0}^{37} \sum_{i=0}^{100} \left(\frac{H_{i,ch} - V_{i,ch}}{\sigma_{ch}} \right)^2$$



Comparison of two crossing datasets

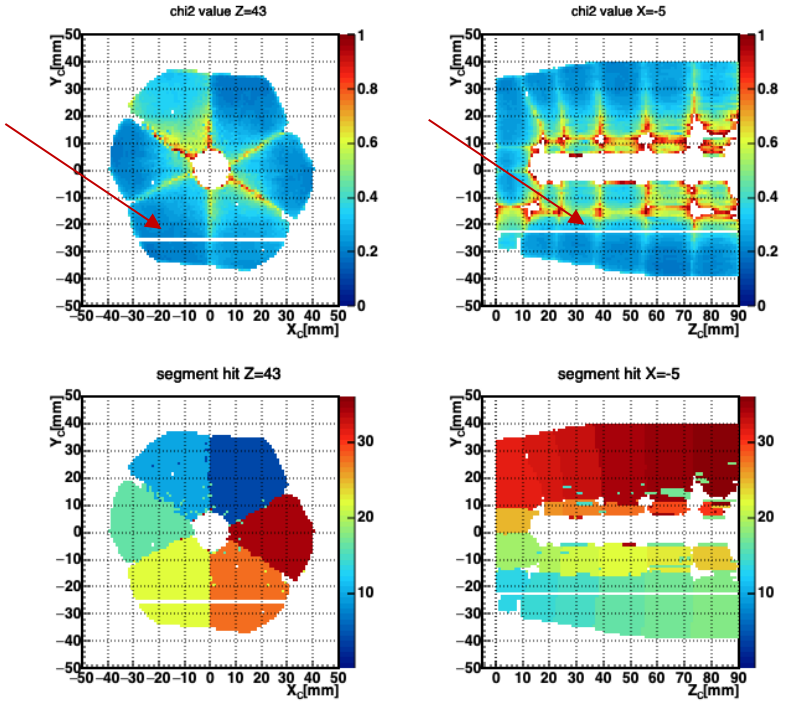
Pulse shape at grid intersection (avg of ~150 best matching pulses)

B. De Canditiis, PhD, Univ. Strasbourg, 2020
G. Duchêne, Gamma Detectors Hands-on School, 2024

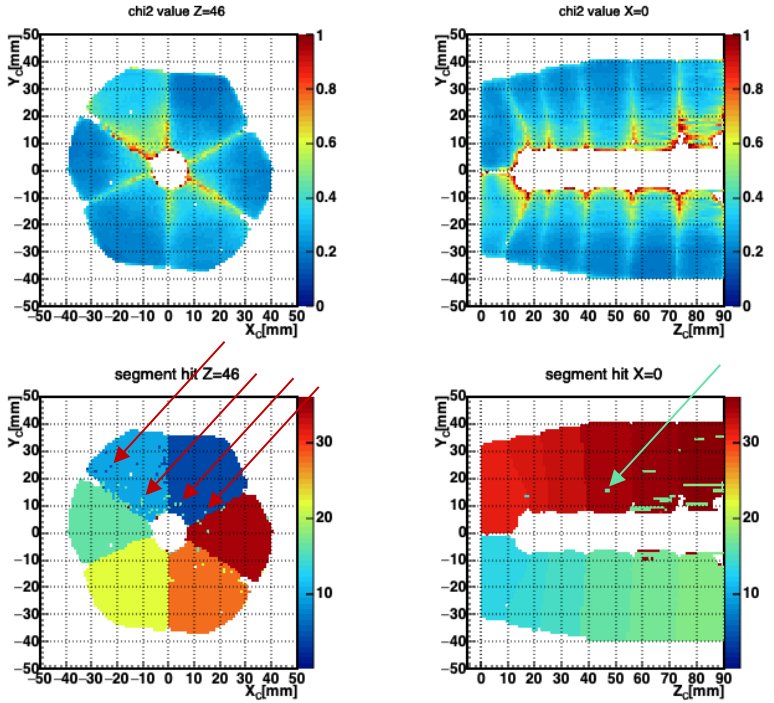
B003 SCANNING – BUILDING THE DATABASE (CORRECTIONS)

We have built up an initial database, but we have observed two undesirable phenomena:

1. **Empty lines**: caused by points that have not been correctly measured, either in the vertical or horizontal scan



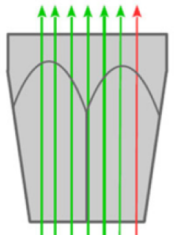
2. **Isolated points** that do not correspond to what they should be



B003 SCANNING – BUILDING THE DATABASE (CORRECTIONS)

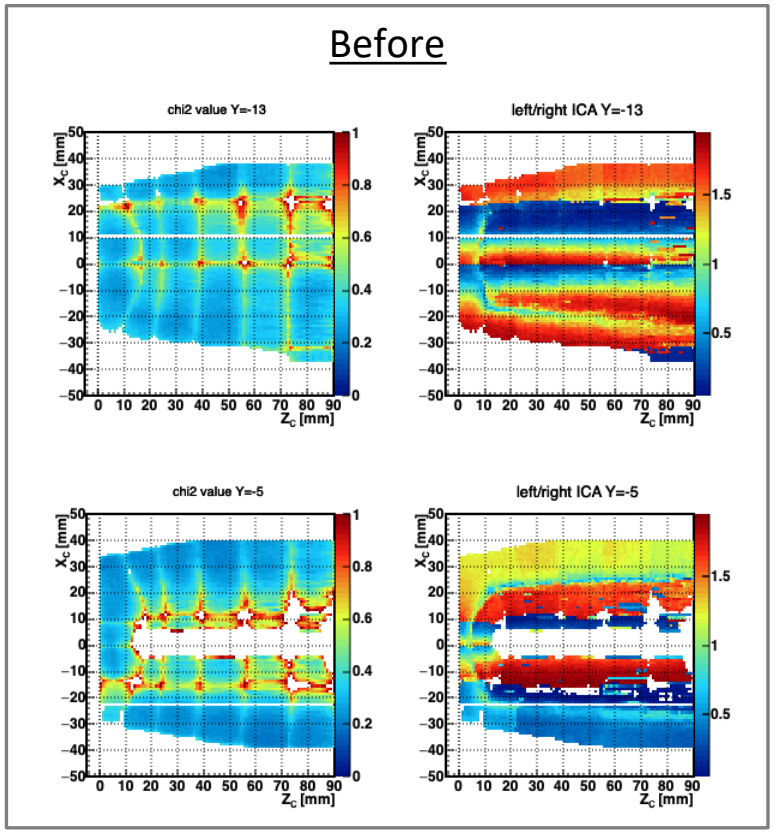
1. Correction of empty lines by interpolating the pulse shapes of neighbouring points

   - For cases where few points have **not been accurately measured in the vertical** configuration (4 points)



X (mm)	Y (mm)	Interpolation*
-23	-5	x
-15	21	x_y
10	-13	x_y
20	-30	x_y

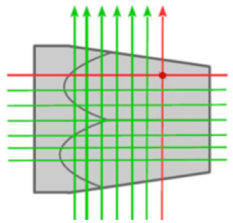
* Axis where the neighbouring points to be considered for interpolation are located



B003 SCANNING – BUILDING THE DATABASE (CORRECTIONS)

1. Correction of empty lines by interpolating the pulse shapes of neighbouring points

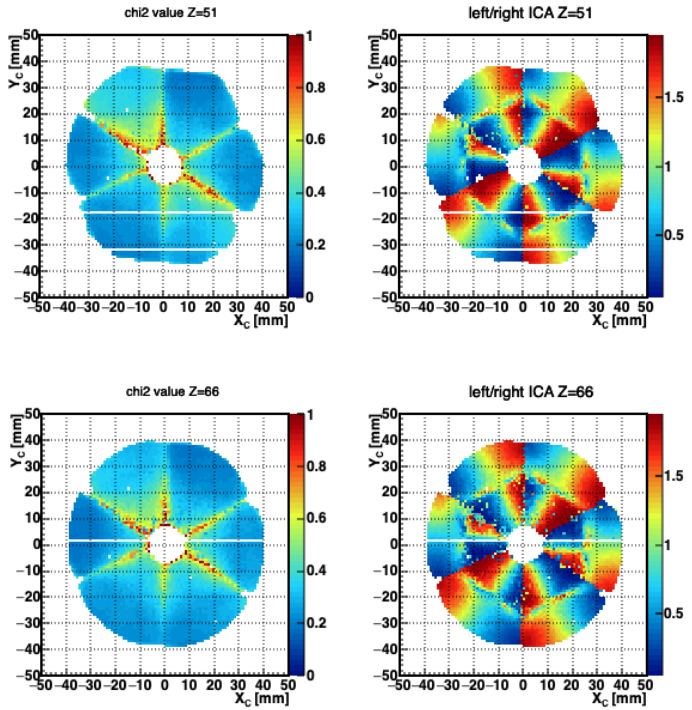
   - For cases where few points have **not been accurately measured in the horizontal** configuration (5 points)



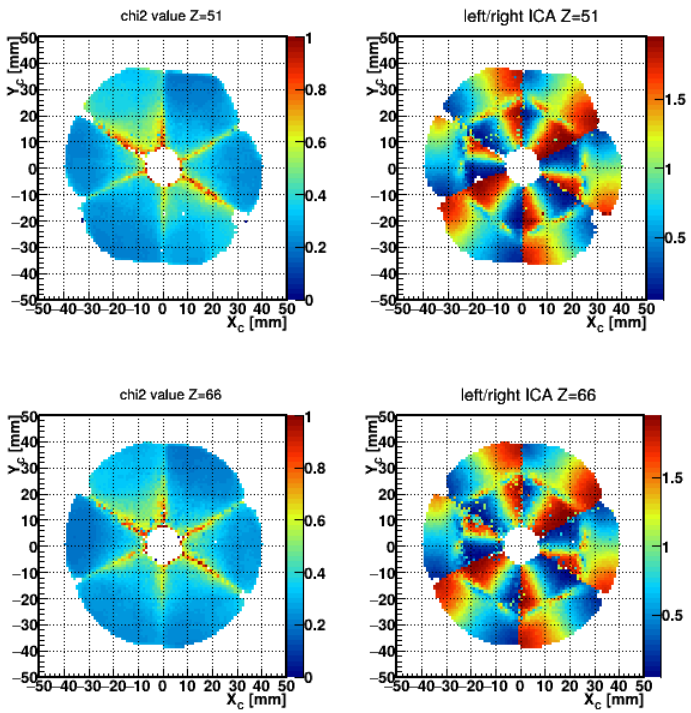
Z (mm)	Y (mm)	Interpolation*
10	25	y
43	-26	y_z
51	-18	y_z
51	-32	y_z
66	1	z

* Axis where the neighbouring points to be considered for interpolation are located

Before



After interpolation

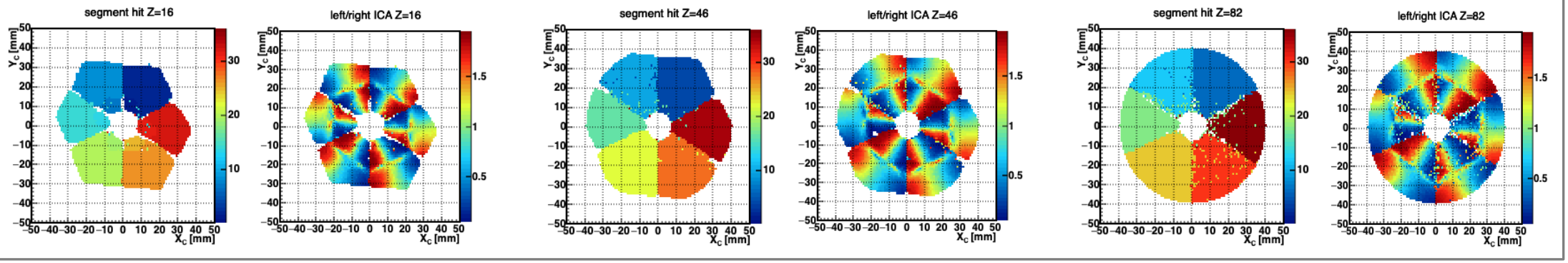


B003 SCANNING – BUILDING THE DATABASE (CORRECTIONS)

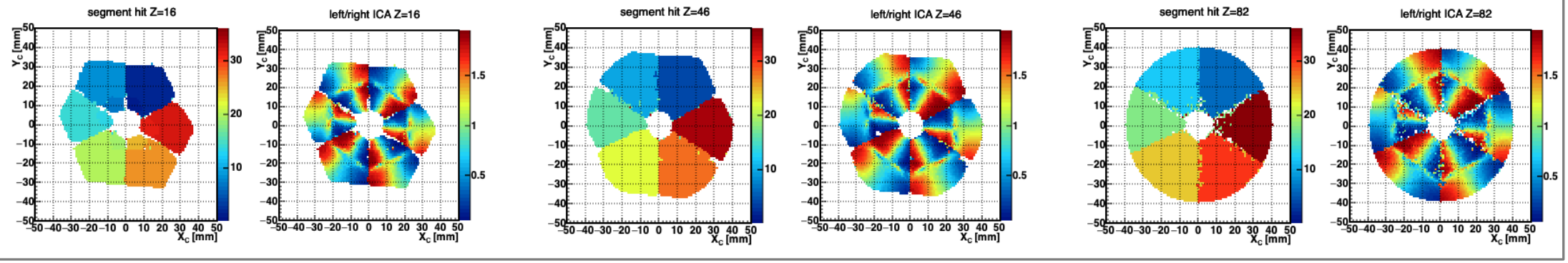
2. Correction of isolated points by interpolating the pulse shapes of neighbouring points

   - **2568 points** were showing an unusual behaviour and were corrected

Before



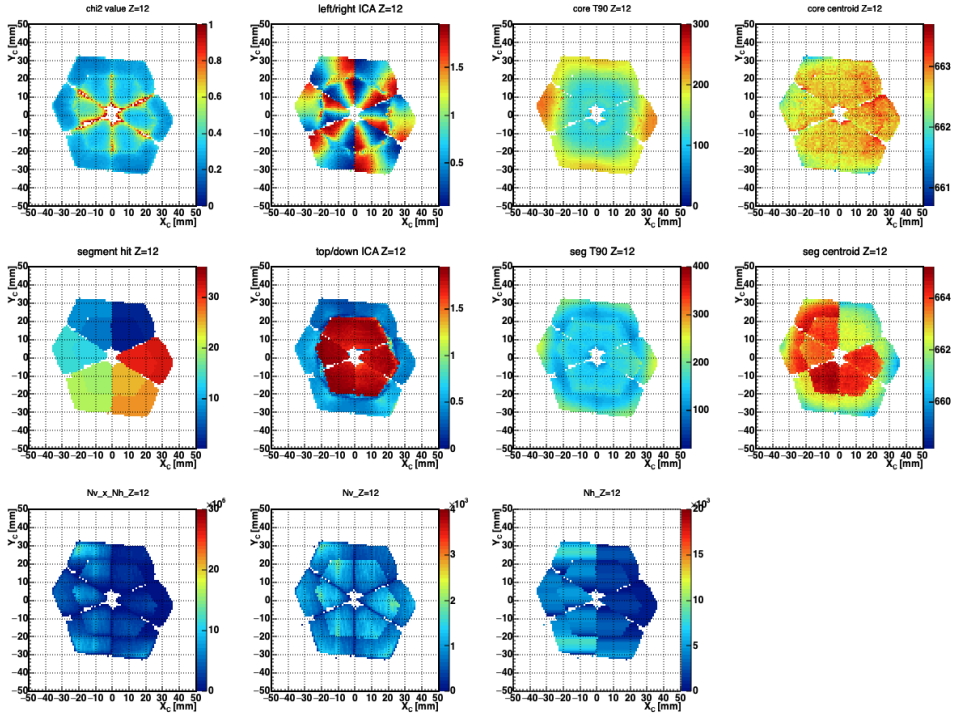
After

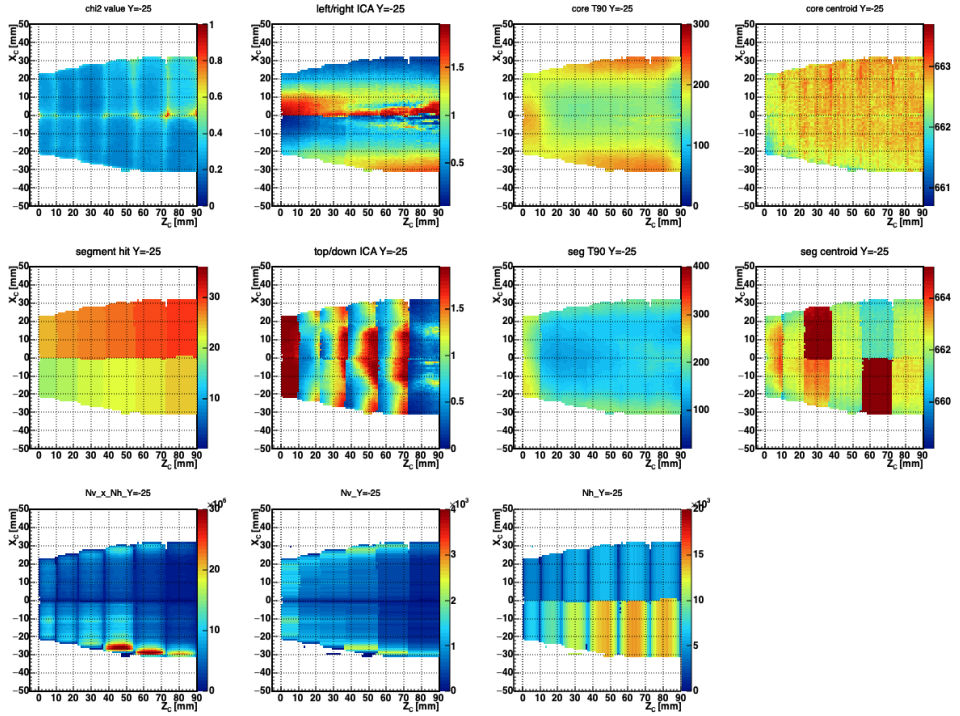


B003 SCANNING – BUILDING THE DATABASE (RESULTS)

The **first 1x1x1 mm³ database for an AGATA detector** (B003) has been built at IPHC

- It contains **372.823 points**



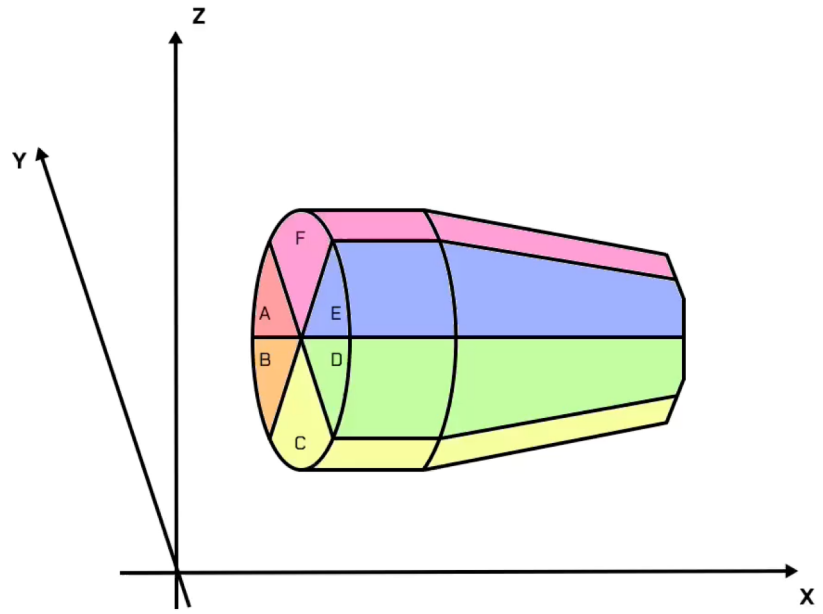


TOMOGRAPHY

B003 TOMOGRAPHY – MEASUREMENT

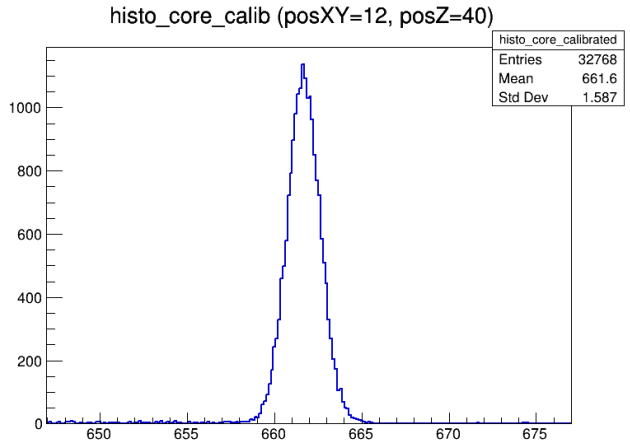
Data acquisition for tomography requires measurements to be taken from **different horizontal configurations** :

