Enhancing AGATA In-Beam Gamma-Ray Spectroscopy with Machine Learning: Study of Nuclear Structure and Shape Coexistence in Neutron-Rich Niobium Isotopes

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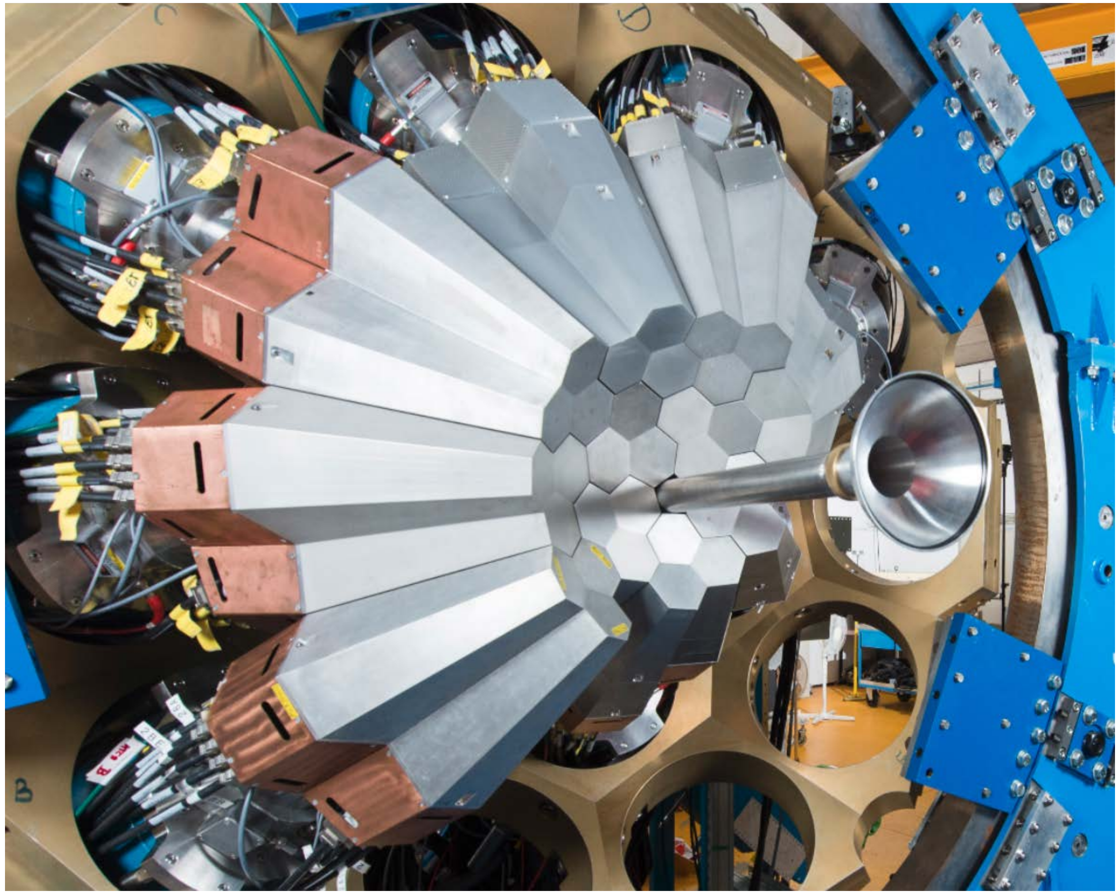
AGATA: Advanced GAmma Tracking Array

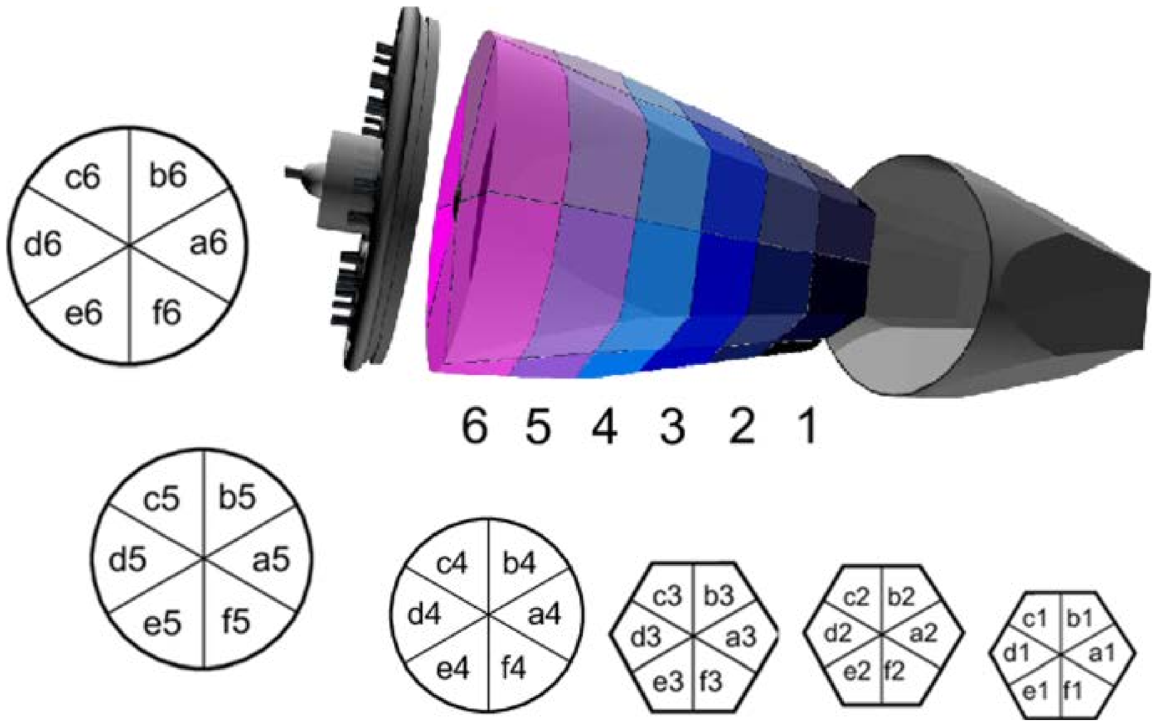
- Consists of 50 HPGe detectors(40 has been used in site and 180 are planned to complete 4π sphere).
  - ✓ High efficiency due to the continuous HPGe crystals.
  - ✓ State of the art energy resolution 2keV at 1.33MeV.

- Capable of tracking Gamma-rays.
  - ✓ Accurate Doppler correction.
  - ✓ Better photopeak to background ratio.