- <u>12 scanned 2D projections: Every 30º</u>
- ^{137}Cs
- Energy mode
- 1x1 mm^2 pitch
- 7256 points
- Collimator: 1 mm, 165 mm long
- 67 s per point
  - $7256\ pts \times 67\ s = 486152\ s \cong 5d\ 15h$ per configuration
  - One week per configuration
  - 12 weeks requires the data taking for the tomography



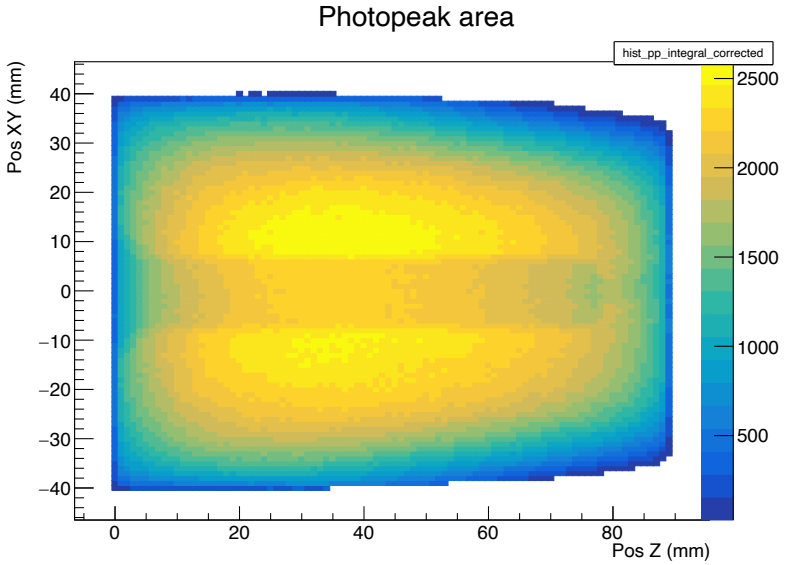
B003 TOMOGRAPHY – DATA PROCESSING – ALGORITHM

For each measurement point, the information we are interested in is the **photopeak area (at 661.7 keV) in the core spectrum**

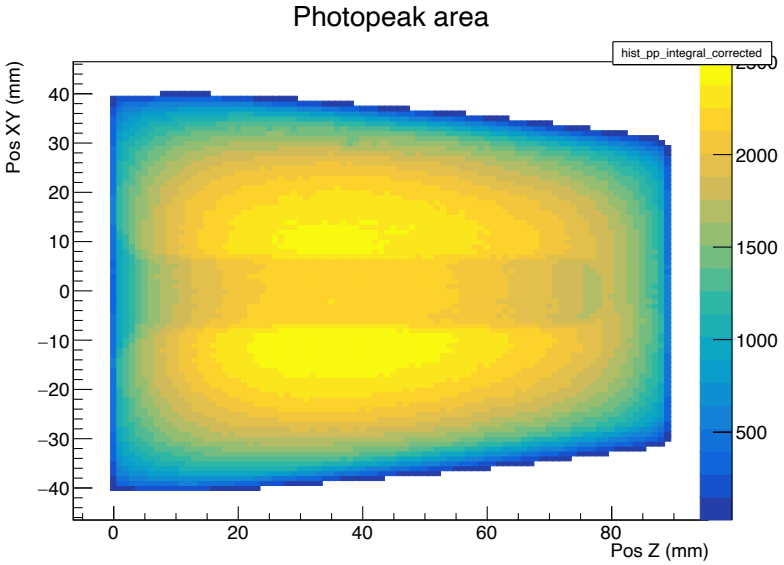


For <u>each point at each measurement angle</u>, the core spectrum is automatically analyzed and the area of the photopeak is determined

At 0º



At 30º

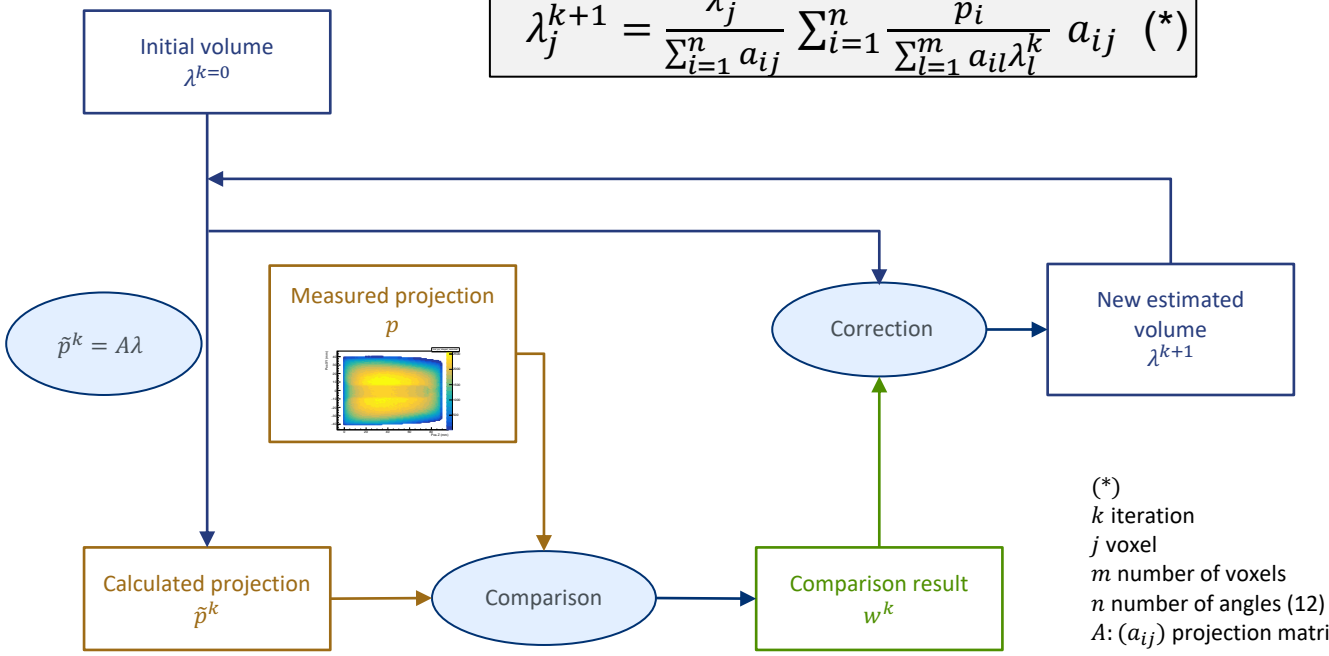


B003 TOMOGRAPHY – DATA PROCESSING – ALGORITHM

To process the data and **obtain the detector reconstruction**, we have developed a **code based on the ML-EM algorithm**

ML-EM (Maximum Likelihood - Expectation Maximization): It is a **statistical and iterative** method that determines the **volume of the object which is most likely** to have generated the experimental measurements

$$\lambda_j^{k+1} = \frac{\lambda_j^k}{\sum_{i=1}^{n} a_{ij}} \sum_{i=1}^{n} \frac{p_i}{\sum_{l=1}^{m} a_{il}\lambda_l^k} a_{ij} \quad (*)$$



(*)
k iteration
j voxel
m number of voxels
n number of angles (12)
A: (a_{ij}) projection matrix

Iterative statistical reconstruction (ML-EM)

1. **Forward projection**

The projection obtained if the detector had the current volume (image)

$$\tilde{p}_i^k = \sum_{l=1}^{m} a_{il}\lambda_l^k$$

2. **Comparison**

Compare the estimated projections with the real data, calculating a ratio

$$r_i = \frac{p_i}{\tilde{p}_i^k}$$

3. **Backprojection**

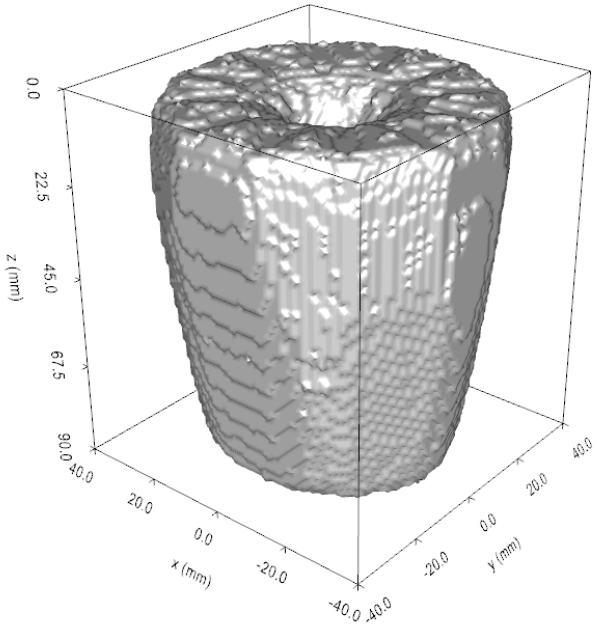
Apply the correction factor to each voxel

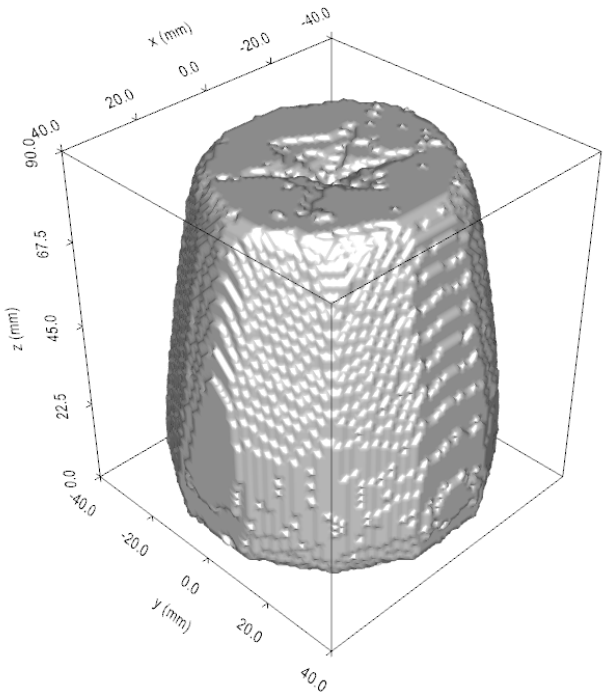
$$b_j = \sum_{i=1}^{n} r_i\, a_{ij}$$

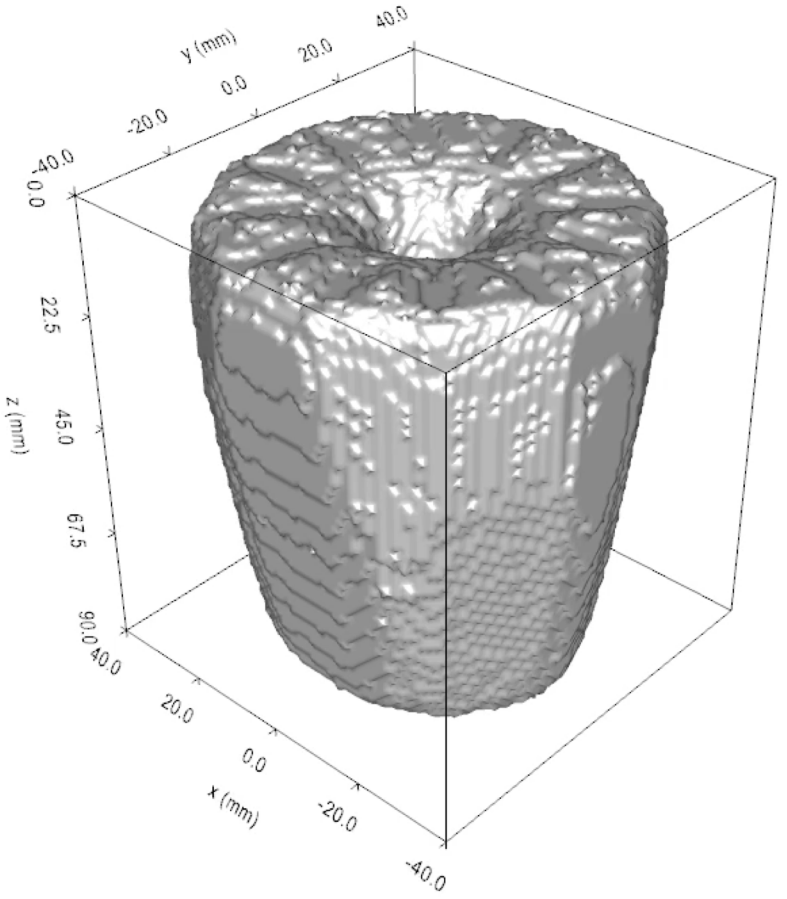
4. **Normalization and updating**

$$\lambda_j^{k+1} = \frac{\lambda_j^k}{\sum_{i=1}^{n} a_{ij}}\, b_j$$

B003 TOMOGRAPHY – RESULTS

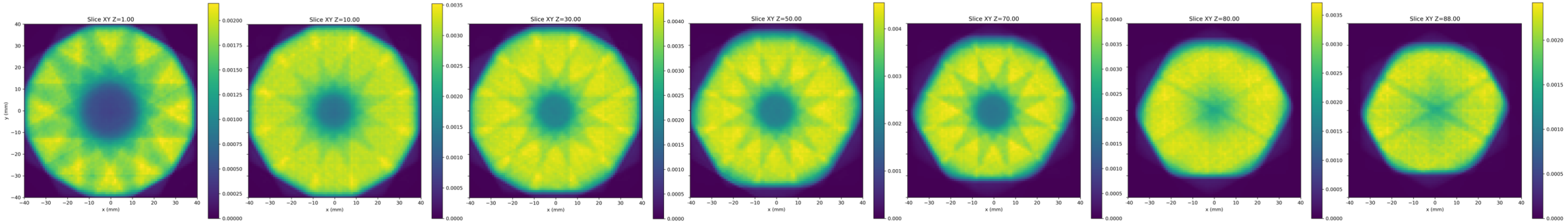




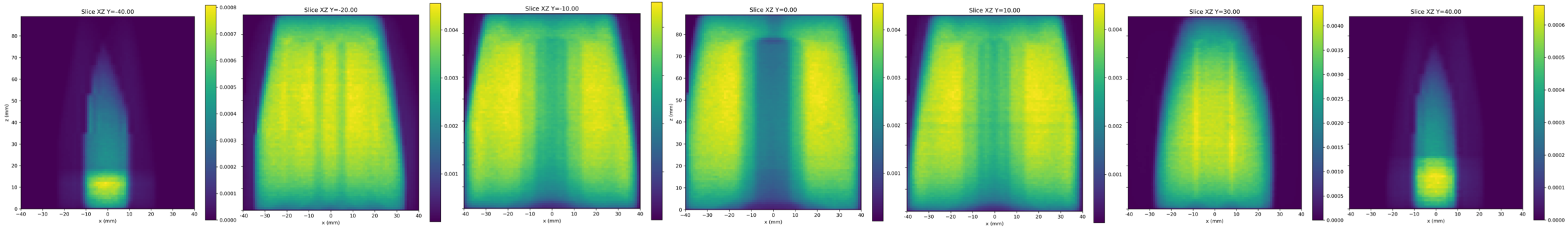


B003 TOMOGRAPHY – RESULTS

XY Slices

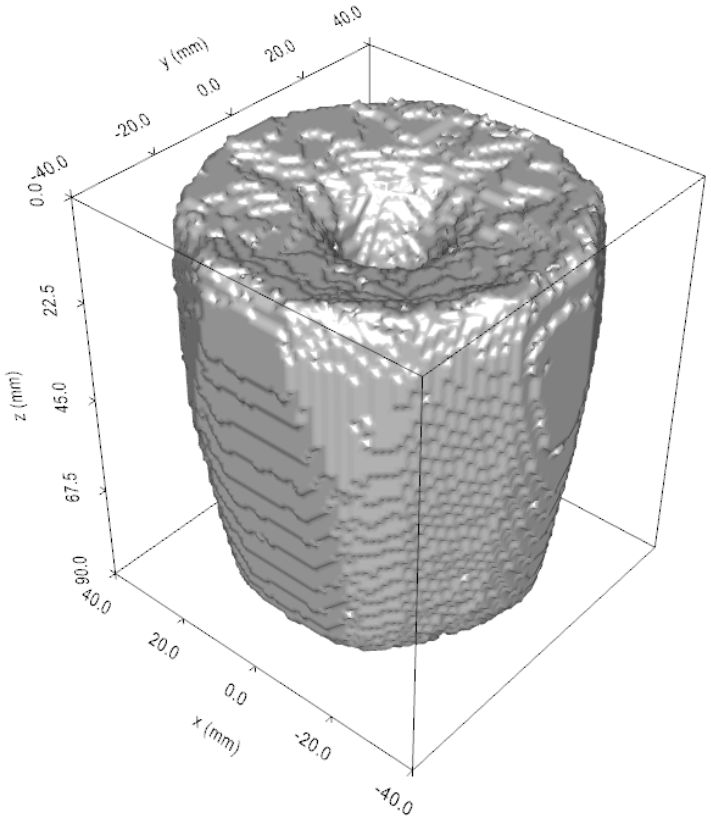


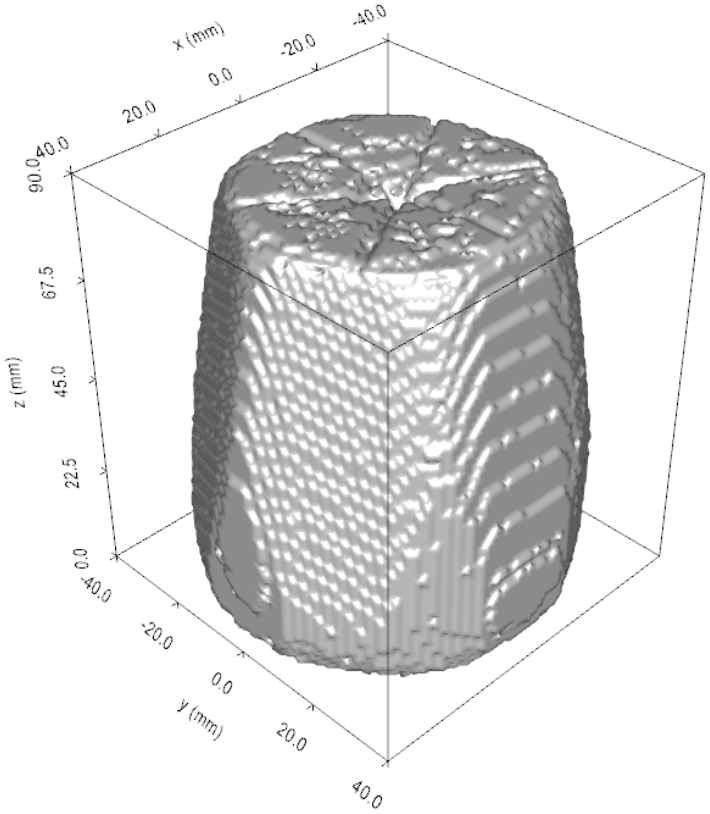
XZ Slices



TOMOGRAPHY – RESULTS

We have also performed the **tomography for the <u>A005 detector</u>**:

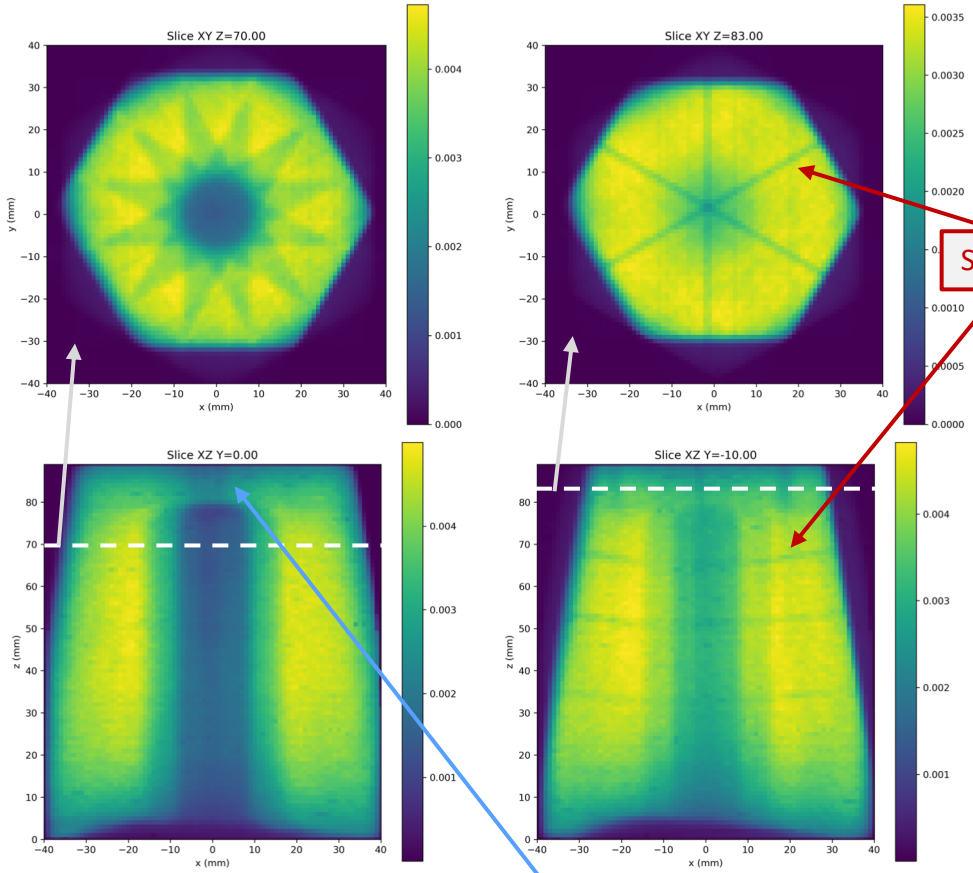




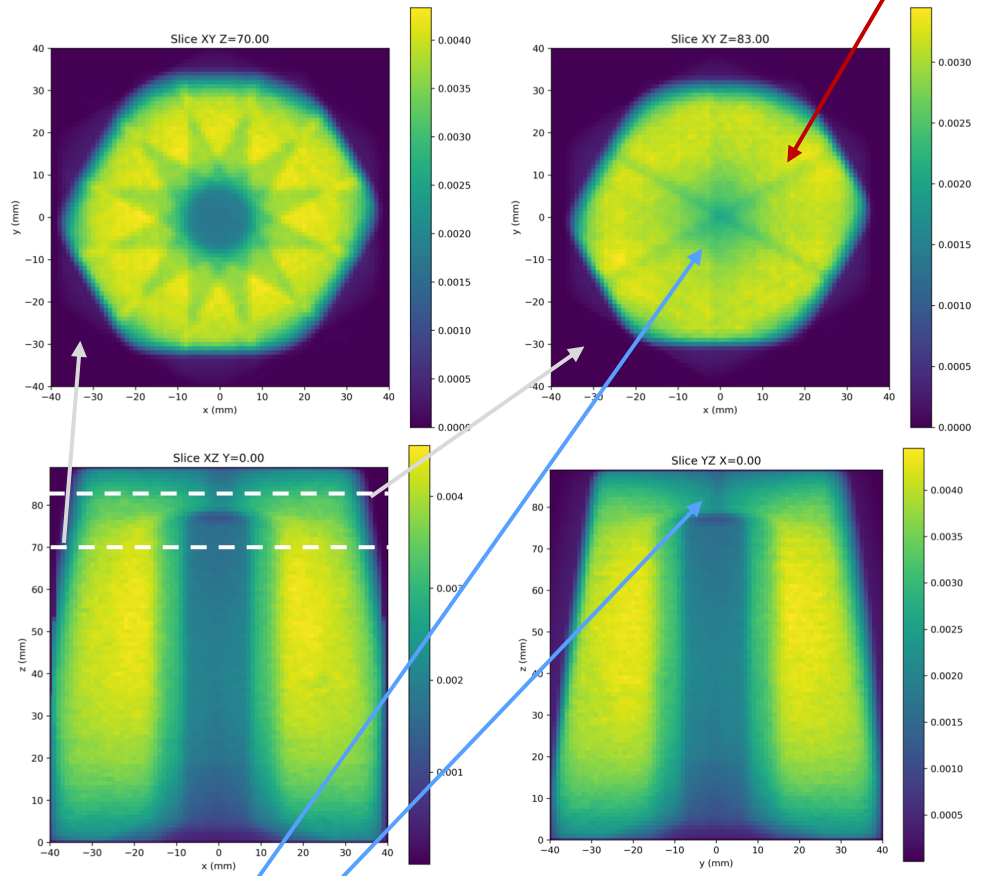
TOMOGRAPHY – RESULTS

Comparing the tomography results for A005 and B003 detectors:

A005



B003



Segmentation lines

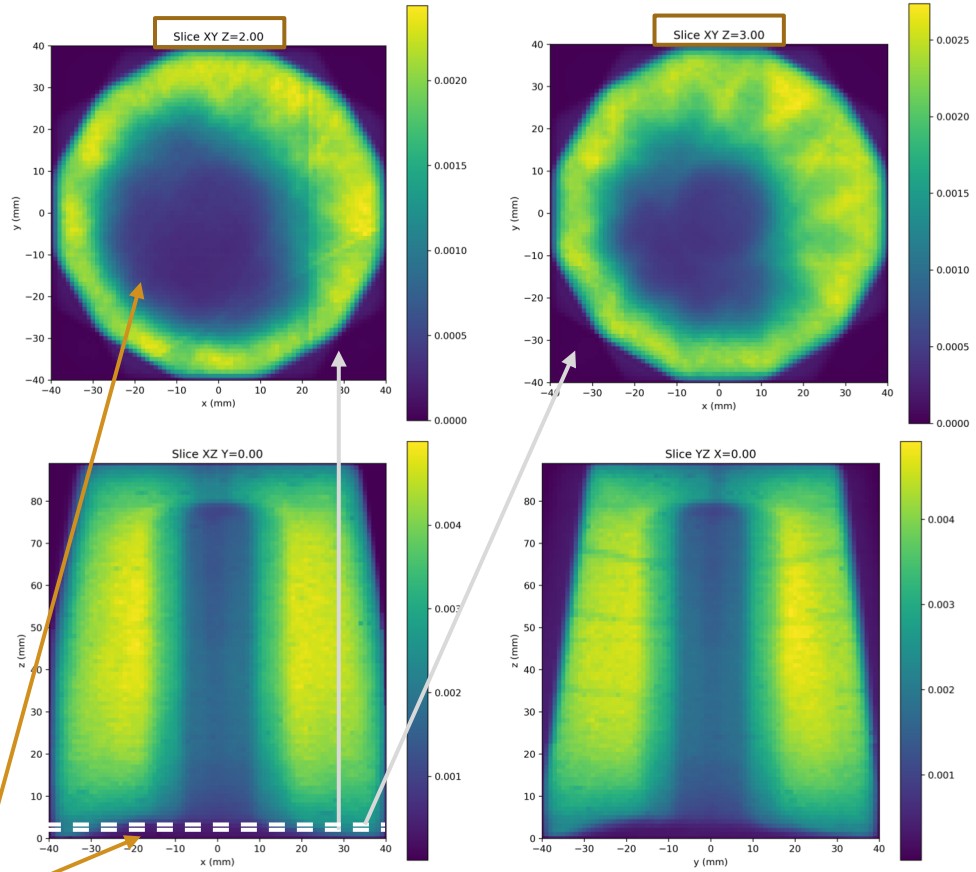
Segmentation lines

Where segmentation lines intersect, there is a remarkable loss of Ge active volume

TOMOGRAPHY – RESULTS

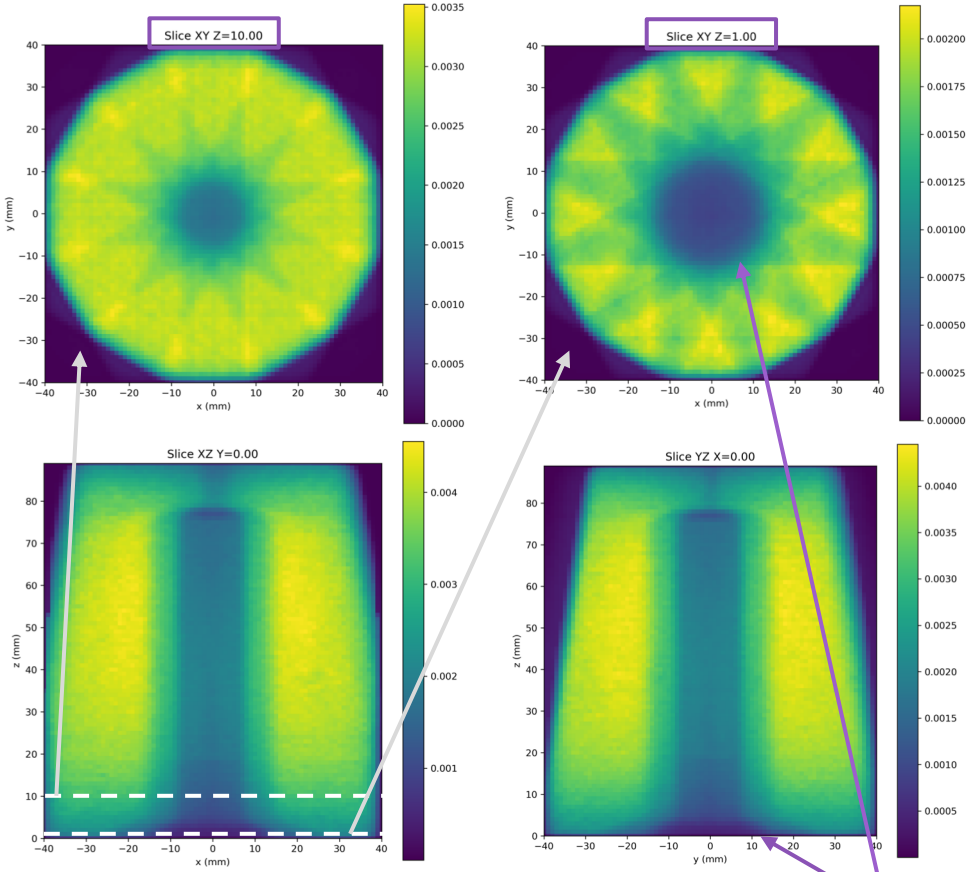
Comparing the tomography results for A005 and B003 detectors:

A005



A005 detector shows greater active volumen loss at the back of the crystal

B003

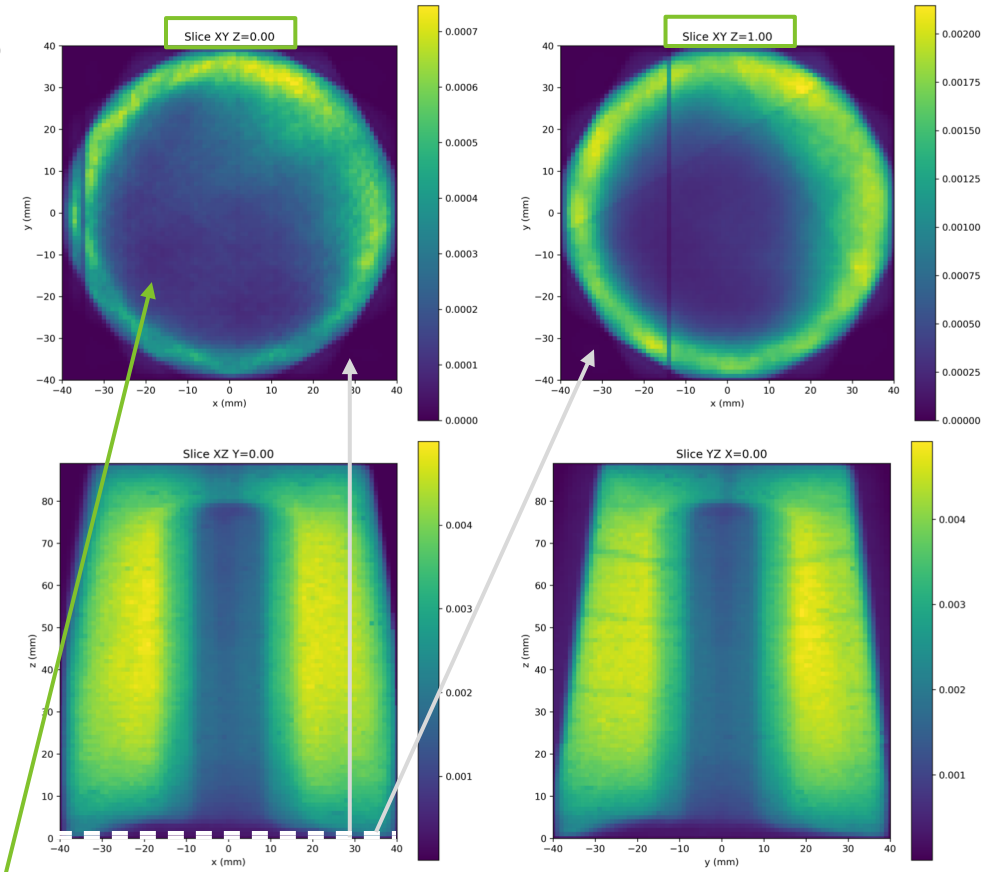


The hole diameter increases towards the back of the crystal

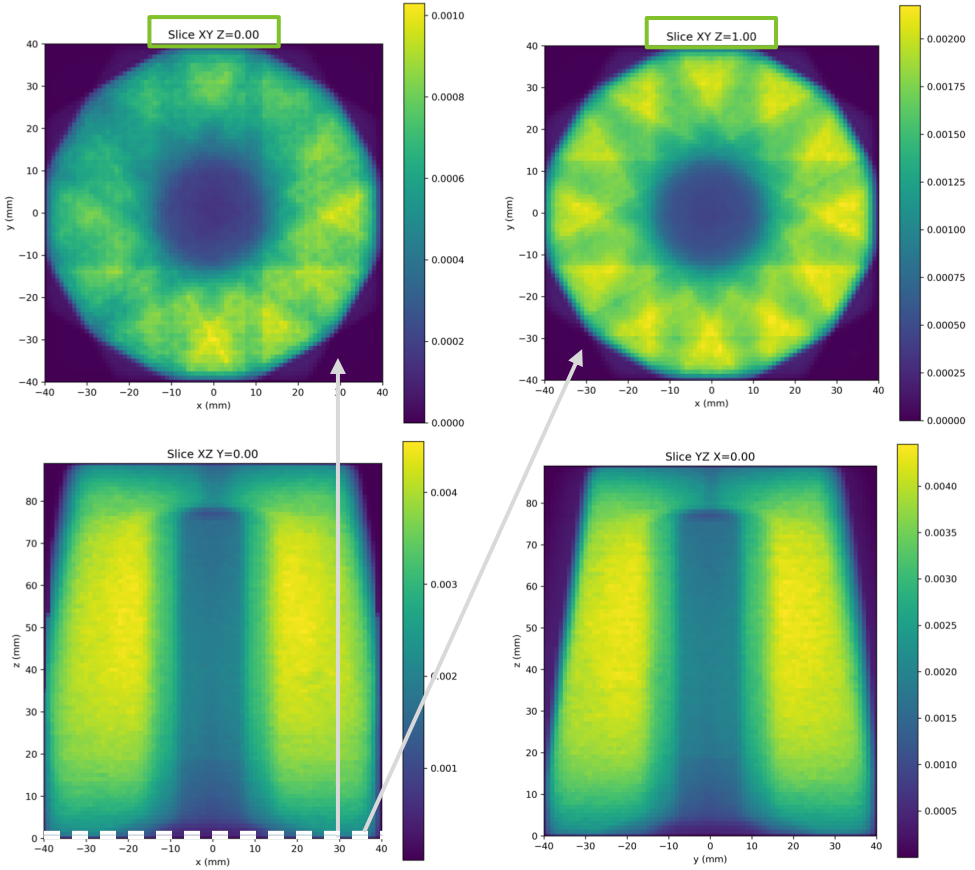
TOMOGRAPHY – RESULTS

Comparing the tomography results for A005 and B003 detectors:

A005



B003



In A005 detector, there is almost no active Ge volume in the last 1 mm

B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

What can we do to **optimise the measurement process and improve the results?**

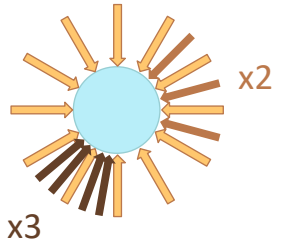
1. To analyse whether it would be possible to reduce the measurement time whilst still obtaining sufficient statistical data



2. To investigate how the scan pitch affects the results, to evaluate whether accurate determinations could still be achieved by increasing the step size



3. To study whether volume reconstruction significantly improves with the number of angles



B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

1. Analysis of measurement time



Measurements are taken for **67 s at each point**

This analysis investigates what would have happened if data acquisition had lasted for:

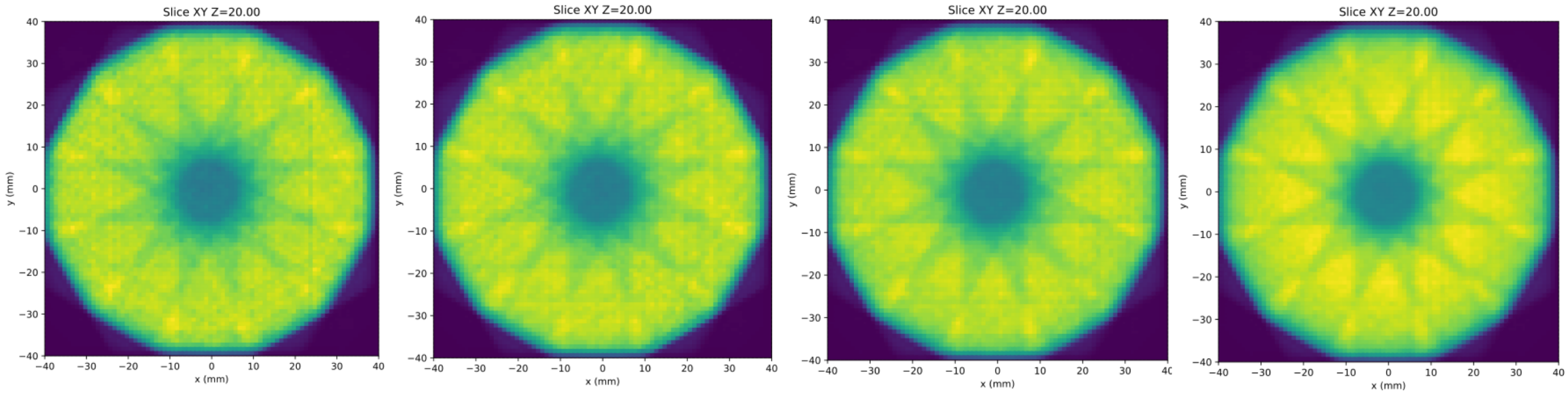
- **22s : 1/3** of the events recorded over the total time are considered
- **33s : 1/2** of the events recorded over the total time are considered
- **44s : 2/3** of the events recorded over the total time are considered

B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

1. Analysis of measurement time

Reconstructed volume slice – XY slice (Z = 20)

22 s (1/3) | **33 s (1/2)** | **44 s (2/3)** | **67 s (original)**



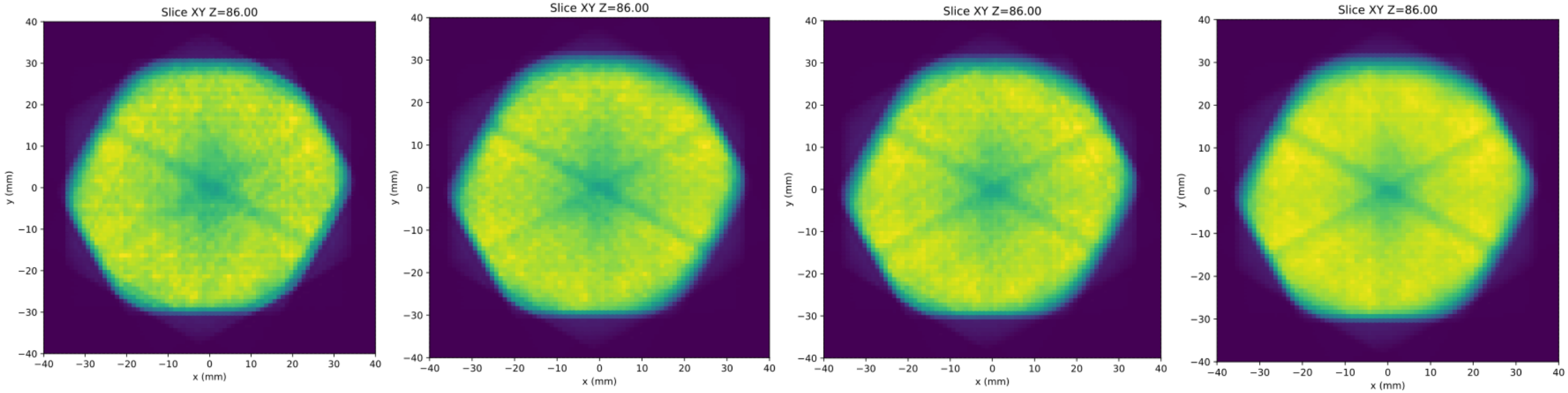
More noise, the artefacts are more noticeable

B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

1. Analysis of measurement time

Reconstructed volume slice – XY slice (Z = 86)