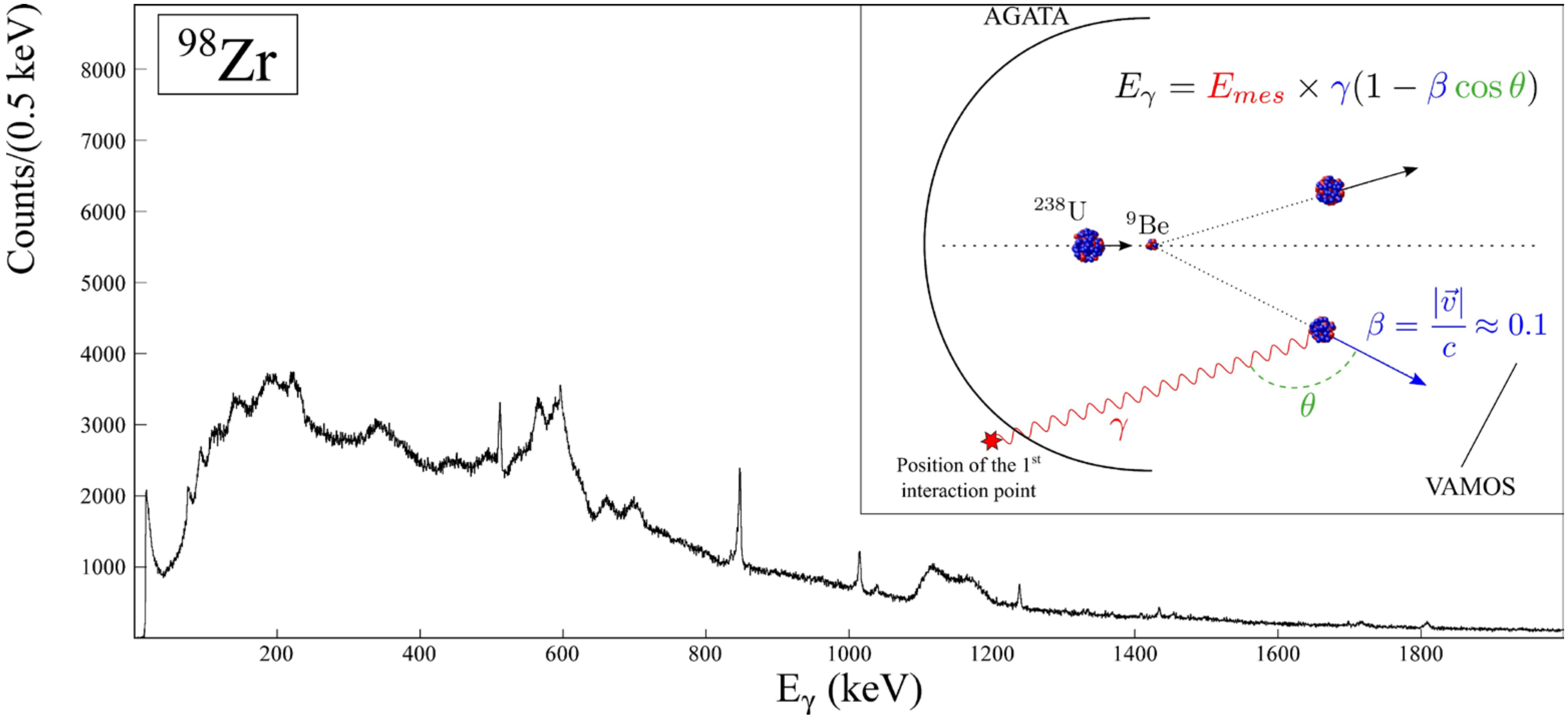


AGATA: highly segmented HPGe

- Electronic segmentation.
  - ✓ No physical segmentation of the crystal(no dead layers between the segments).
  - ✓ Increases the detection efficiency.
- Allows for accurate measurement of the interaction point of the gamma ray.
- We have 36 signals from the segments and 1 signal from the central contact(core signal)



In-beam Gamma-ray spectroscopy: Doppler correction



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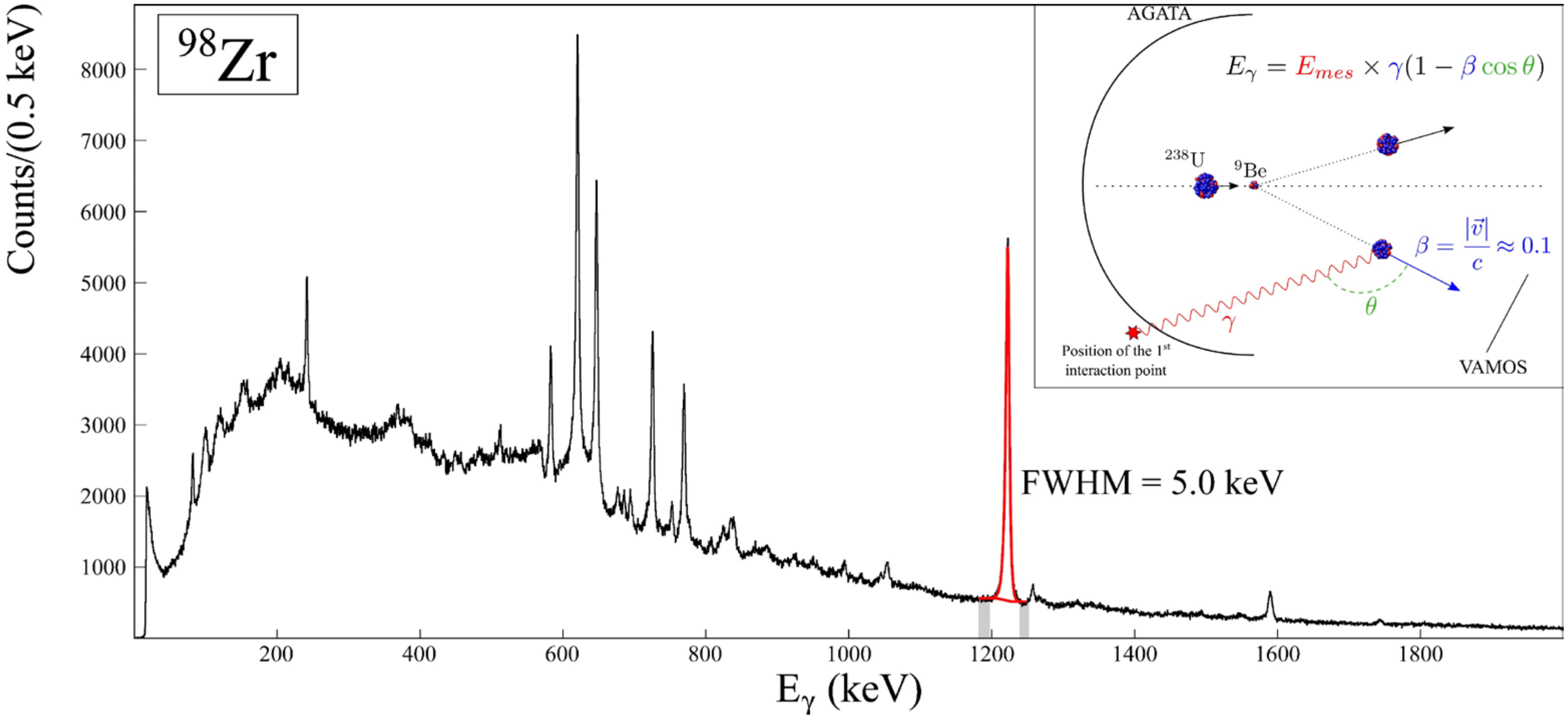
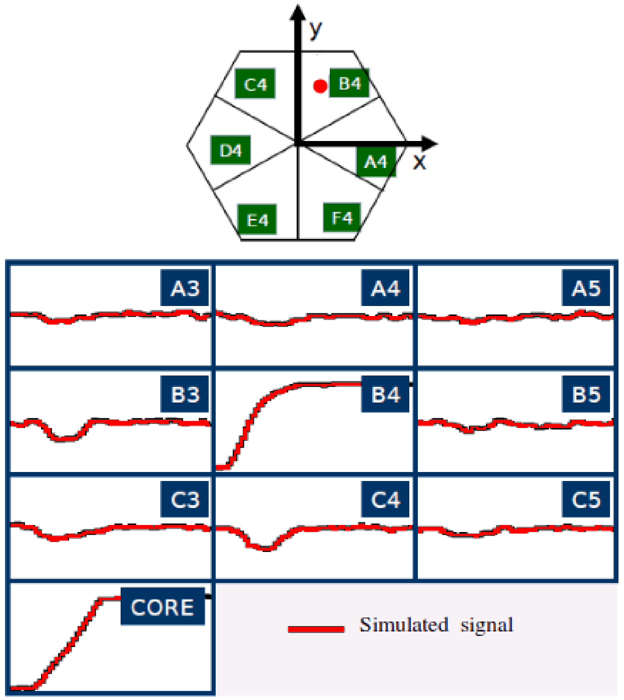


PSA: Pulse Shape Analysis algorithm

- Simulated databases of signals are built for each crystal.
  - ✓ Each database has a 2mm Cartesian grid of points.
  - ✓ 700-2000 Points per segment.
- An adaptive grid search is used to find the point with the closest simulated signal to the measured one.
  - ✓ A wide grid is first evaluated.
  - ✓ Then a full grid search is done to the voxel with the closest signal.



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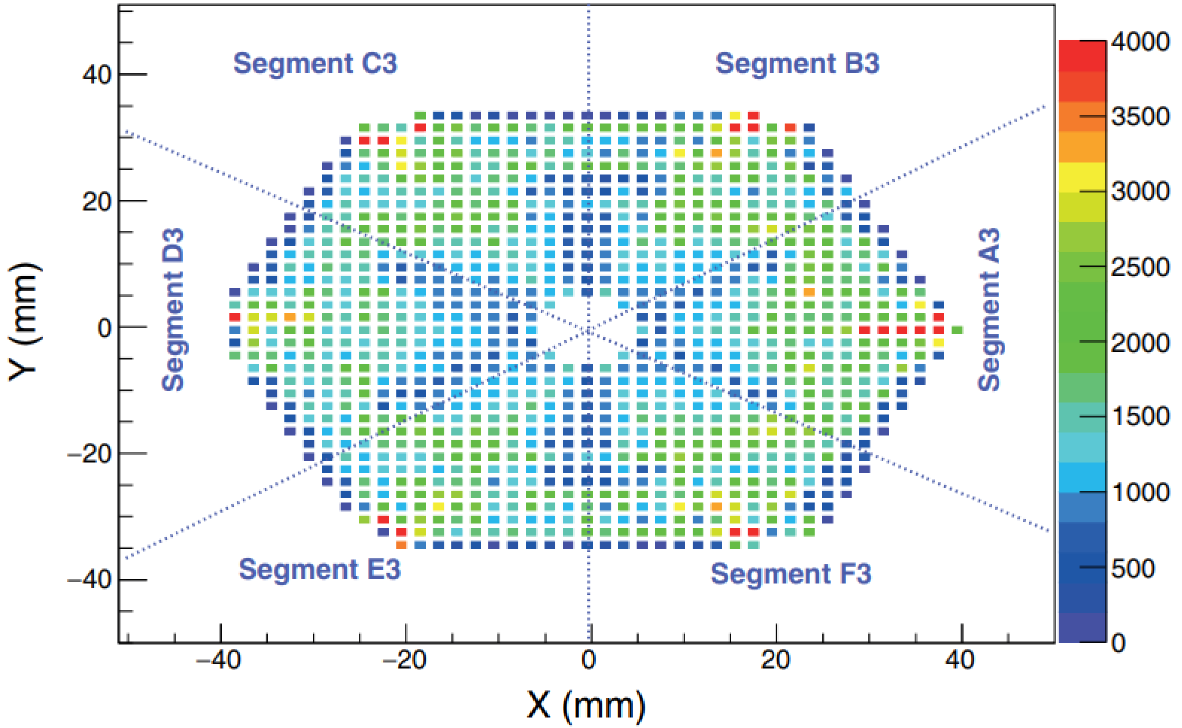

Korichi, A., Lauritsen, *Eur. Phys. J. A* **55**, 121 (2019)

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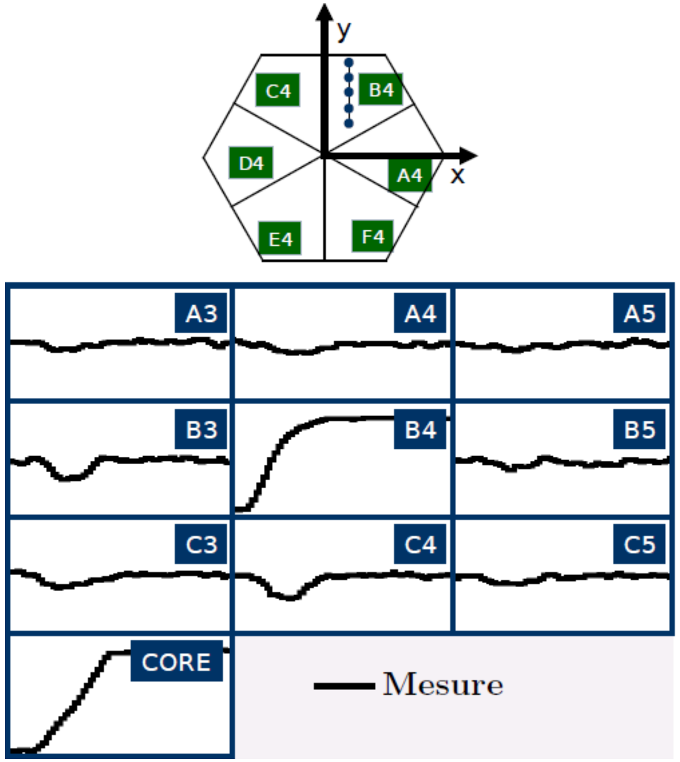

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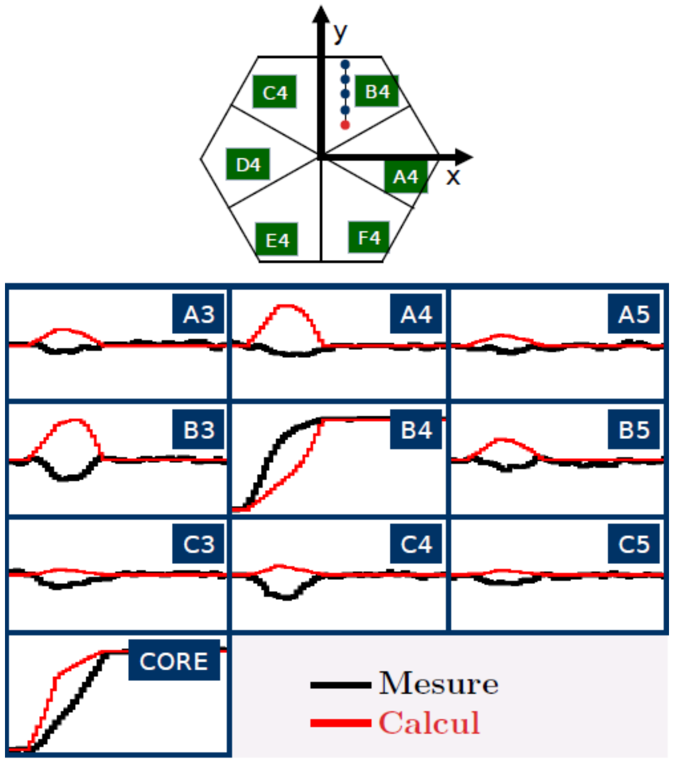

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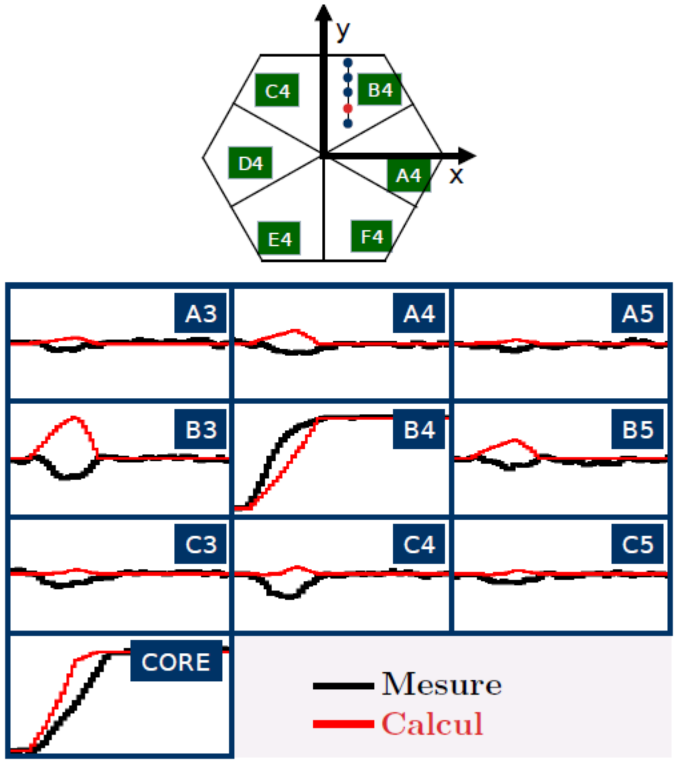

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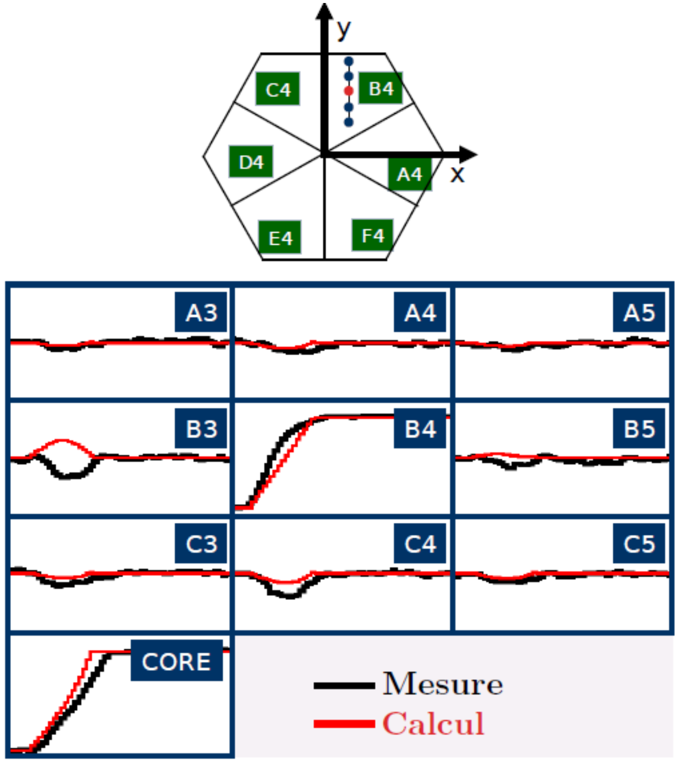