22 s (1/3) **33 s (1/2)** **44 s (2/3)** **67 s (original)**

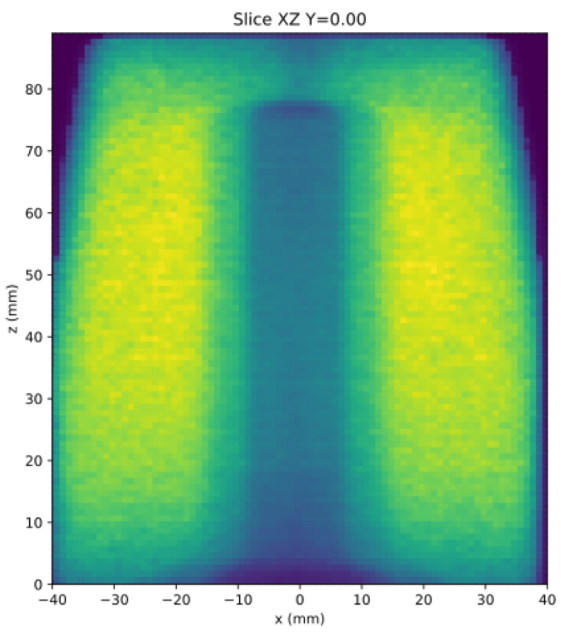


B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

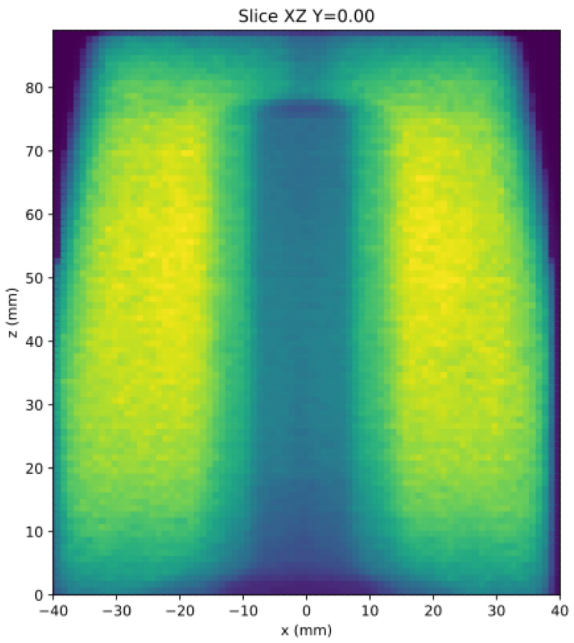
1. Analysis of measurement time

Reconstructed volume slice – XZ slice (Y = 0)

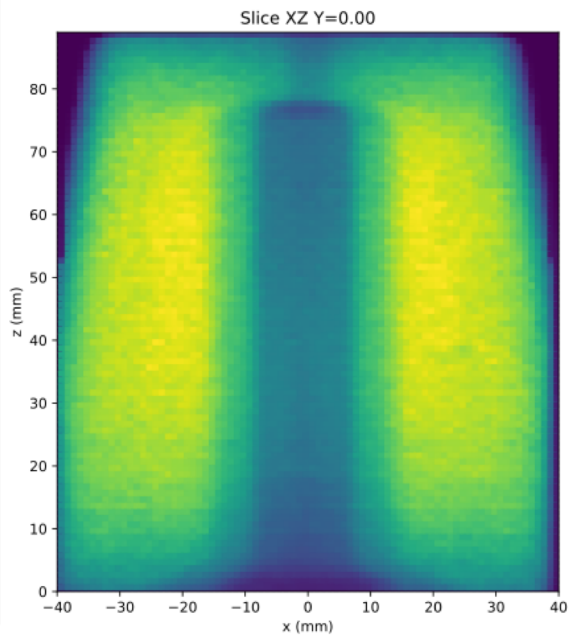
22 s (1/3)



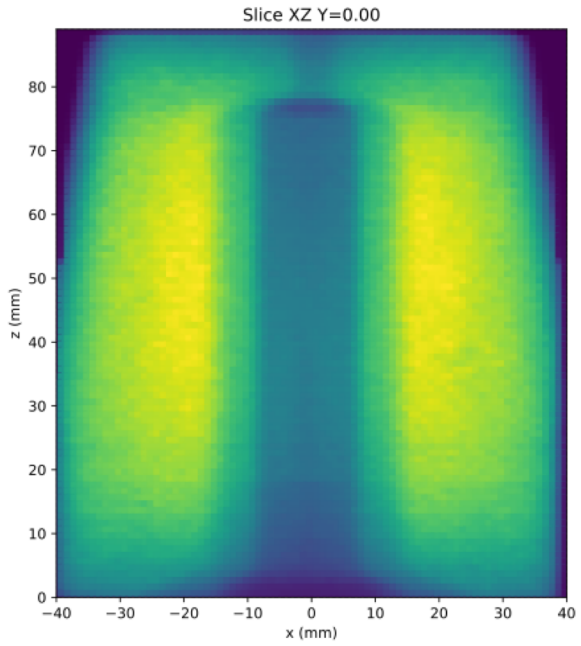
33 s (1/2)



44 s (2/3)



67 s (original)

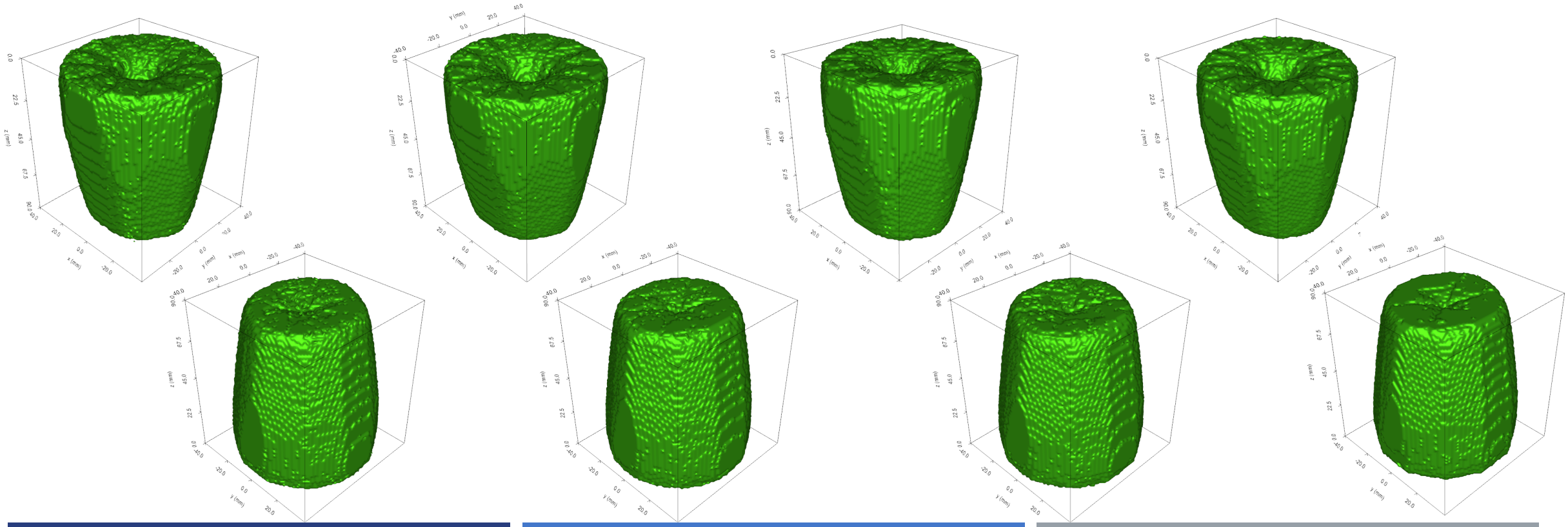


B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

1. Analysis of measurement time

Reconstructed volume

22 s (1/3) **33 s (1/2)** **44 s (2/3)** **67 s (original)**



B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

1. Analysis of measurement time

• To obtain a general reconstruction of the volume, with a quick data acquisition	20-30 s
• To start visualising, resolving, the segmentation lines	30-40 s
• To achieve a reconstruction with well-defined segmentation lines and volume	> 40 s

The measurement time could be reduced from 67 to 40 s per point whilst ensuring a reliable result

B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

2. Analysis of pitch



Measurements are taken in a 2D scan every mm, in a **1x1 mm^2 grid**

The present study examines what would have happened if data had been recorded with a **pitch of 2 mm**, that is, **on a 2x2 mm^2 grid**.

This would **reduce the total measurement time to a quarter** of the current time

To this end, **one out of every two** actual measurement points is selected

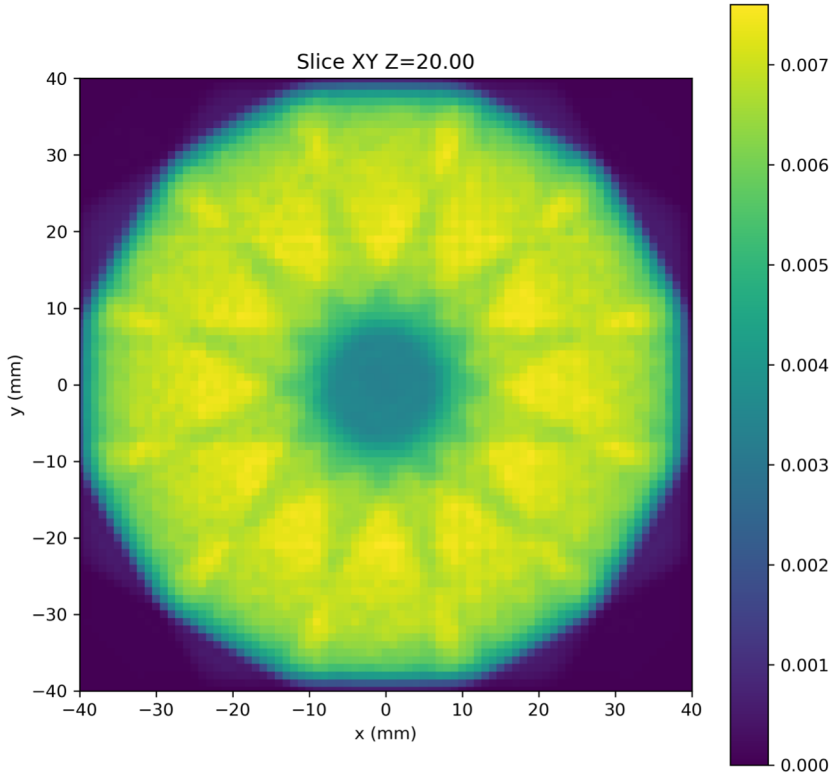
B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

2. Analysis of pitch

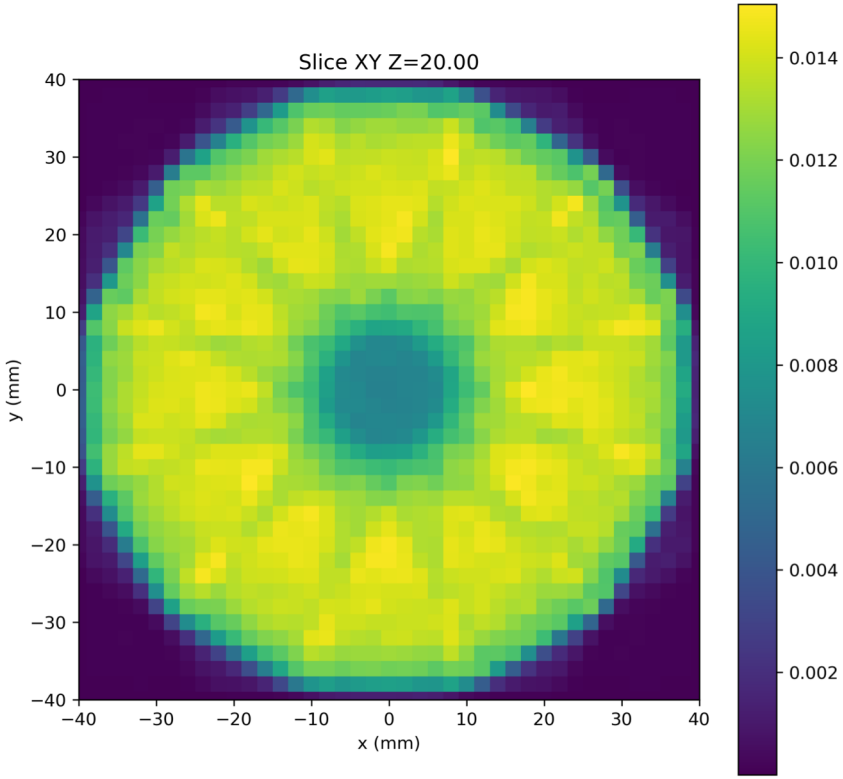
Reconstructed volume slice – XY slice (Z = 20)

Main features are preserved
A fair amount of details is lost

1x1 mm²



2x2 mm²



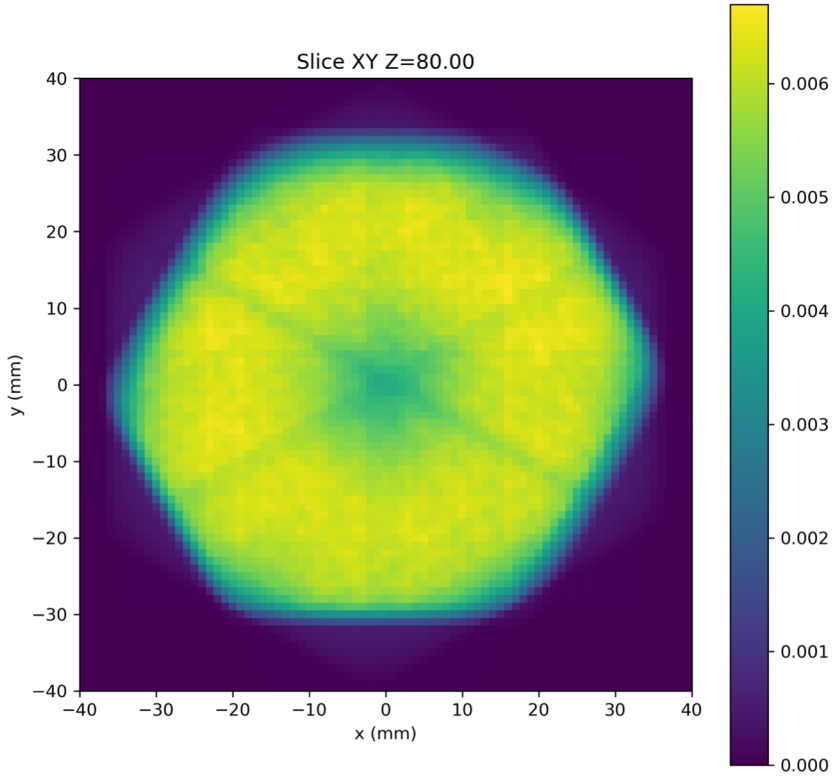
B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

2. Analysis of pitch

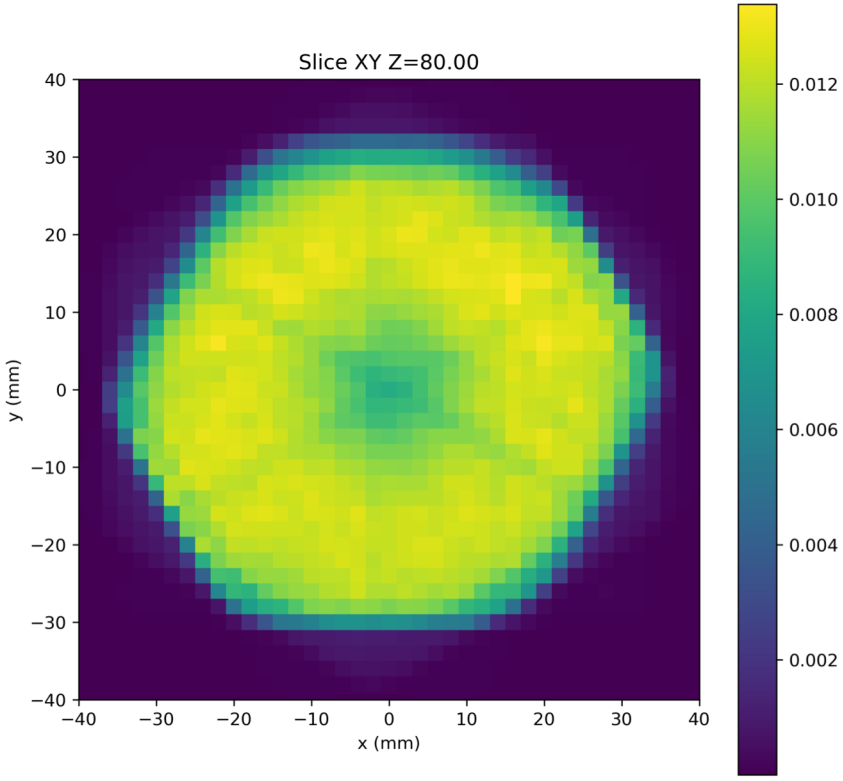
Reconstructed volume slice – XY slice (Z = 80)

Segmentation lines are still visible

1x1 mm²



2x2 mm²

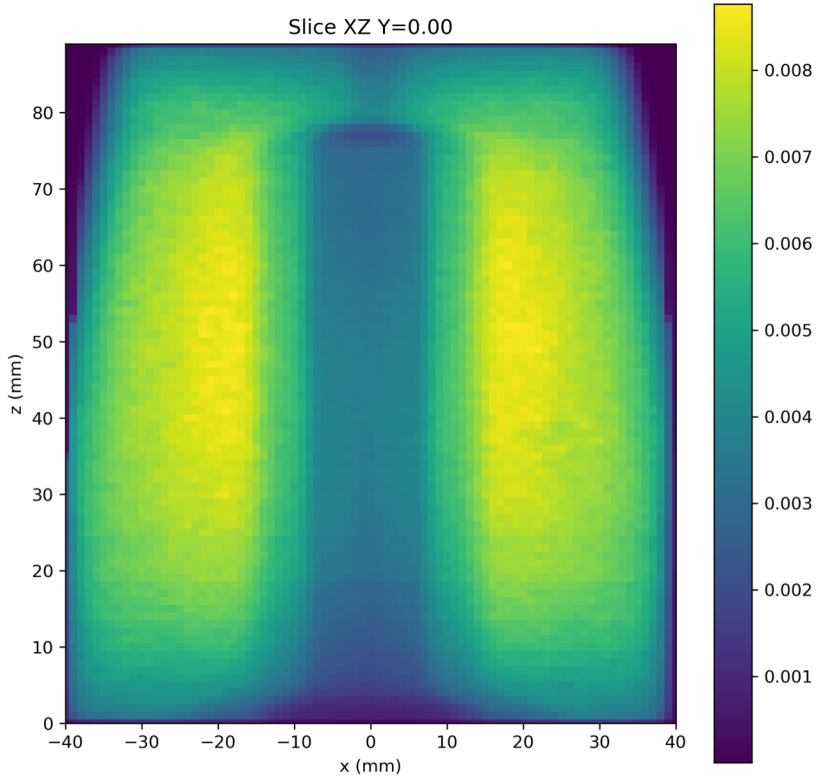


B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

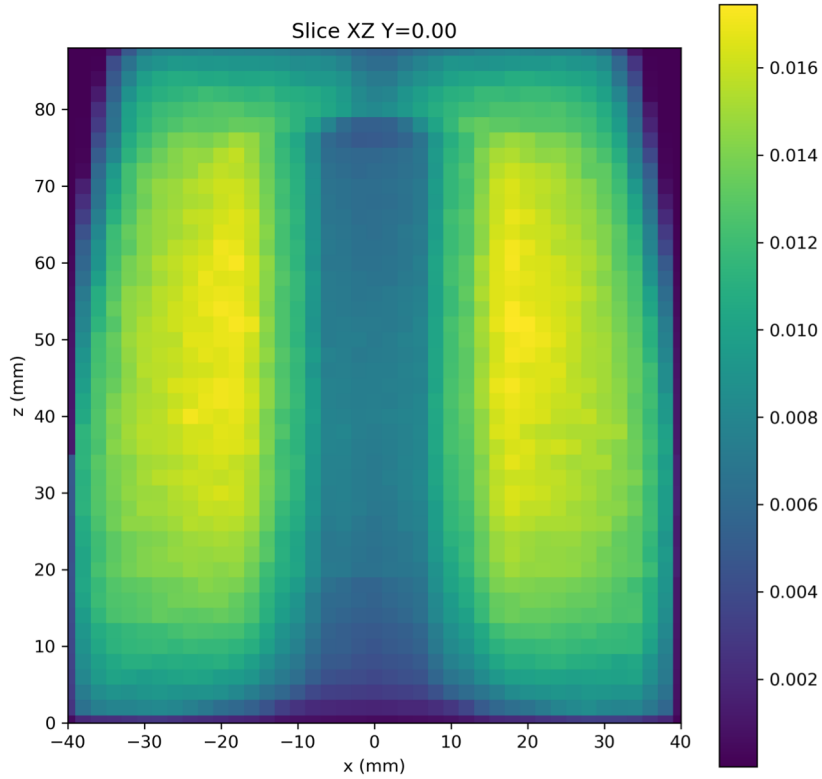
2. Analysis of pitch

Reconstructed volume slice – XZ slice (Y = 0)