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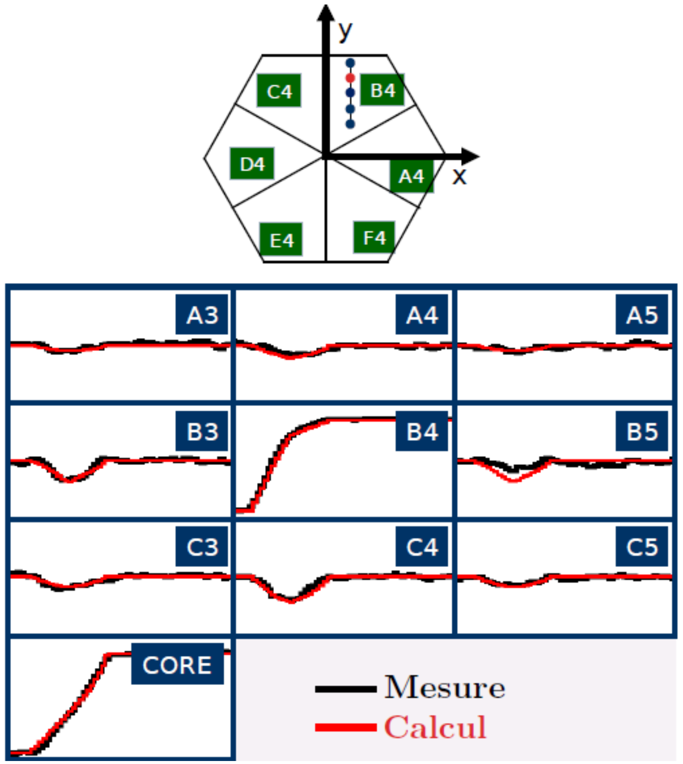

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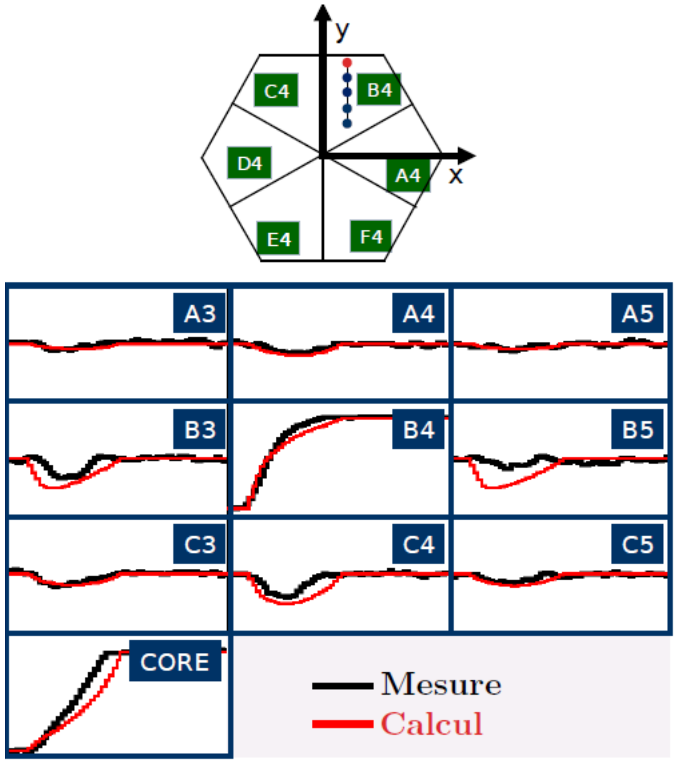

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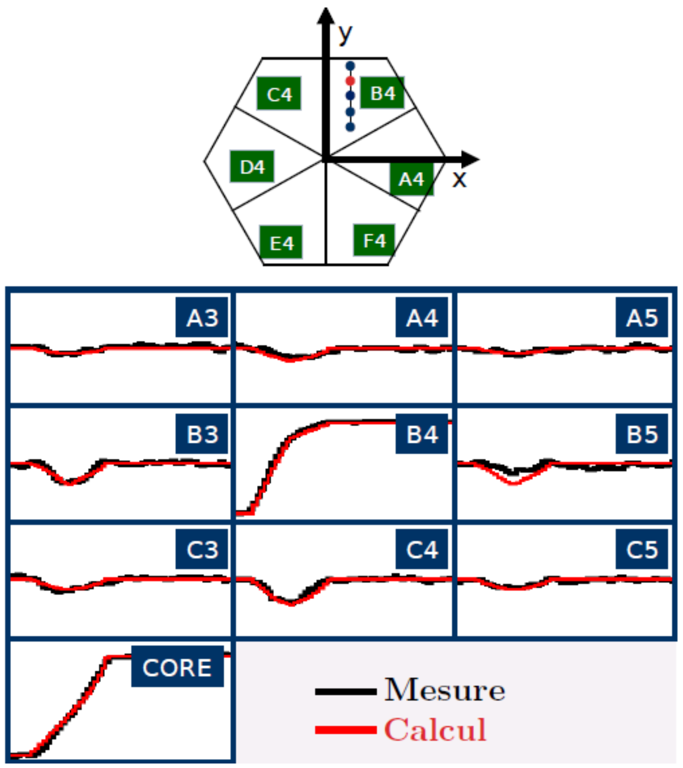
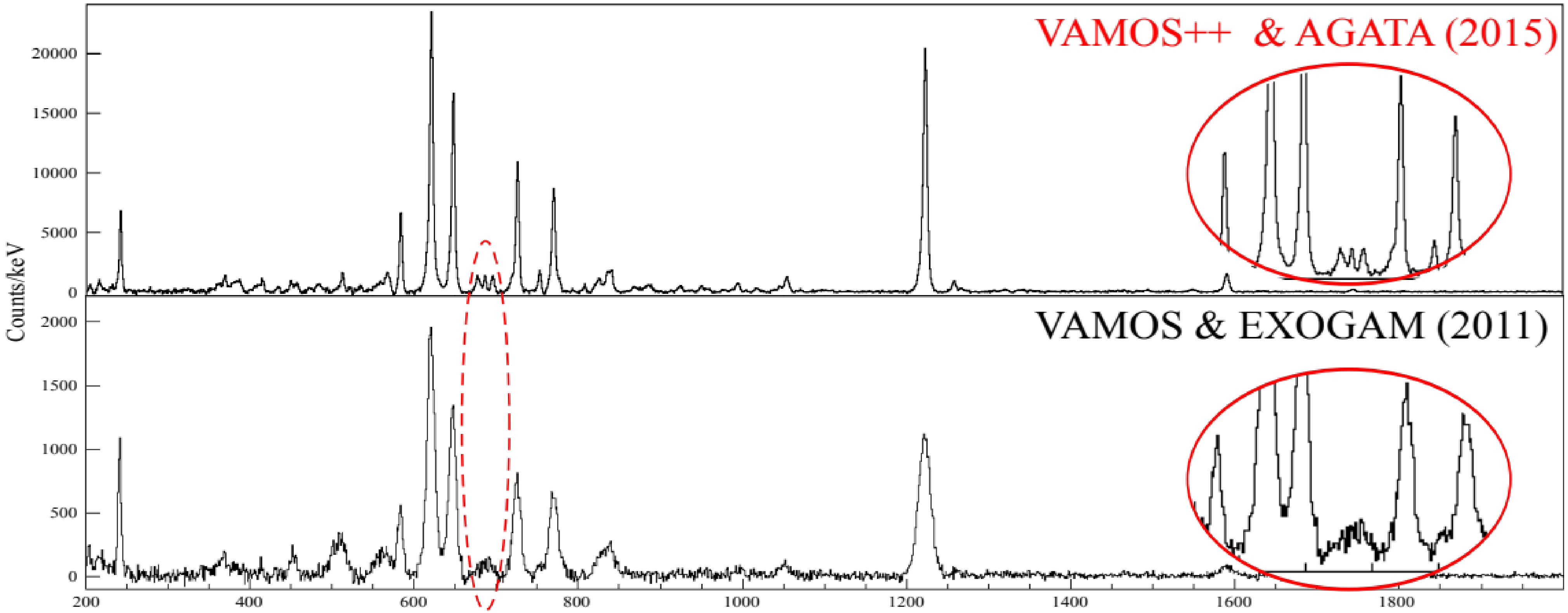