1x1 mm²



2x2 mm²

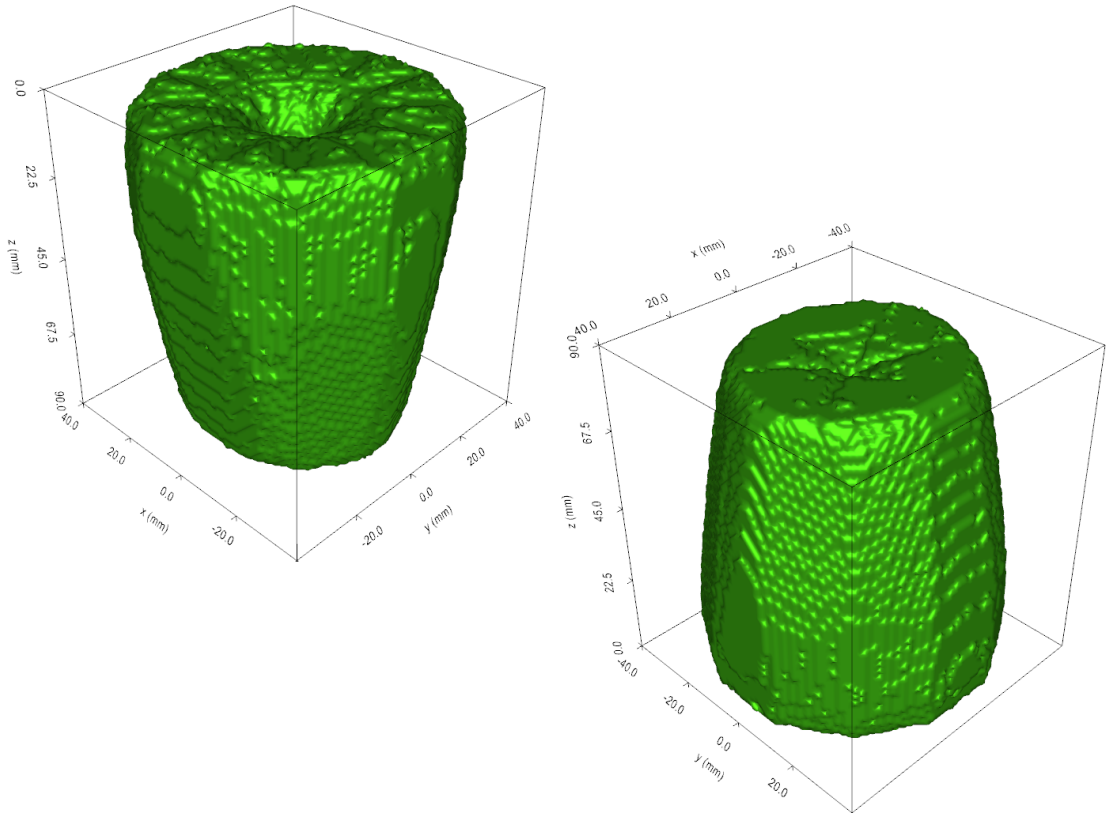


B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

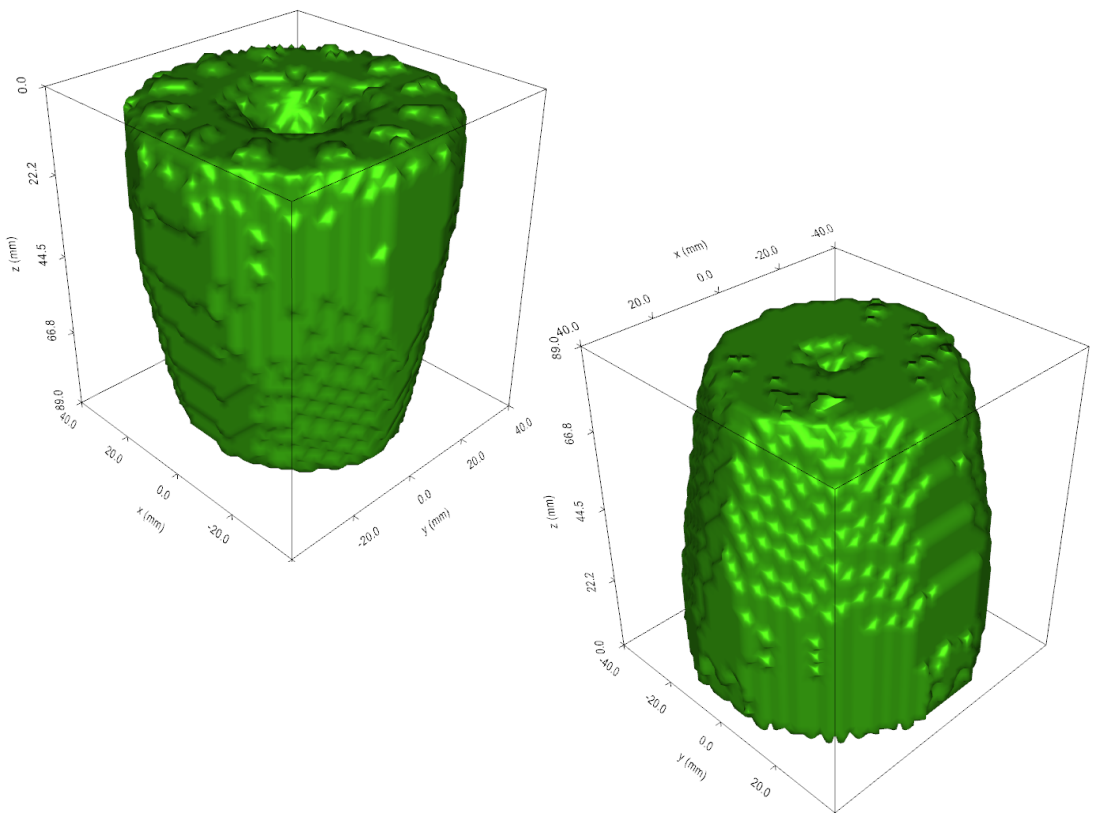
2. Analysis of pitch

Reconstructed volume

1x1 mm²



2x2 mm²



B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

2. Analysis of pitch

Increasing the step to 2 mm, i.e. 2x2 mm^2 grid:

- 👍🏼 Reduces the measurement time to a quarter of the total
- 👍🏼 The reconstructed volume is quite similar to that of 1x1 mm^2 grid scan and structures such as the segmentation lines can be observed. It preserves the main features
- 👎🏼 A fair amount of details is lost

It is worth keeping the 1x1 mm^2 grid for the tomography or **setting an intermediate one of 1.5x1.5 mm^2**, which would reduce the total acquisition time by almost the half ($^4/_9\ T$)

B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

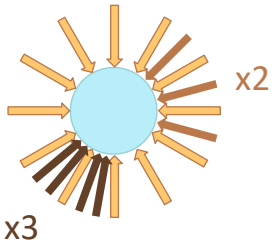
3. Analysis of the number of 2D projections ↔ number of angles

Given the results, it seems that employing **12 projections is insufficient and leads to artefacts** in the final image. Currently, the reconstruction achieved is severely **limited by the number of angles** from which measurements were taken. Increasing the number of proyections would yield better results.

The data are acquired using a **Geant4 simulation of a symmetric detector**. In this way we generate the spectra that would be obtained at each measurement angle. After that, we use the **same code for the spectrum analysis and the tomographic reconstruction** as we do with the experimental data.

The following cases are considered:

1. 12 projections, every 30º (current procedure)
2. 24 projections, every 15º: This would double the acquisition time
3. 36 projections, every 10º: This would triple the acquisition time

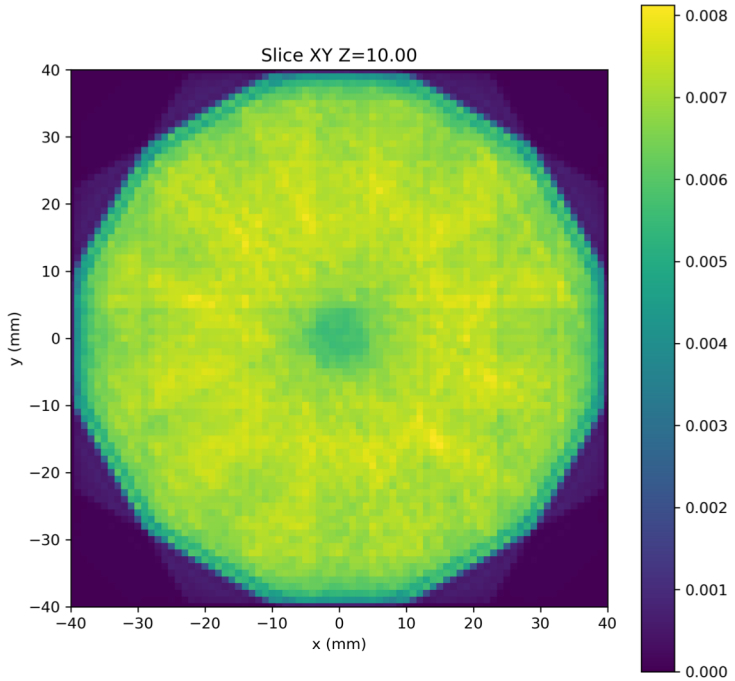


B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

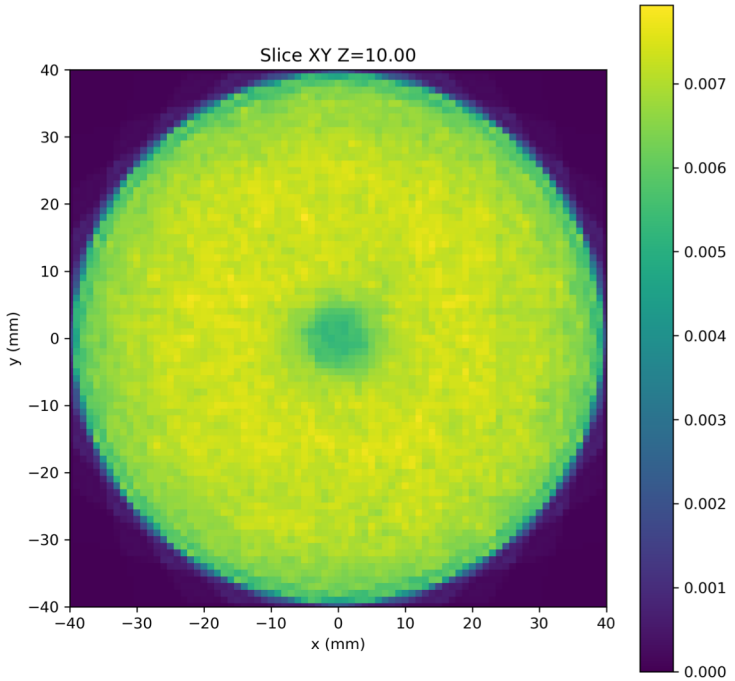
2. Analysis of the number of 2D projections ↔ number of angles

Reconstructed volume slice – XY slice (Z = 10)

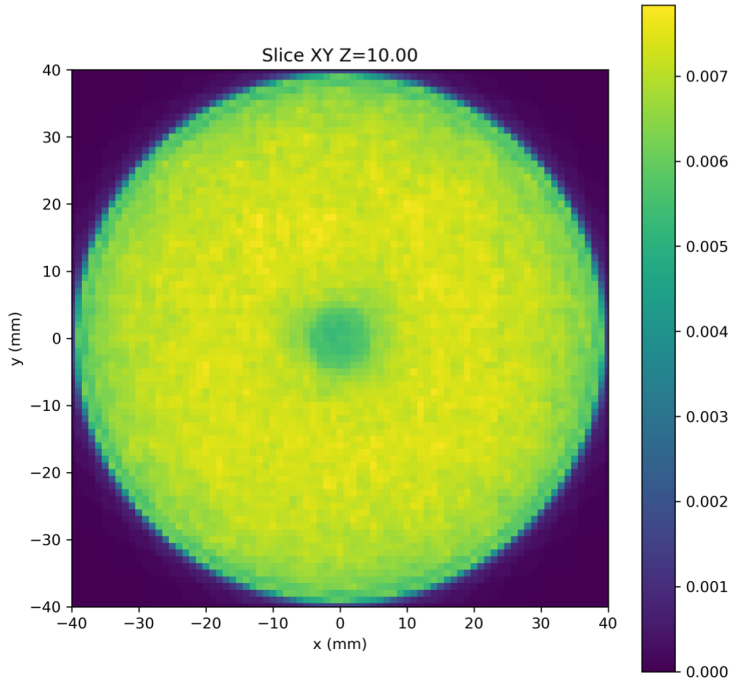
12 angles (every 30º)



24 angles (every 15º)



36 angles (every 10º)



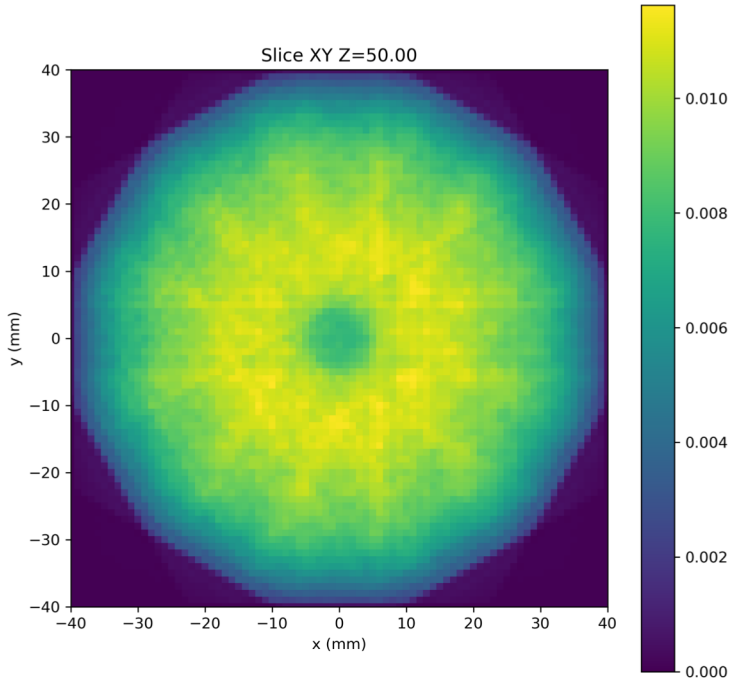
More accurate reconstruction:
- Reconstruction artefacts are noticeable reduced
- Edge surface and central hole are closer to reality

B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

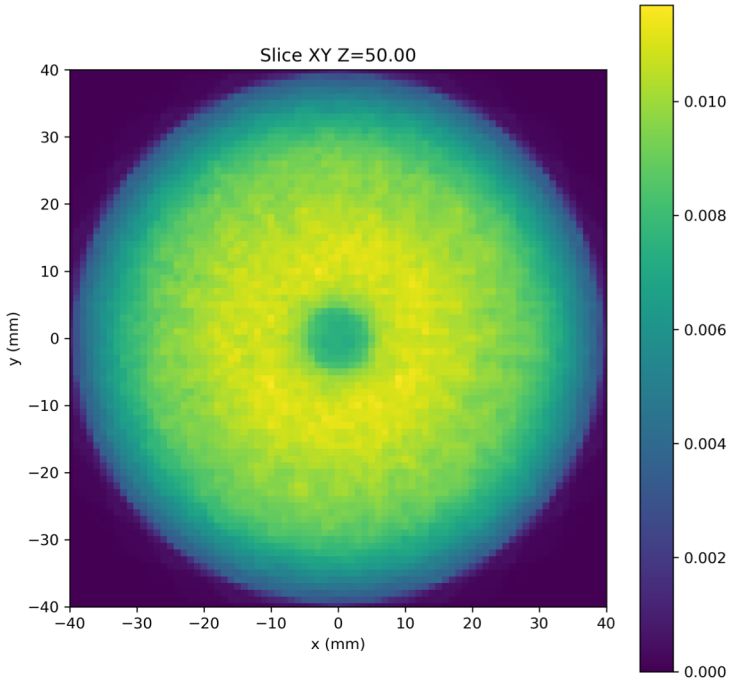
2. Analysis of the number of 2D projections ↔ number of angles

Reconstructed volume slice – XY slice (Z = 50)

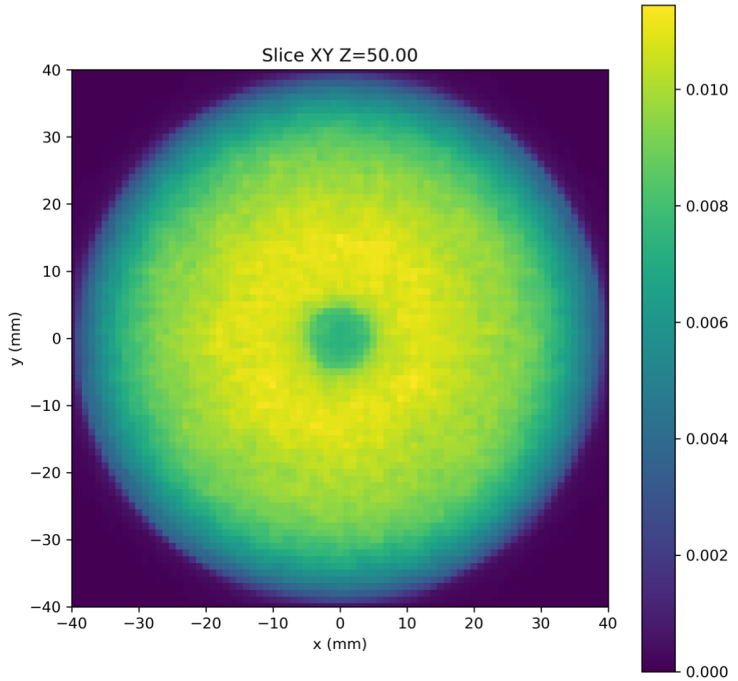
12 angles (every 30º)



24 angles (every 15º)



36 angles (every 10º)

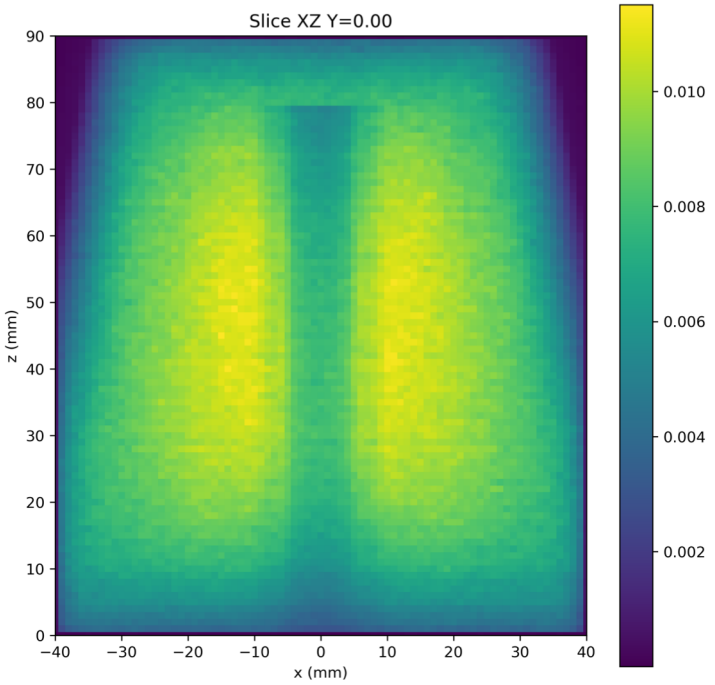


B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

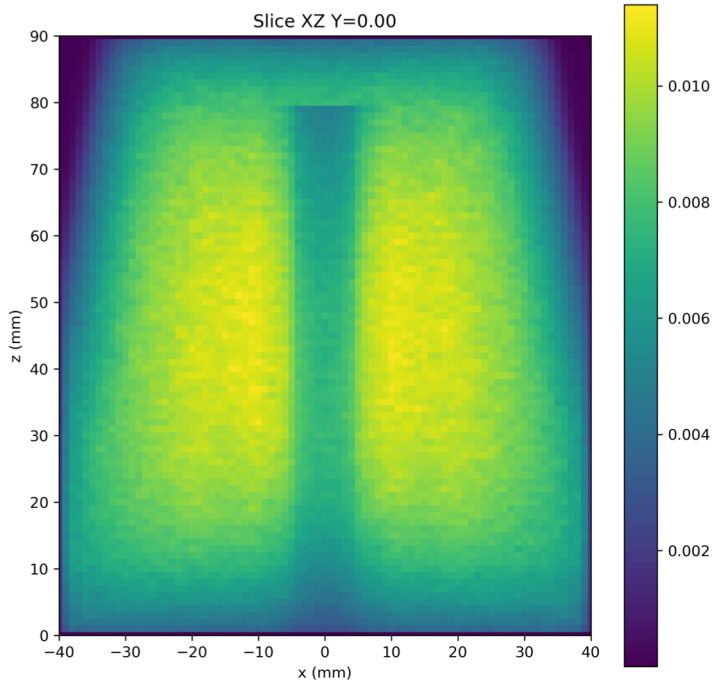
2. Analysis of the number of 2D projections ↔ number of angles

Reconstructed volume slice – XZ slice (Y = 0)

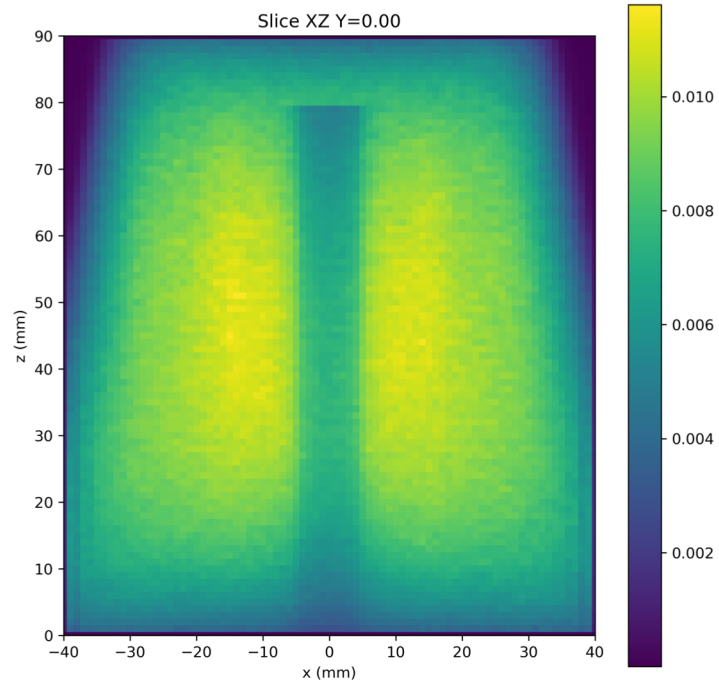
12 angles (every 30º)



24 angles (every 15º)



36 angles (every 10º)



More accurate reconstruction: - Reconstruction artefacts are noticeable reduced
- Edge surface and central hole are closer to reality

B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

3. Analysis of the number of 2D projections ↔ number of angles

Increasing the number of angles (projections) significantly improves the quality and the accuracy of the image obtained

Acquire data from 24 angular configurations:

- 👍 It considerably improves the accuracy of the reconstructed volume
  - 👍 The star-shaped artefacts are greatly reduced
  - 👍 The edges and the central hole are closer to reality and better defined
- 👎 The measurement time needs to be twice as long

The improvements offered by upgrading to 36 angles (compared with 24) do not seem significant enough to make it worthwhile

B003 TOMOGRAPHY – PROCEDURE OPTIMISATION (SUMMARY)

Having analysed the **three experimental factors that are most likely to influence the final image** obtained by tomography, we conclude that the best proposals for future measurements are:

Configuration	$\boldsymbol{t_P\ (s)}$	$\boldsymbol{g}$	$\boldsymbol{N_a}$	$\boldsymbol{t_T}$
Current	67	1 x 1 mm^2	12 (30º)	$\boldsymbol{T}$ **(~ 12 weeks)**
Proposal 1	40	1.5 x 1.5 mm^2	24 (15º)	$\sim \frac{2}{3} \times \frac{4}{9} \times 2\,T \cong$ **59 %** $\boldsymbol{T}$ **(~ 7 weeks)**
Proposal 2	40	1 x 1 mm^2	24 (15º)	$\sim \frac{2}{3} \times 1 \times 2\,T \cong$ **133 %** $\boldsymbol{T}$ **(~ 16 weeks)**

* Where:

t_P refers to the measurement time for each point,

g to the grid,

N_a to the number of angles from which to measure, projections, and

t_T to the total time required for data acquisition

THANK YOU
FOR YOUR ATTENTION

Special thanks to:

G. Duchêne, M-H. Sigward, F. Didierjean, M. Moukaddam, A. Corbel and the other members of the IPHC AGATA team

V. Bekaert, D. Brasse

B003 SCANNING

Key steps of scanning:

1. Detector alignment in vertical configuration (~ 6 days)
2. Data acquisition with the detector in vertical configuration (14 days)
3. Placement of the detector in horizontal configuration
4. Laser alignment (~ 2 days)
5. Detector alignment in horizontal configuration(~ 4 days)
6. Data acquisition with the detector in horizontal configuration (19 days)

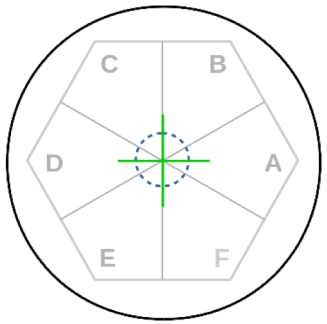
B003 SCANNING – DETECTOR ALIGNMENT IN VERTICAL CONFIGURATION

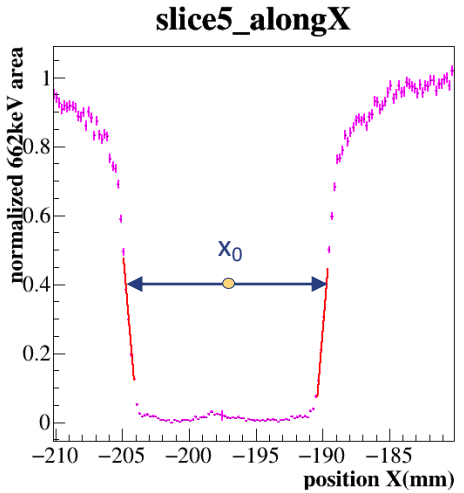
Central hole alignment along the X and Y axes allows to:

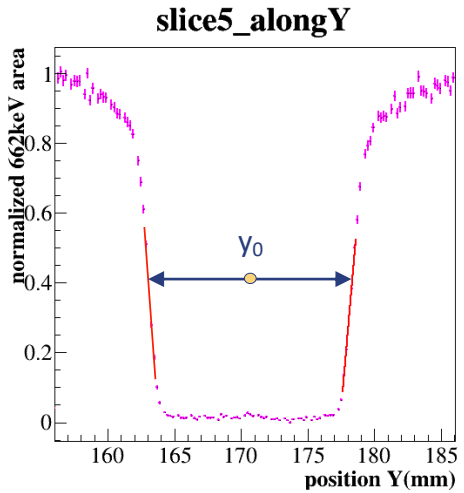
- **Correct any tilt** of the crystal relative to the scanning table
- Determine the **position of the centre** of the crystal
- Obtain the **hole diameter**

Scan across the hole (**cross pattern**), to align the X and Y positions of the hole borders of segment slices 2 to 6:

- ^{137}Cs (661.7 keV)
- Energy mode
- 40 mm scan along X/Y axes
- 200 µm pitch
- Collimator: 1 mm, 165 mm long





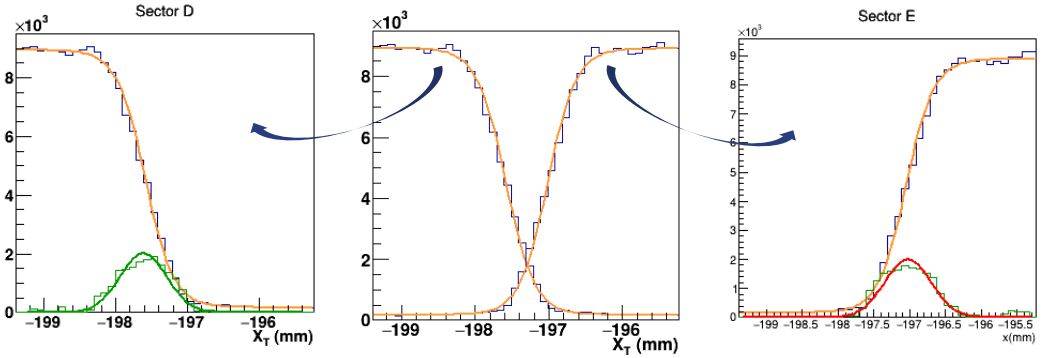


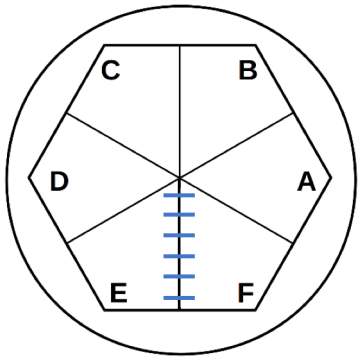
B003 SCANNING – DETECTOR ALIGNMENT IN VERTICAL CONFIGURATION

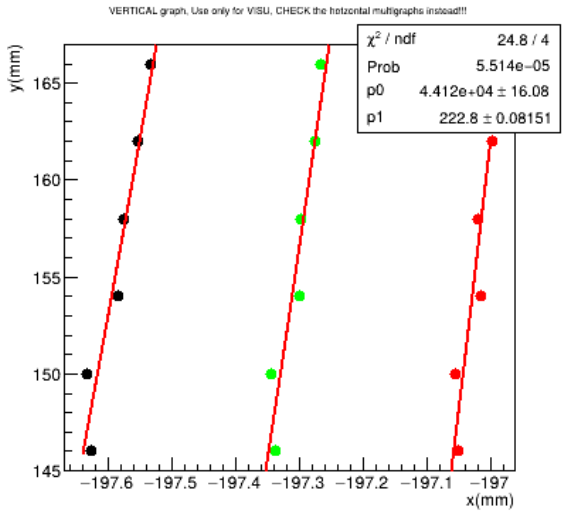
<u>Alignment to place BC-EF segmentation lines parallel to Y-axis</u>

Scan across the BC and EF segmentation lines, to align them on the Y-axis:

- ^{241}Am (59.5 keV)
- Energy mode
- 4 mm scan parallel to X axis for 6 Y positions
- 100 µm pitch
- Collimator: 1 mm, 165 mm long



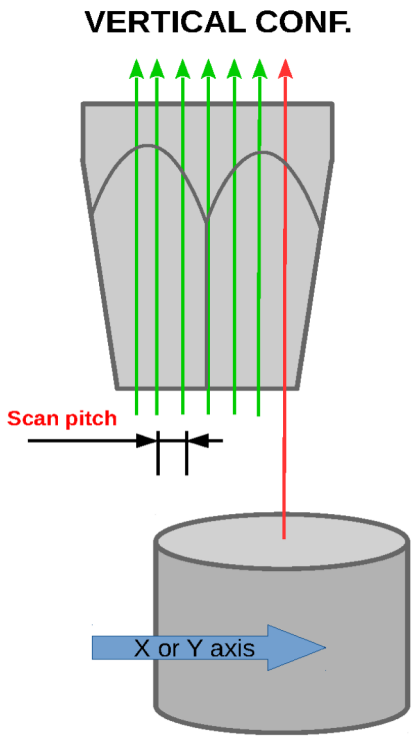


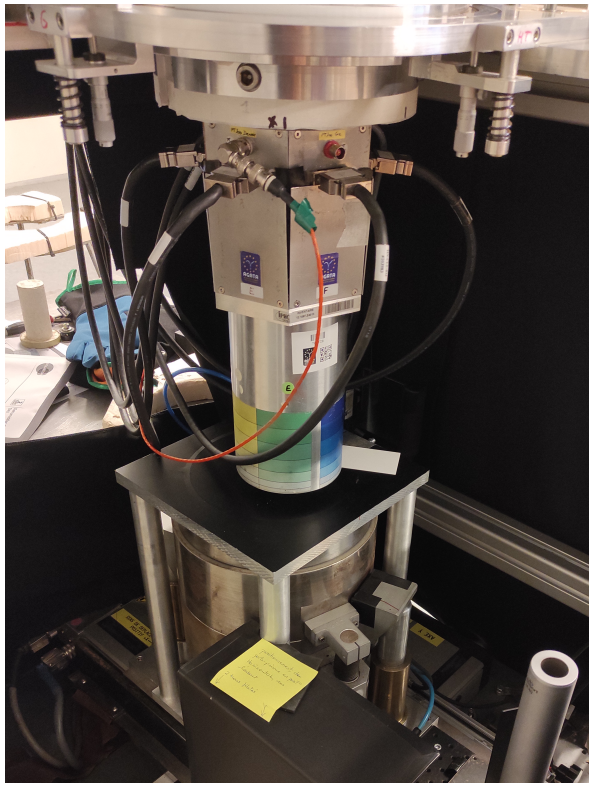


B003 SCANNING – MEASUREMENT IN VERTICAL CONFIGURATION

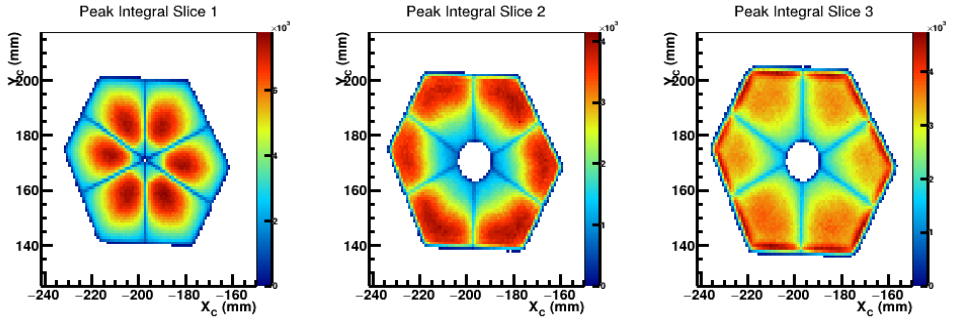
Once the detector is properly aligned in the vertical configuration, we start the data acquisition:

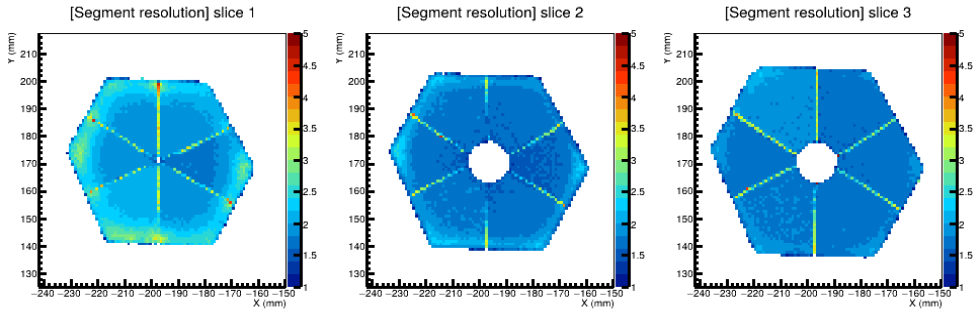
- ^{137}Cs (661.7 keV)
- Mixed mode: energy and pulse shapes
- 1 mm pitch
- 5418 points
- Collimator: 1 mm, 165 mm long
- 14 days

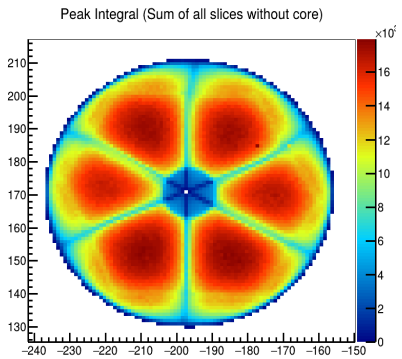


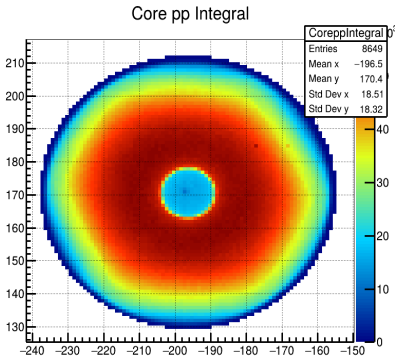


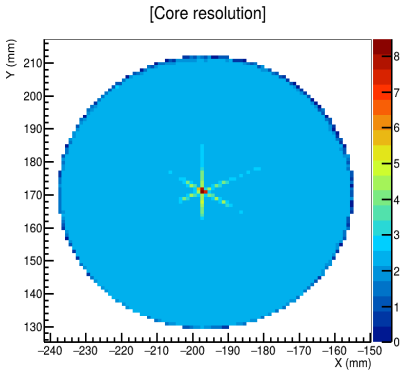
B003 SCANNING – MEASUREMENT IN VERTICAL CONFIGURATION





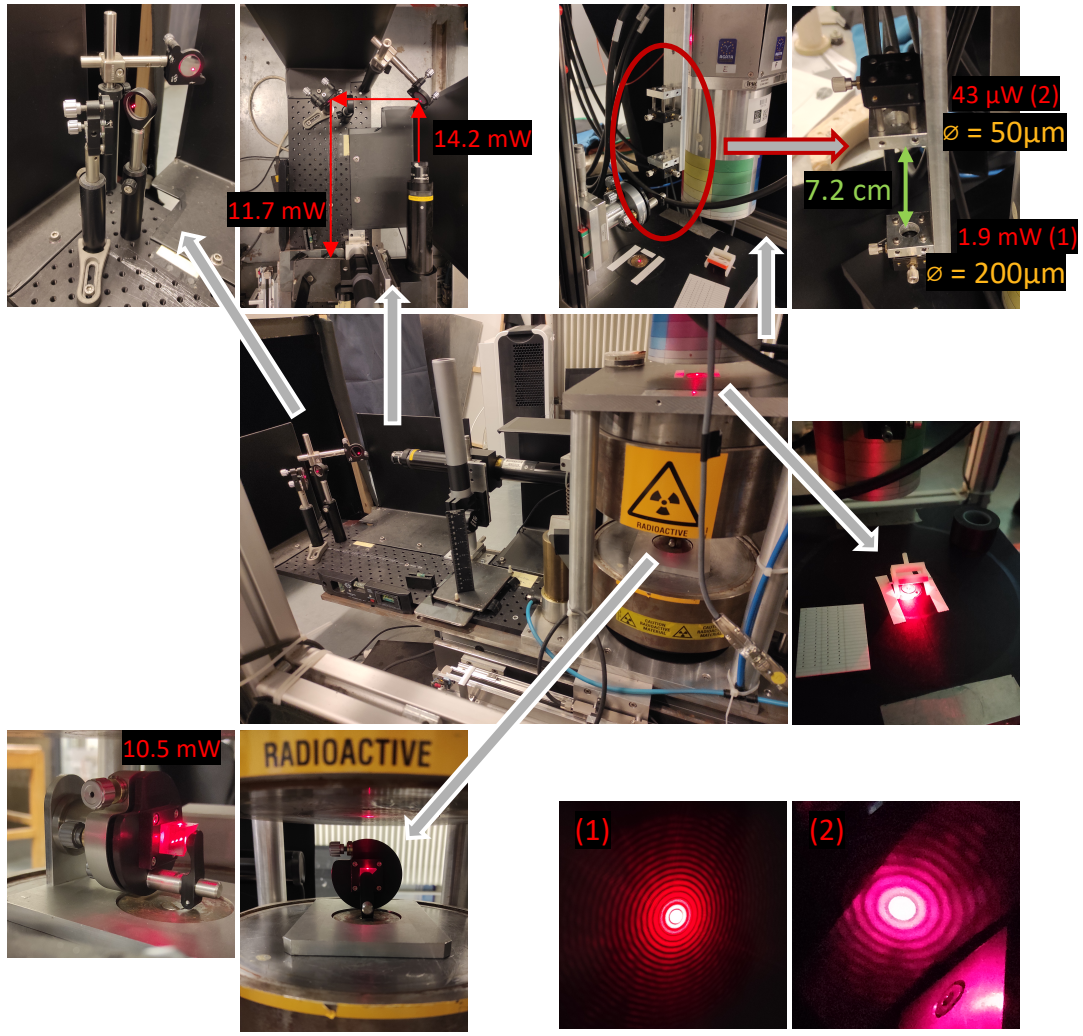






B003 SCANNING – LASER ALIGNMENT

- The **detector hole** is previously **aligned vertically**, parallel to the Z-axis.
- An optical system, composed by **two sights**, is **attached to the cryostat**.
- We adjust the screws on the two sights in order to be sure that the **laser passing trough is at its maximum along the vertical axis**, parallel to z. In this way, we ensure that the **optical system is aligned vertically** and, therefore, **parallel to the detector hole**.
- Without altering the optical setup, the detector is placed in the **horizontal configuration**.
- The cryostat is aligned so that the laser beam passes through the sights with maximum amplitude. This guarantees that the **optical system is aligned horizontally** and, consequently, the **detector hole** is.