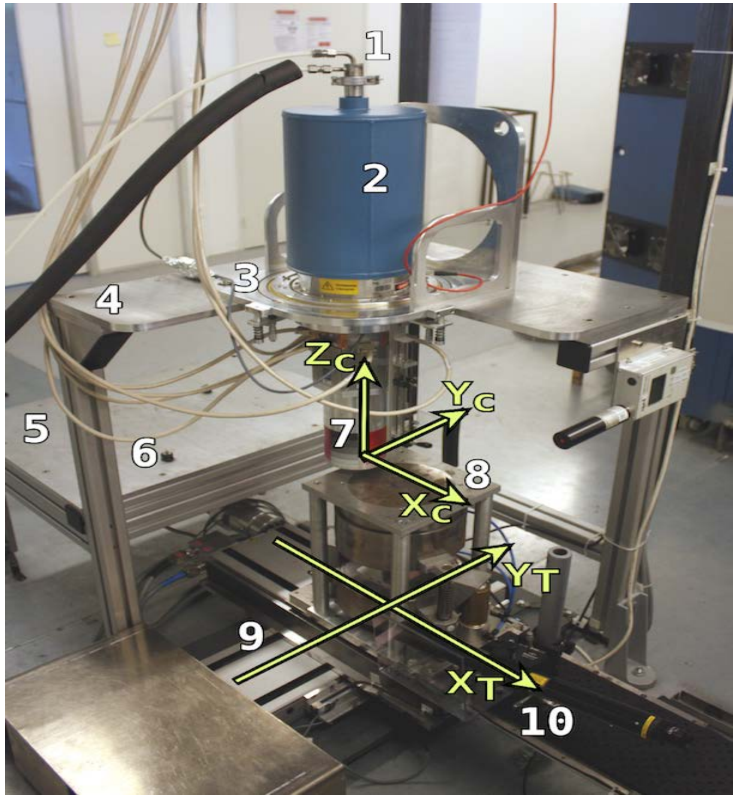
Doppler correction with PSA

- Although the PSA is working well we still need to improve it to get the best possible accuracy.



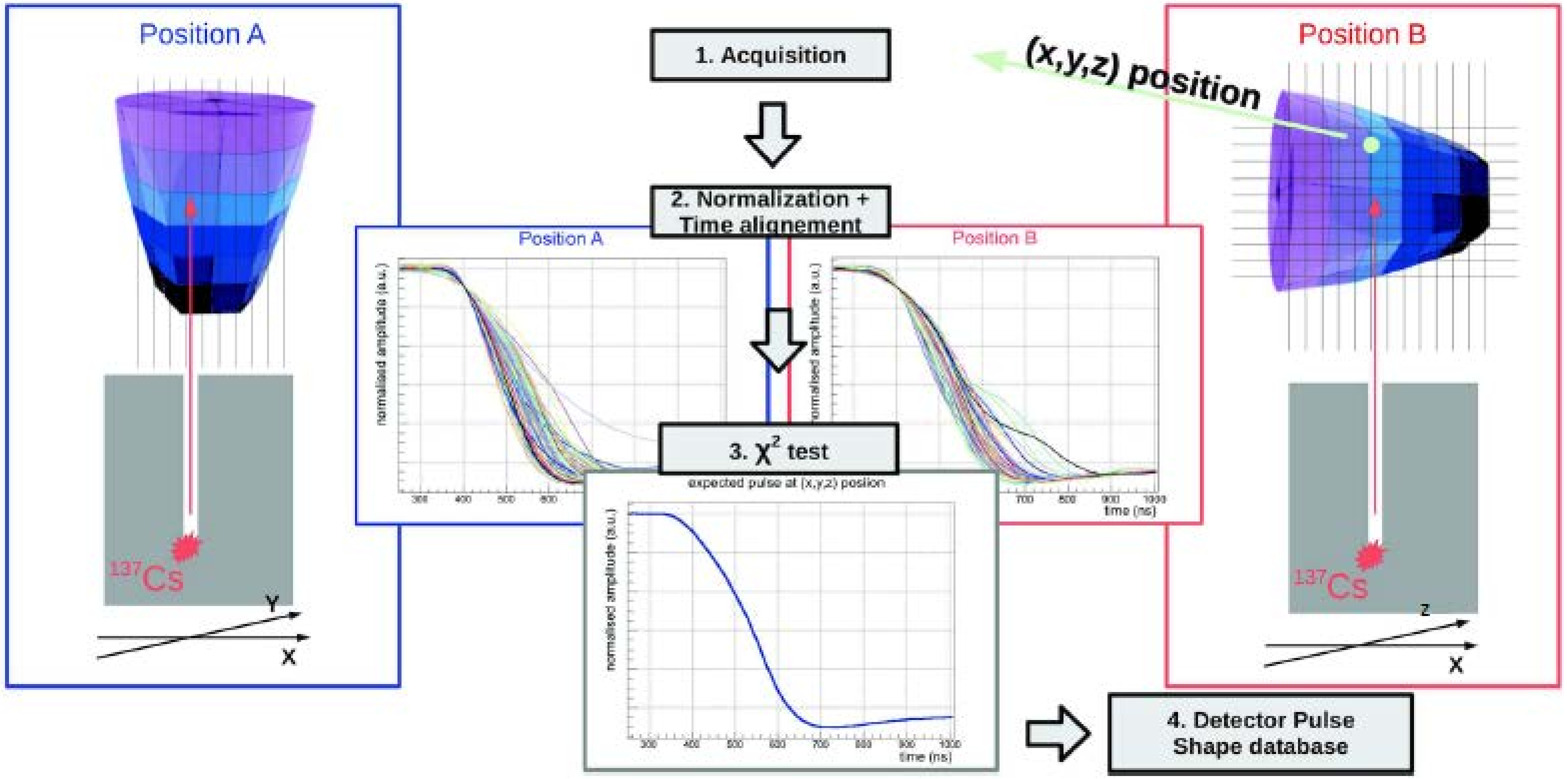
Improving the PSA

- To improve the PSA we need to improve the databases.
  - ✓ By improving the simulations.
  - ✓ By replacing the simulations with experimental data.
  - ✓ In both cases we need experimental databases.
- Experimental databases were produced at Strasbourg.
  - ✓ To produce the databases the crystal had to be scanned.
  - ✓ Scanning the crystal means that we measure signals at every point of the crystal.
  - ✓ A prototype crystal was scanned
  - ✓ The source used is 137Cs.



The scanning process

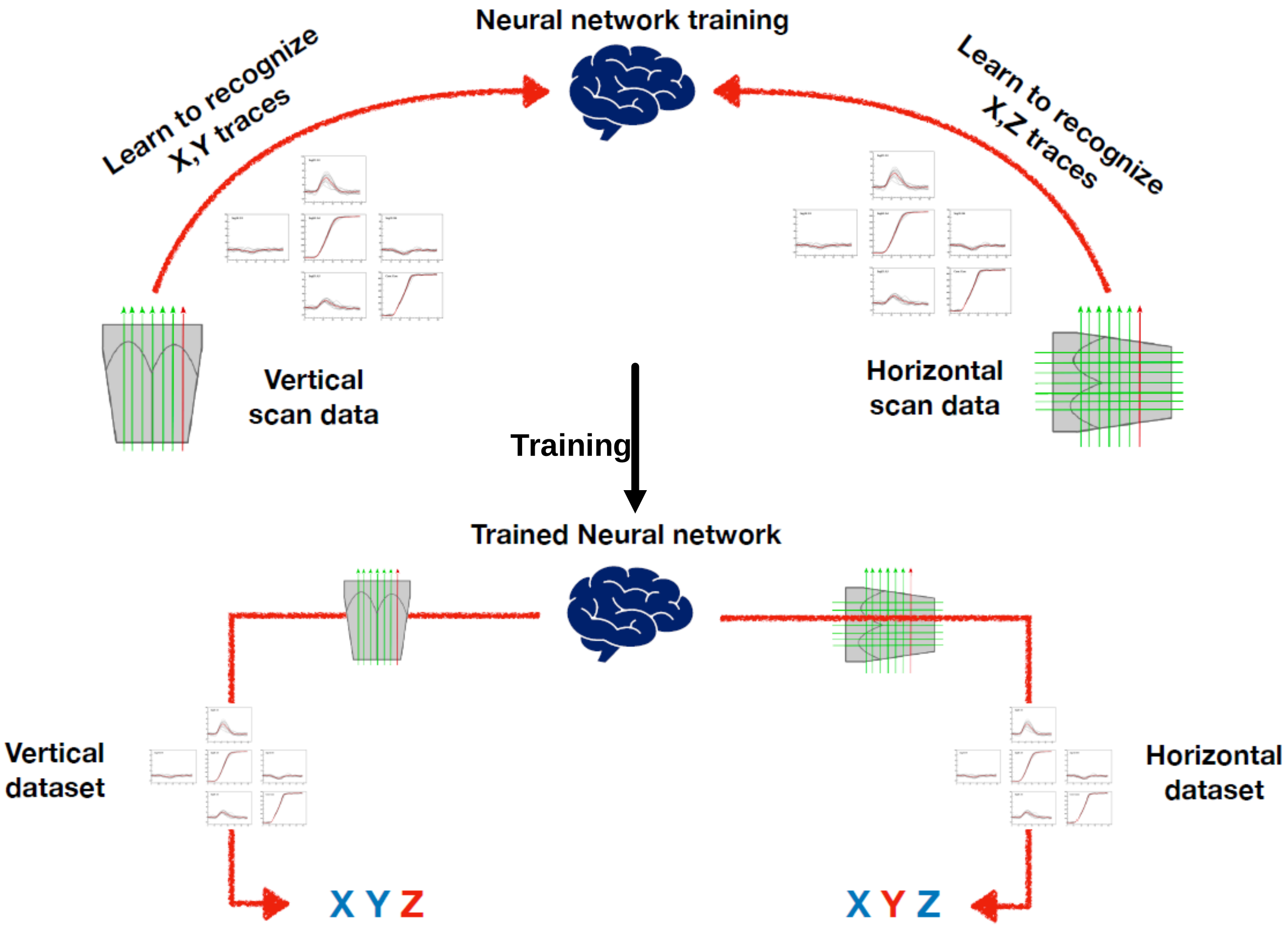
- 1 vertical (X,Y) and 1 horizontal(X,Z) scan.
- To get a 3D databases, a $\chi 2$ analysis of both datasets is done.
- This method has been validated and published but it's very time consuming (5 days for the PSCS analysis)



B. De Canditiis *et al.*, Eur. Phys. J. A 57 (2021), B. De Canditiis and G. Duchêne, Eur. Phys. J. A 56 (2020)

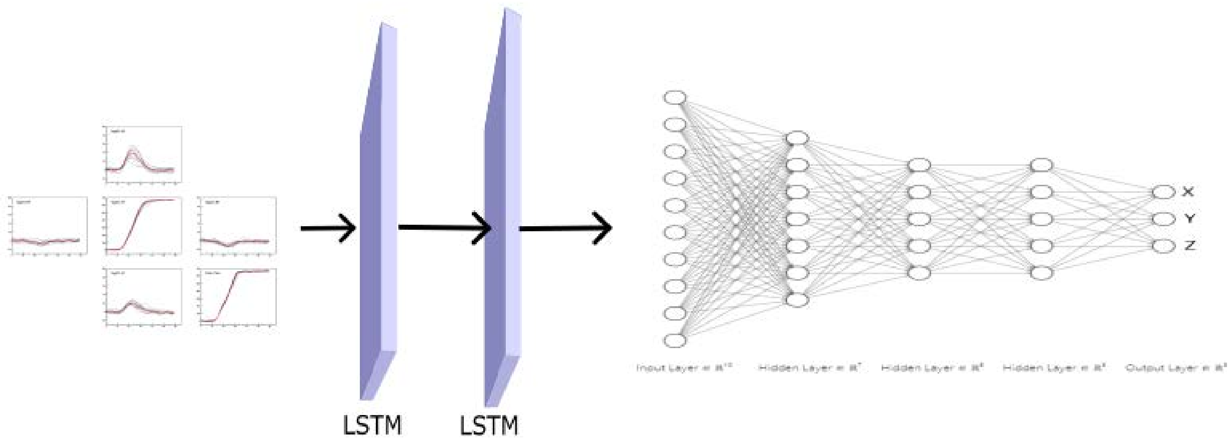
Picture from Michael Ginsz's PhD thesis

Neural networks to produce the 3D databases

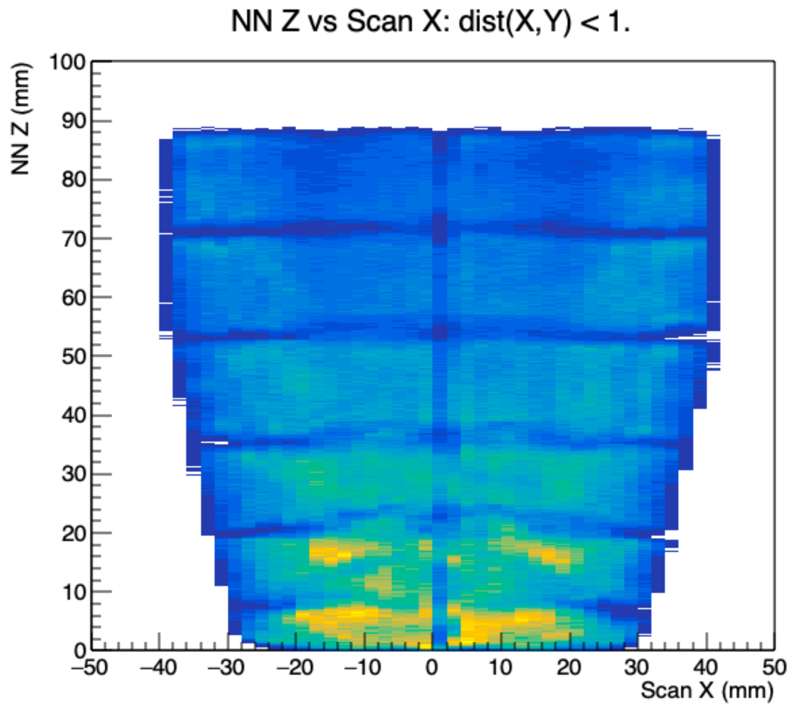


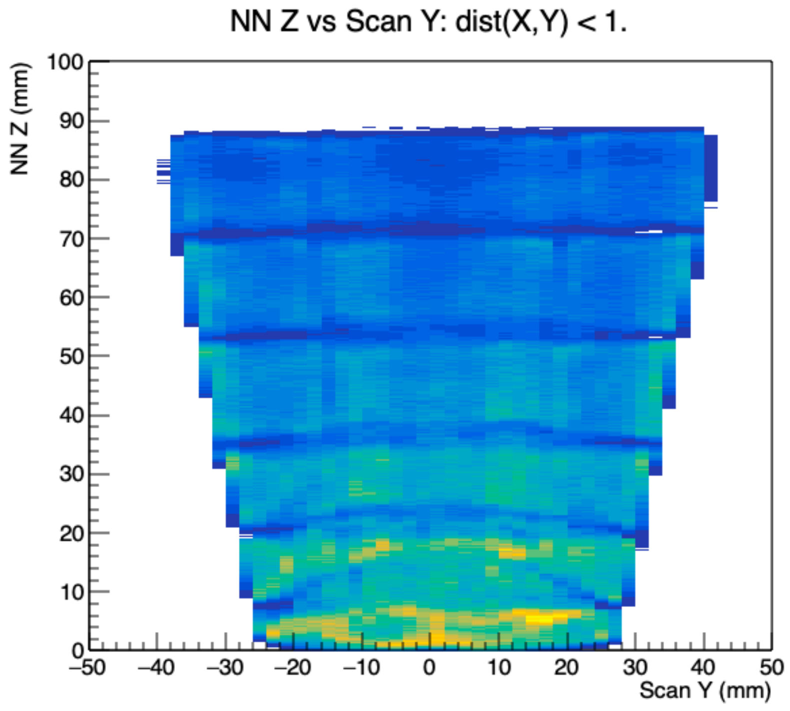
Neural networks: LSTM

- 2 Long short-term memory (LSTM) layers were used.
  - ✓ LSTMs can process sequences of data like the signals.
  - ✓ Are very robust and are not affected by time misalignments.
- The loss function was calculated only for the two known axis, this allows the network to learn patterns of each dataset without affecting the other.