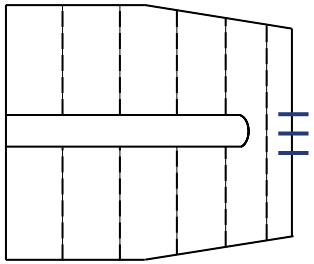


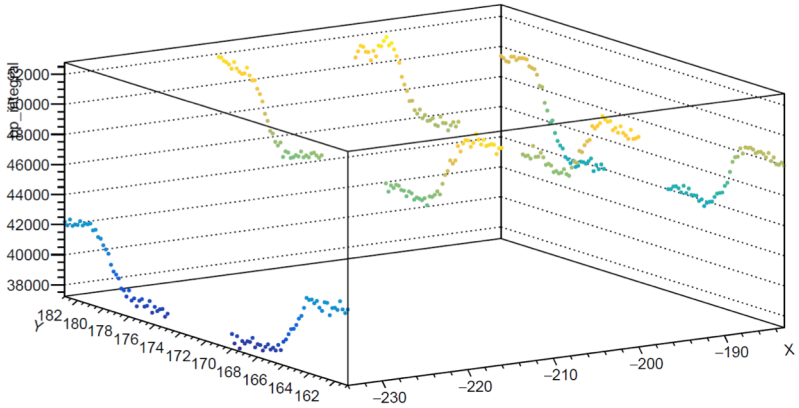
B003 SCANNING – ALIGNMENT IN HORIZONTAL CONFIGURATION

To check that the detector is correctly aligned, the central hole on the X-axis, perpendicular to the YZ-plane

1st scan: At the tip of the detector (check tilt)

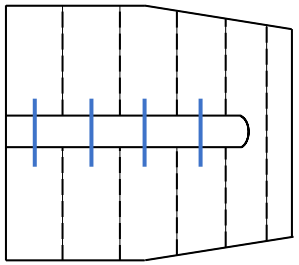
- ^{241}Am (59.5 keV)
- Energy mode
- 2 mm scan (3 lines)
- 100/200 µm pitch
- Collimator: 1 mm, 165 mm long

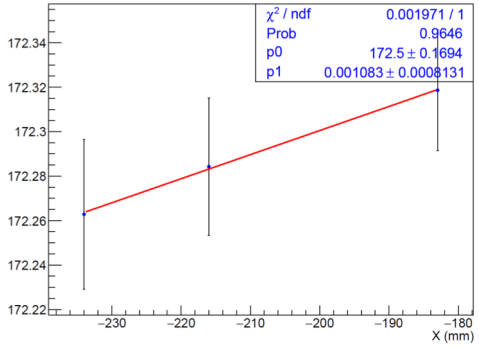




2nd scan: Across the hole, CD segments (parallel to X-axis)

- ^{137}Cs (661.7 keV)
- Energy mode
- 40 mm scan (4 lines)
- 200 µm pitch
- Collimator: 1 mm, 165 mm long





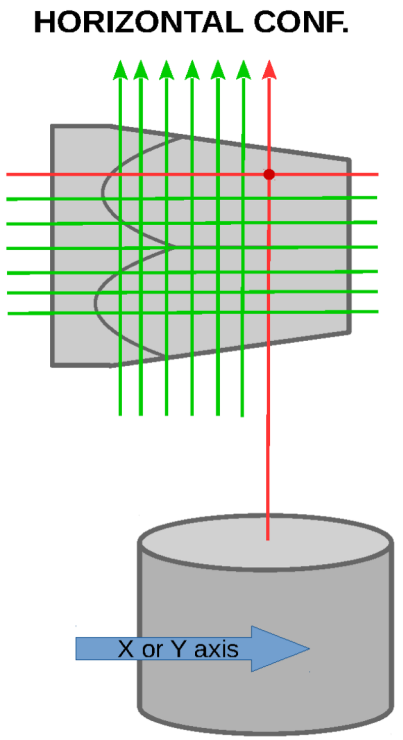
Accuracy:

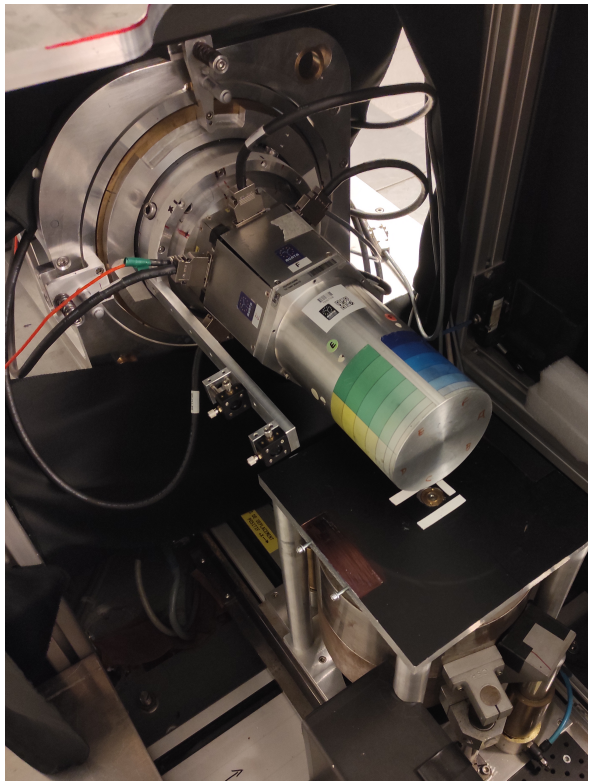
$\theta = (0.064 \pm 0.041)º$

B003 SCANNING – MEASUREMENT IN HORIZONTAL CONFIGURATION

Once the detector is properly aligned in the horizontal configuration, we start the data acquisition:

- ^{137}Cs (661.7 keV)
- Mixed mode: energy and pulse shapes
- 1 mm pitch
- 7344 points
- Collimator: 1 mm, 165 mm long
- 19 days



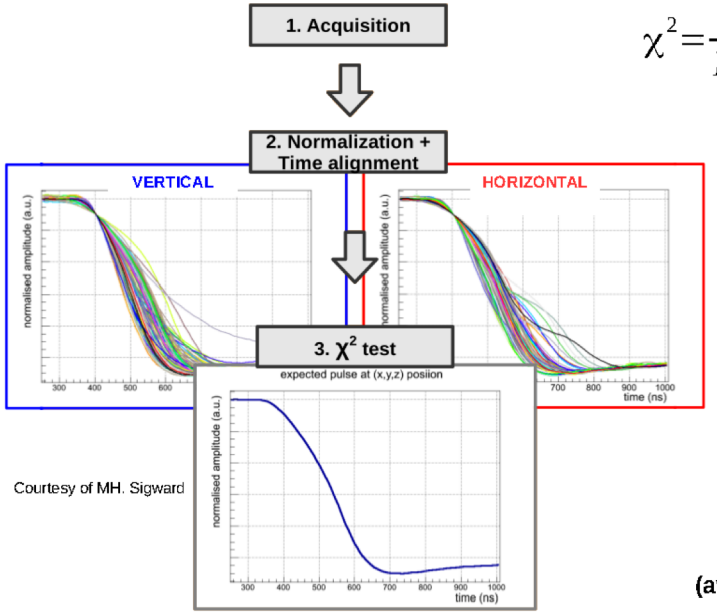


B003 SCANNING – BUILDING THE DATABASE

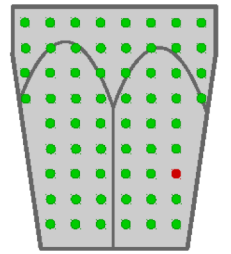
We carry out the PSCS technique: to compare the pulse shapes using the χ^2 statistical test

- All the measured vertical points are crossed with all the horizontal ones
- We select the **~150 best matching pulses** to calculate the average:

Several iterations are performed in which the **10% of pulses that differ most from the average are rejected**



$$\chi^2 = \frac{1}{N} \cdot \sum_{ch=0}^{37} \sum_{i=0}^{100} \left(\frac{H_{i,ch} - V_{i,ch}}{\sigma_{ch}} \right)^2$$



Comparison of two crossing datasets

Pulse shape at grid intersection (avg of ~150 best matching pulses)

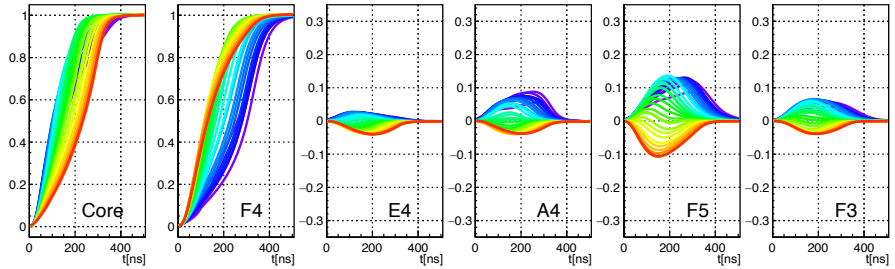
B. De Canditiis, PhD, Univ. Strasbourg, 2020
G. Duchêne, Gamma Detectors Hands-on School, 2024

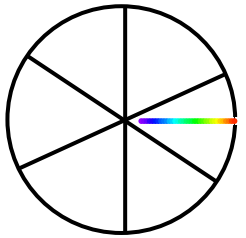
* The code must be updated to incorporate the change made in the measurement method: the detector is no longer rotated to position it horizontally

B003 SCANNING – BUILDING THE DATABASE (RESULTS)

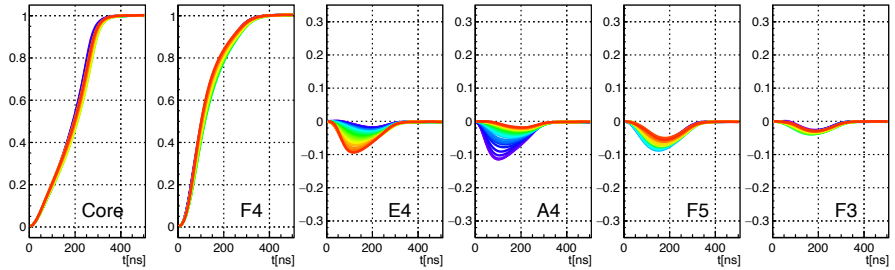
The relationship between the interaction position and the generated signals is investigated in the following cases:

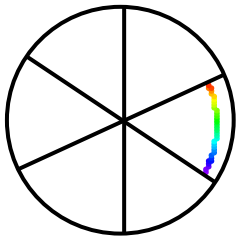
Radial (e.g. Y = 0 mm, Z = 50 mm, F4)



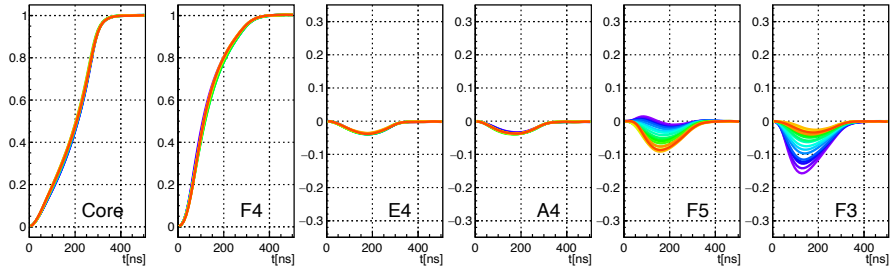


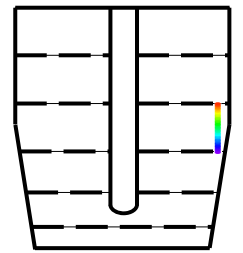
Azimuthal (e.g. *r* = 35 mm, Z = 50 mm, F4)





Height (e.g. X = 35 mm, Y = 0 mm, F4)

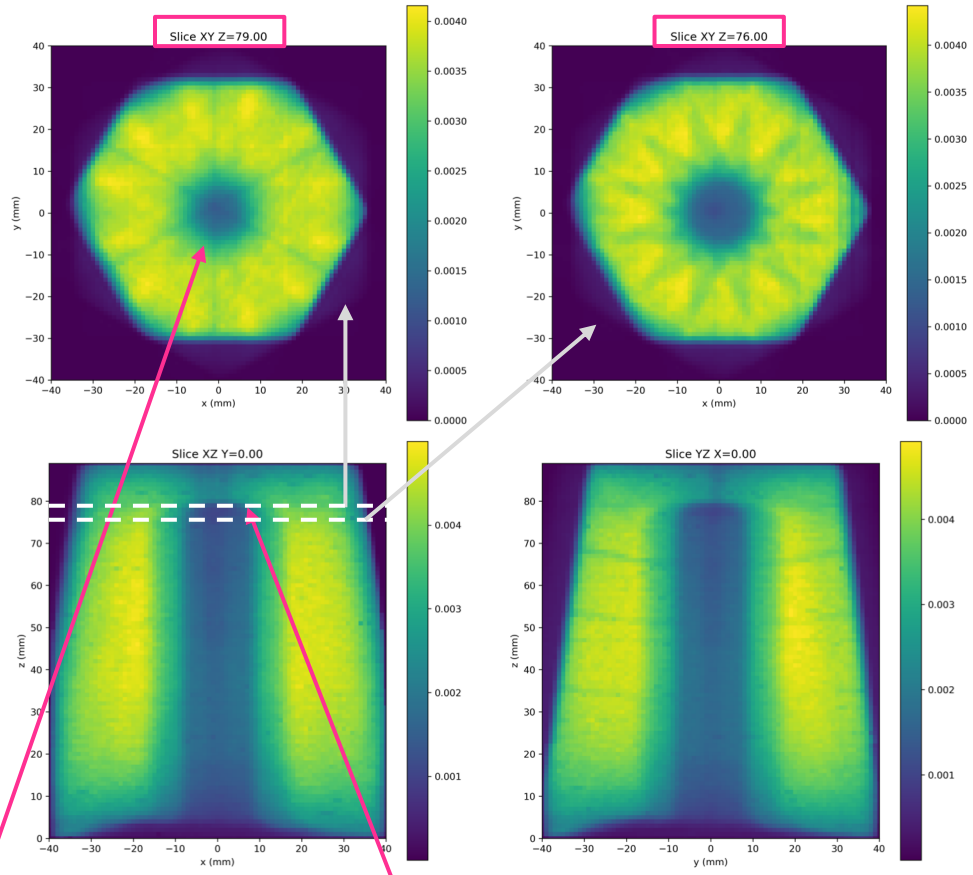




TOMOGRAPHY – RESULTS

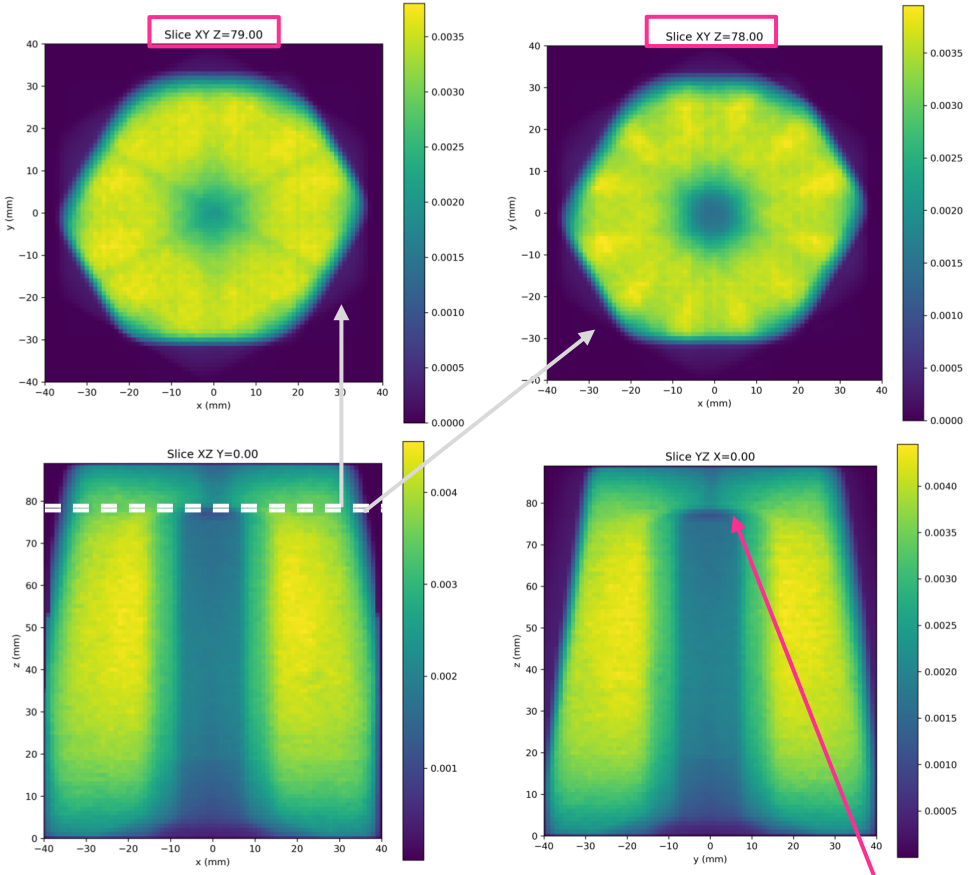
Comparing the tomography results for A005 and B003 detectors:

A005



A005: The hole starts ~11 mm from the front of the detector and widens until reaching a constant diameter at ~ 14/15 mm

B003



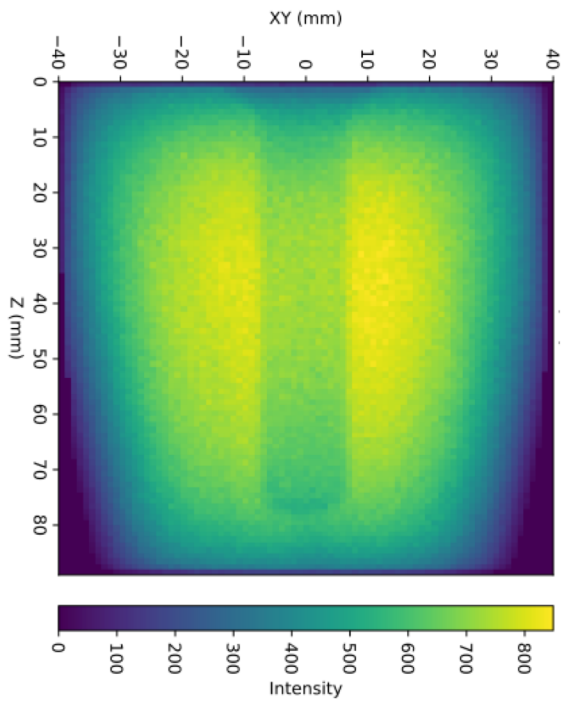
B003: Starts at ~11/12 mm and widens until ~ 15 mm

B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

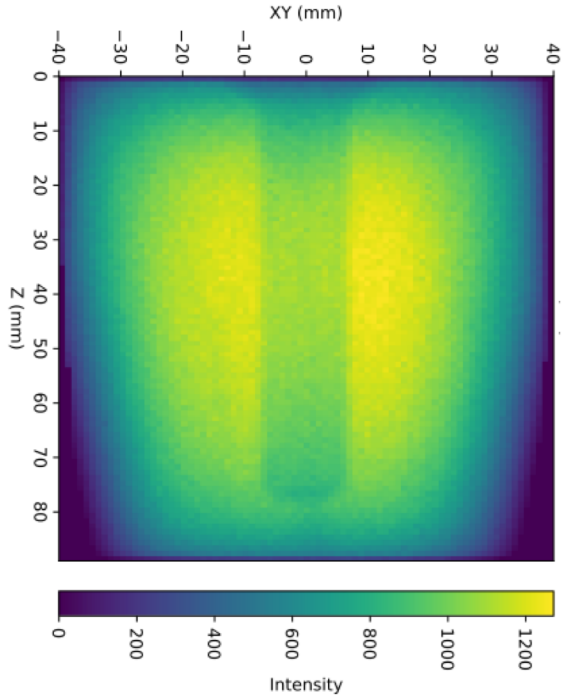
1. Analysis of measurement time

Measured projections (0º)

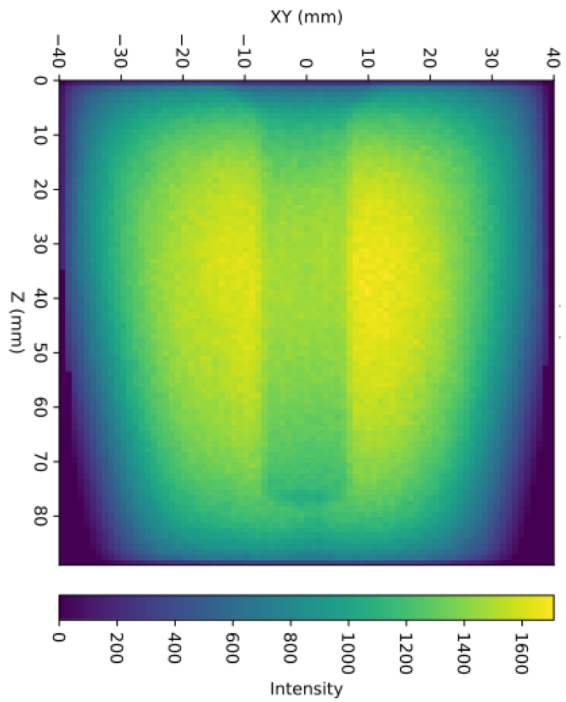
22 s (1/3)



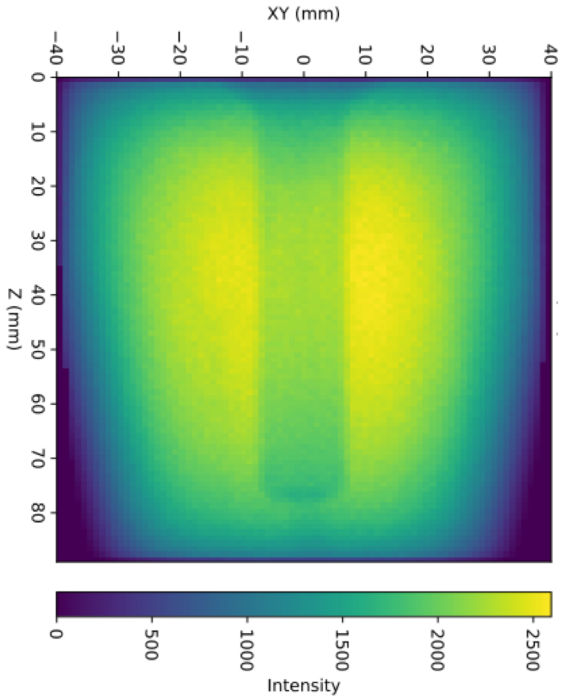
33 s (1/2)



44 s (2/3)



67 s (original)