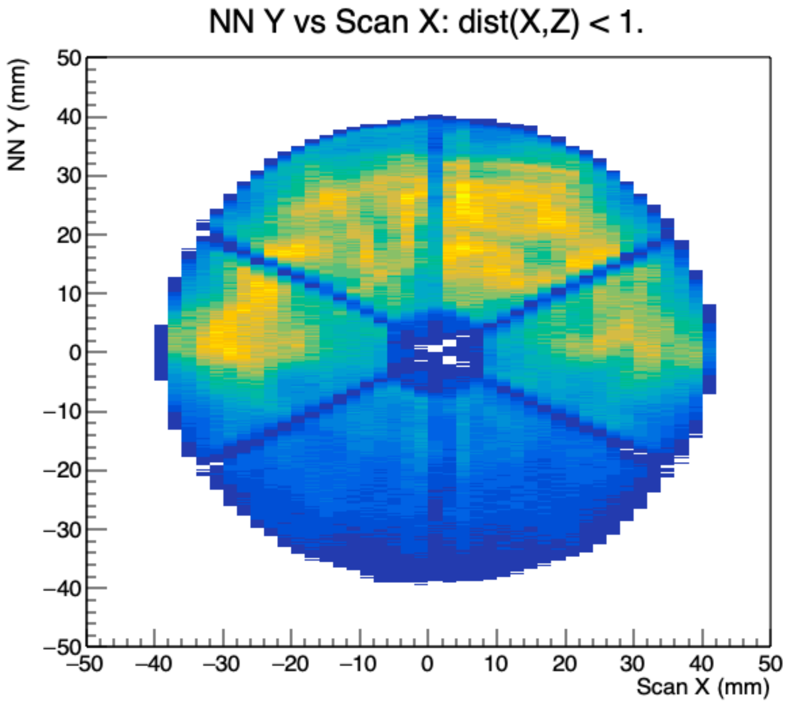


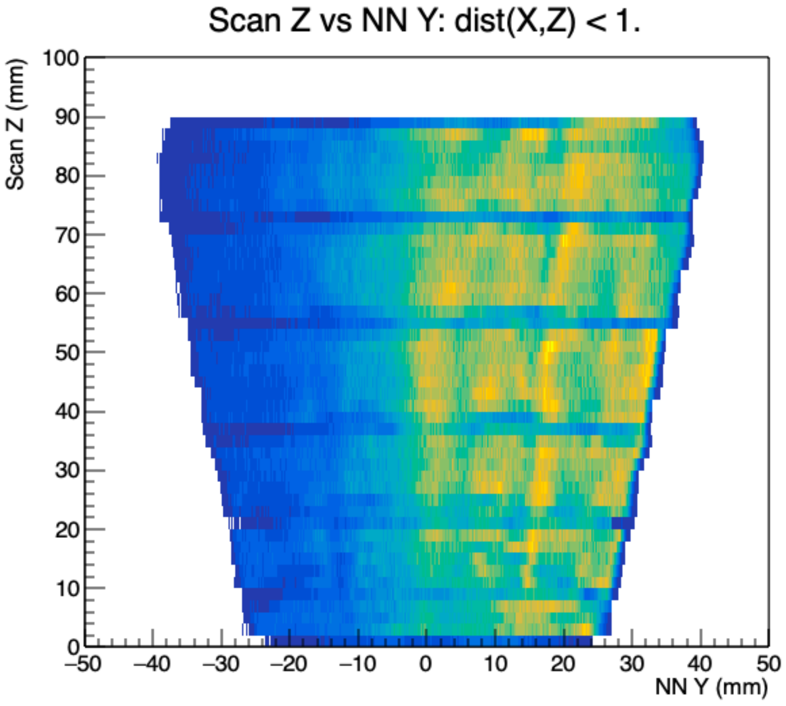
Neural network results: Vertical scan distribution





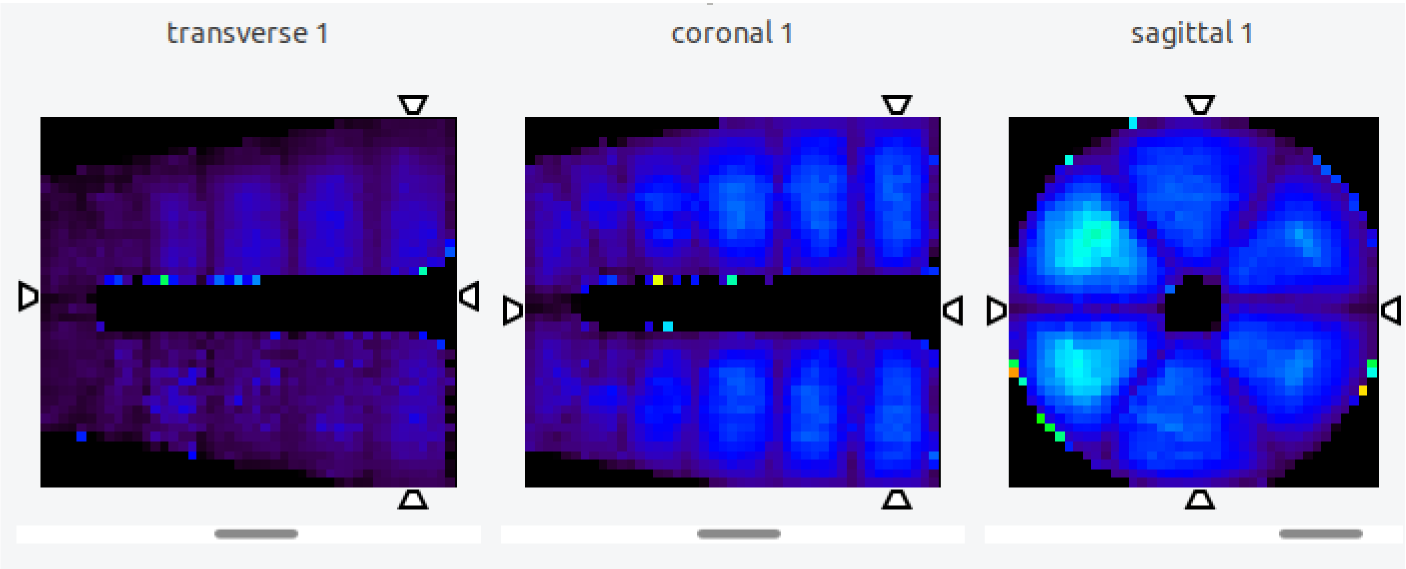
Neural network results: Horizontal scan distribution





Analysis of neural network results

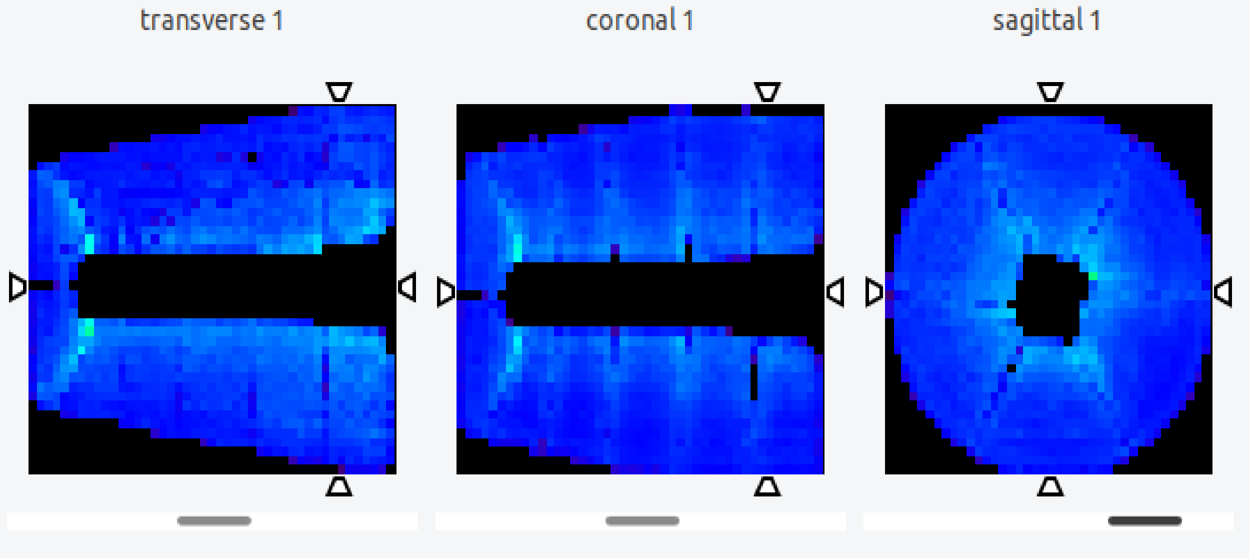
- The two known axis are compared with the predictions of the network.