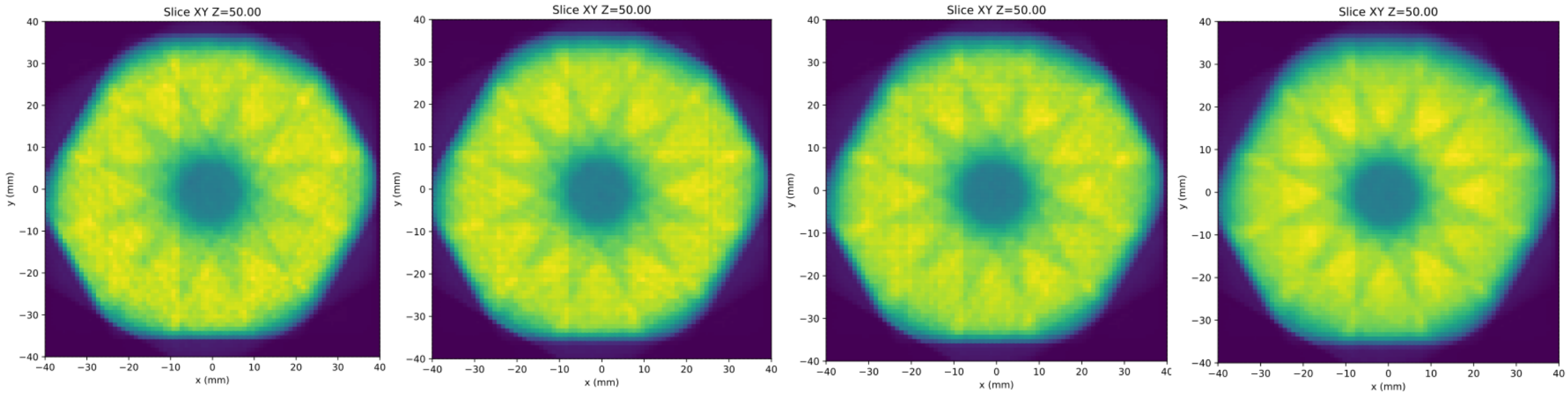


B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

1. Analysis of measurement time

Reconstructed volume slice – XY slice (Z = 50)

22 s (1/3) **33 s (1/2)** **44 s (2/3)** **67 s (original)**

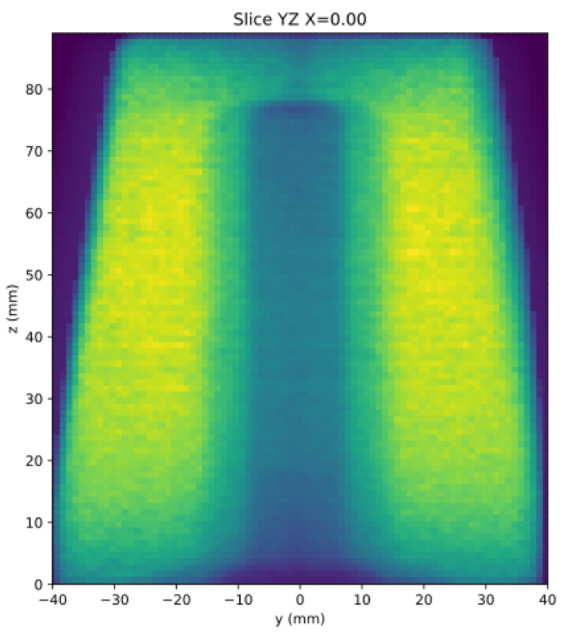


B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

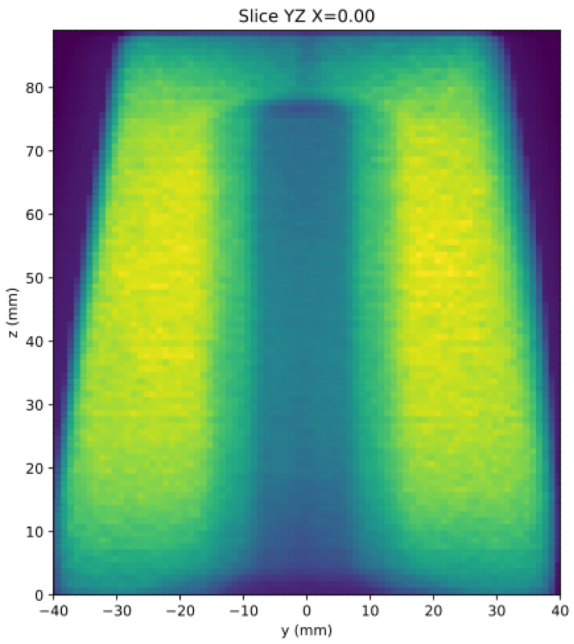
1. Analysis of measurement time

Reconstructed volume slice – YZ slice (X = 0)

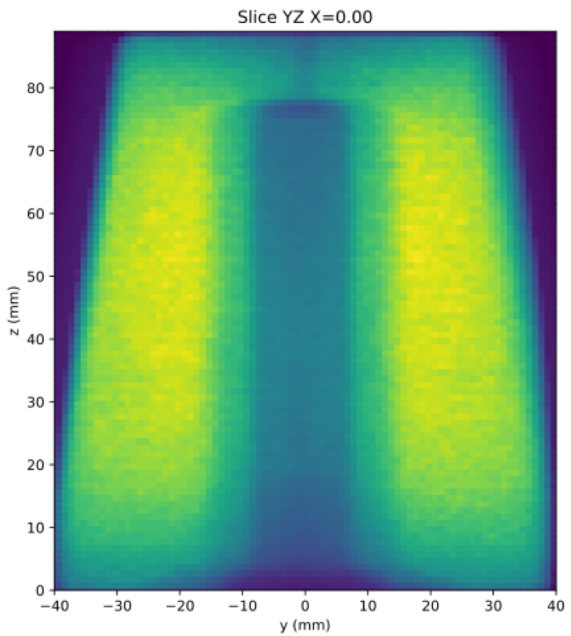
22 s (1/3)



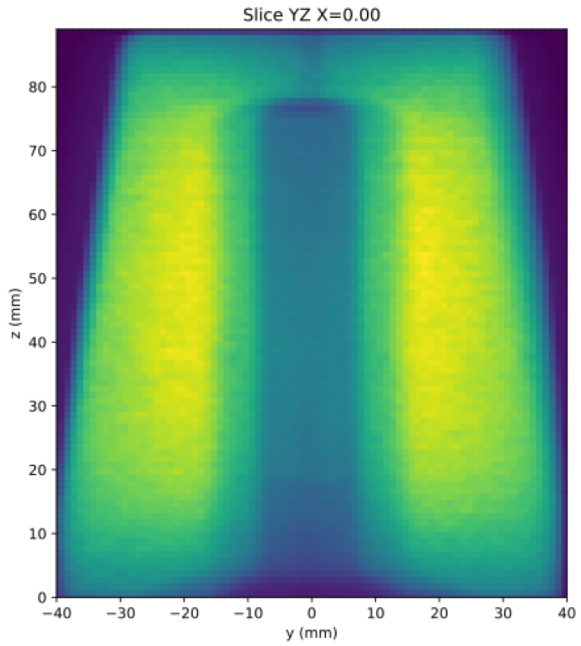
33 s (1/2)



44 s (2/3)



67 s (original)

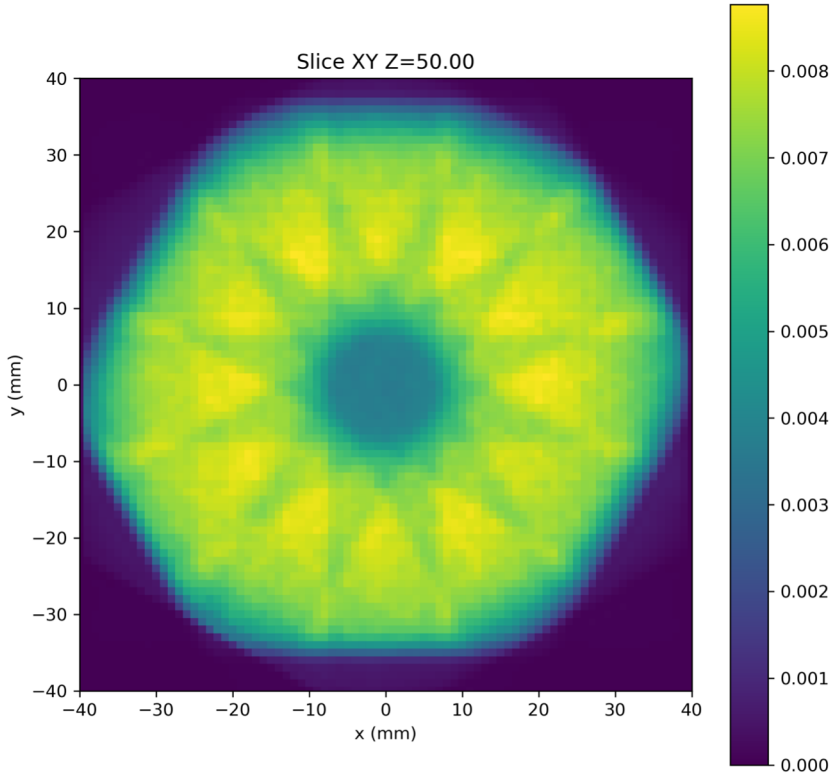


B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

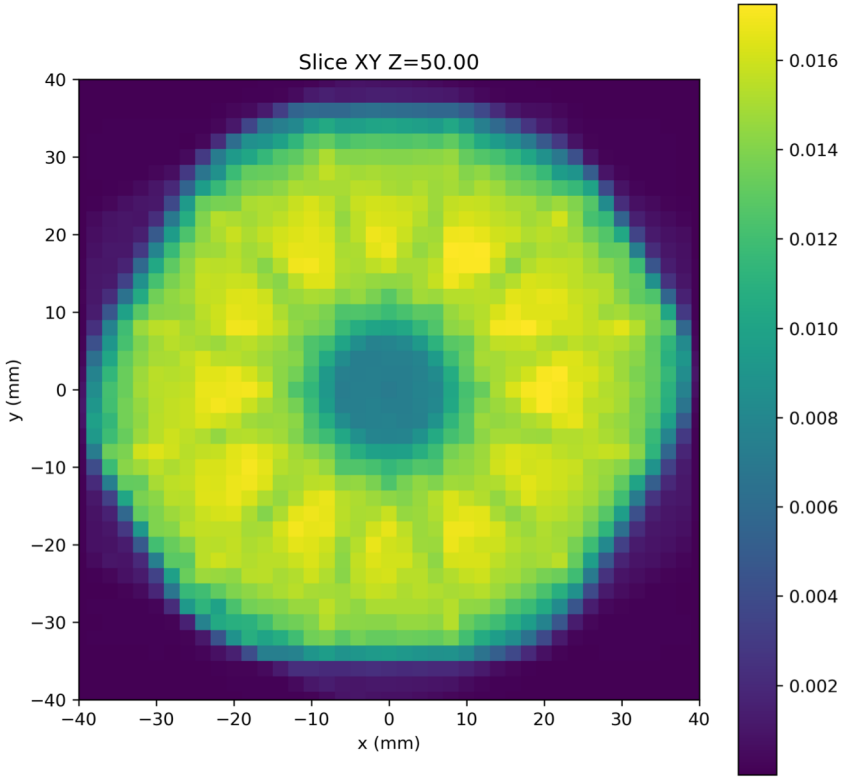
2. Analysis of pitch

Reconstructed volume slice – XY slice (Z = 50)

1x1 mm²



2x2 mm²

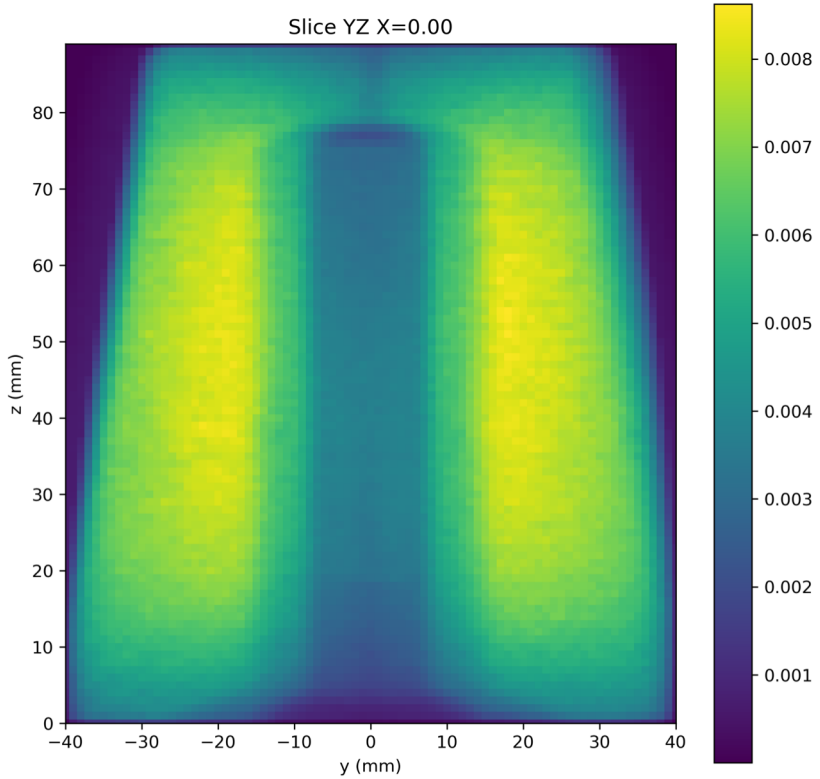


B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

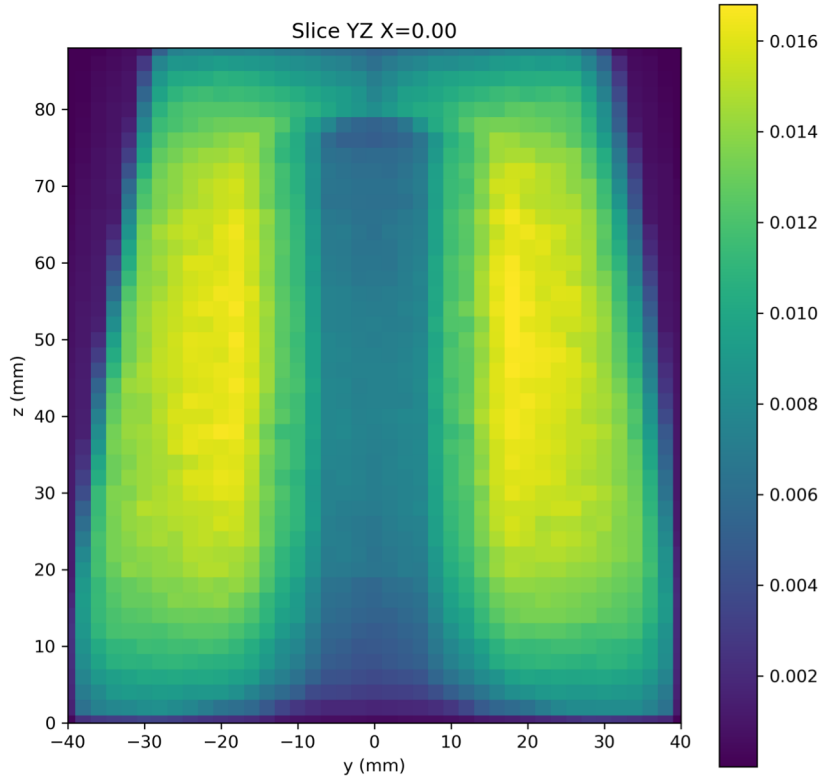
2. Analysis of pitch

Reconstructed volume slice – YZ slice (X = 0)

1x1 mm²



2x2 mm²

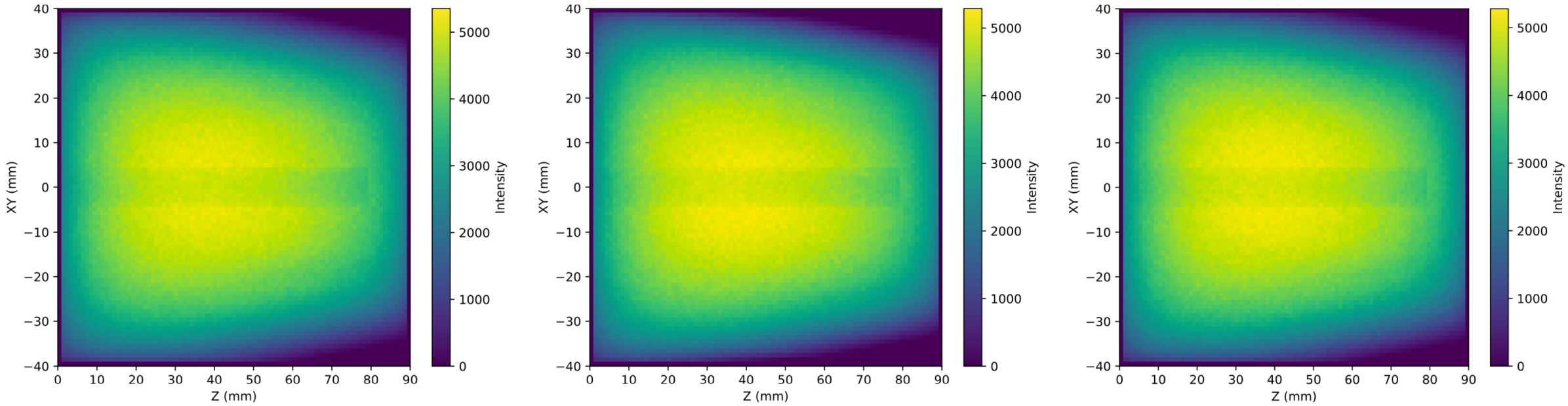


B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

3. Analysis of the number of 2D projections ↔ number of angles

Simulated projections (r_{hole} = 5 mm)

0º **10º** **15º**

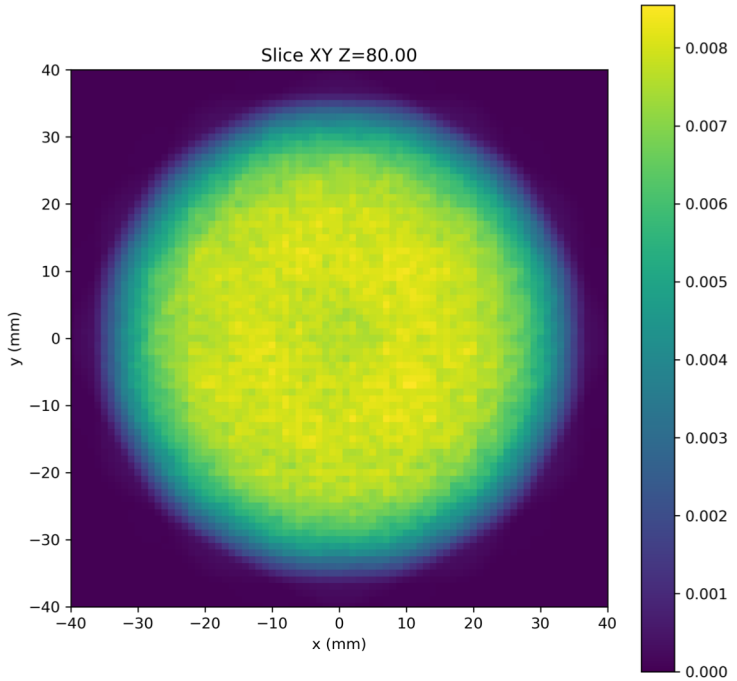


B003 TOMOGRAPHY – PROCEDURE OPTIMISATION

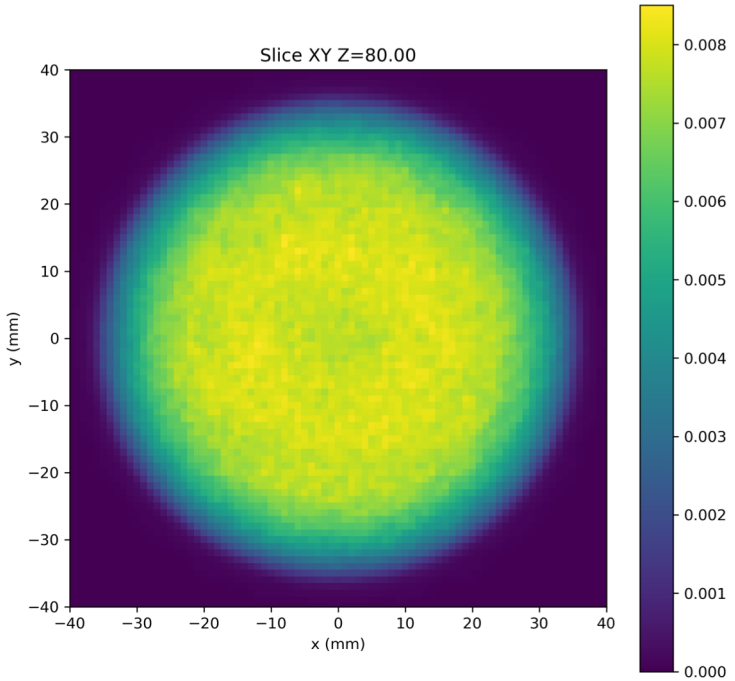
2. Analysis of the number of 2D projections ↔ number of angles

Reconstructed volume slice – XY slice (Z = 80)

12 angles (every 30º)



24 angles (every 15º)



36 angles (every 10º)