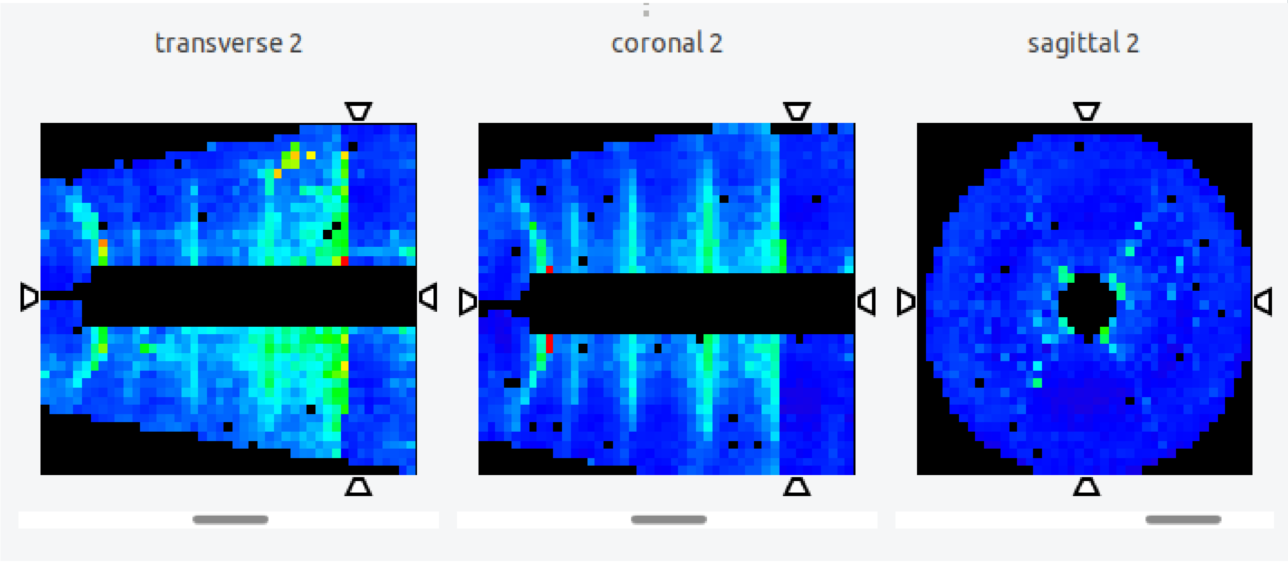
Analysis of neural network results: Mean standard deviation comparison

- Mean standard deviation of signals at the same position is used as a metric to evaluate each method.

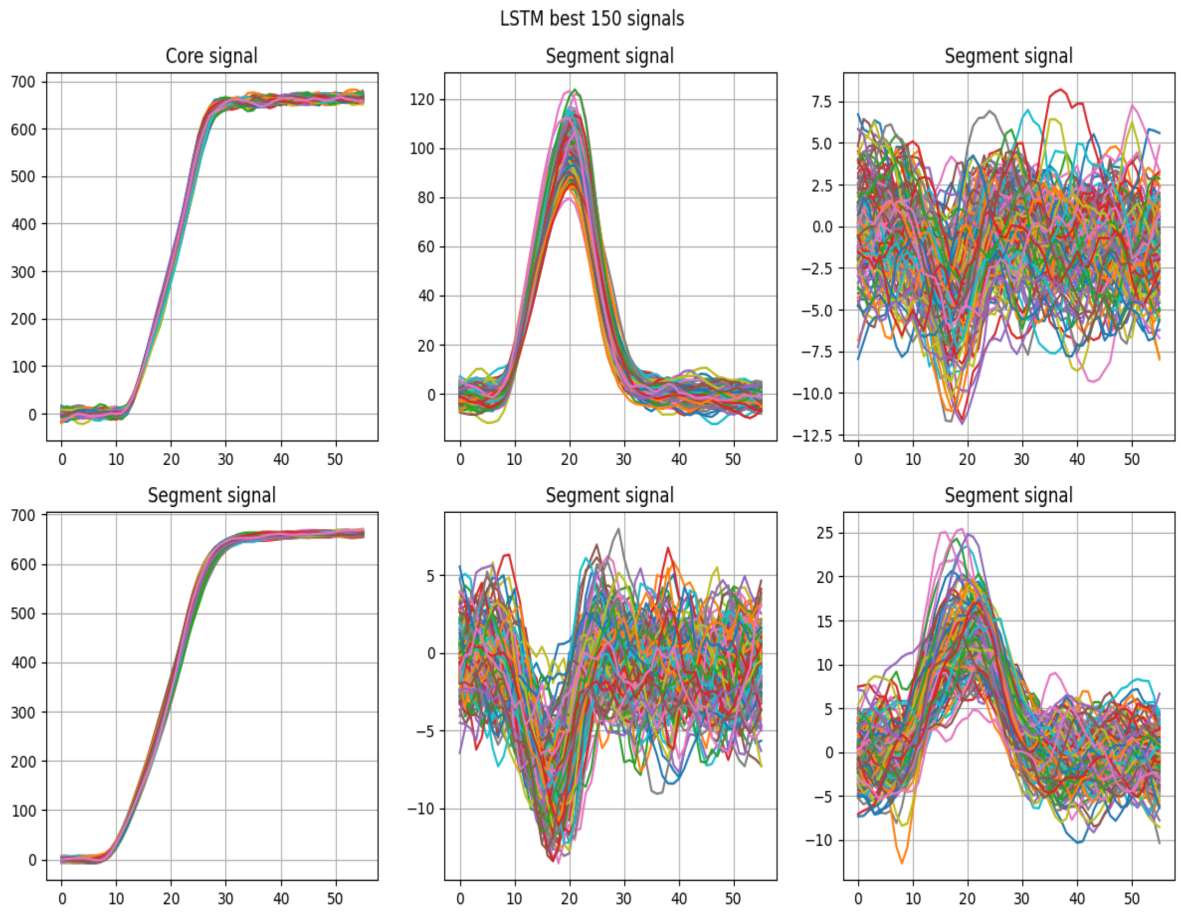
Neural network

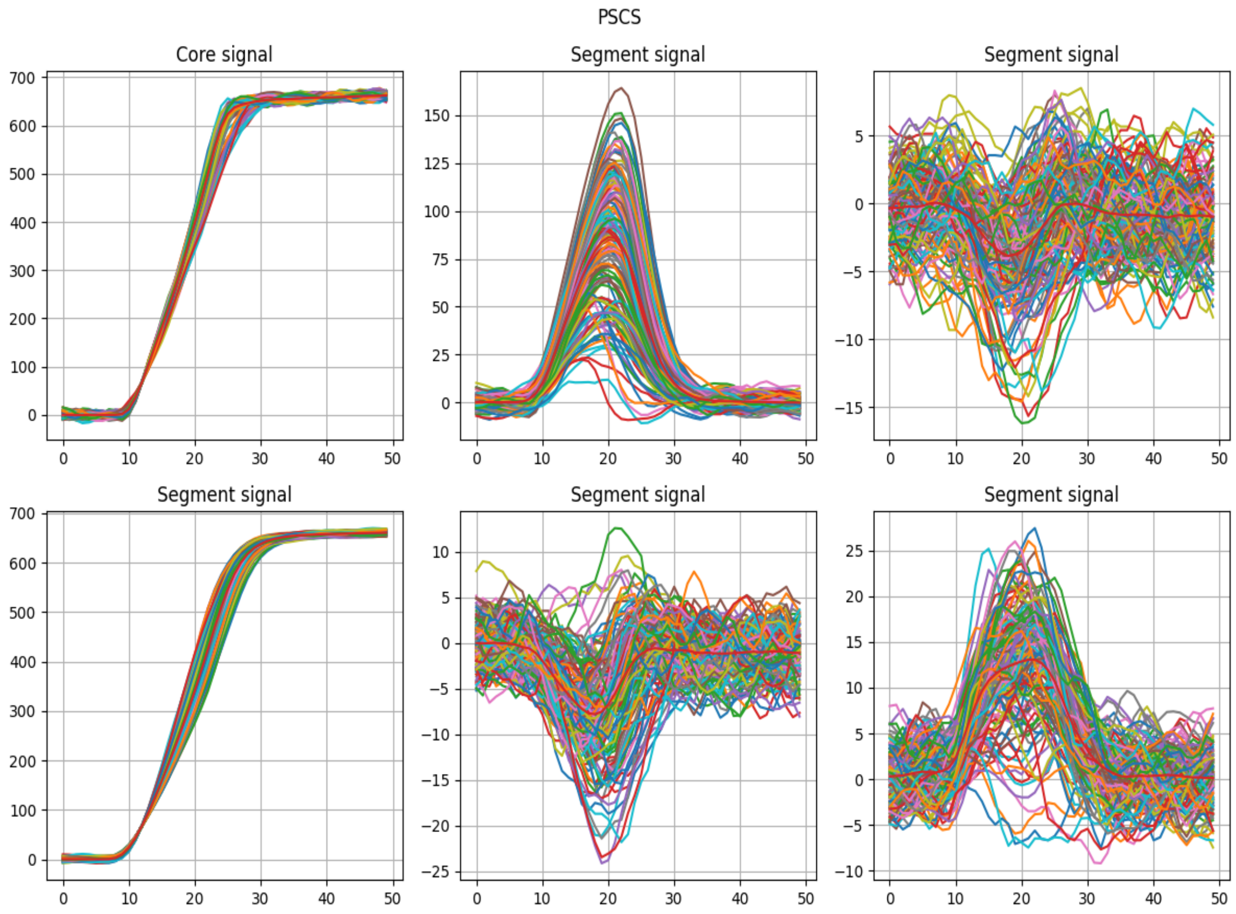


PSCS method



Neural network vs PSCS: Signals at (22, 0, 34) in segment 2

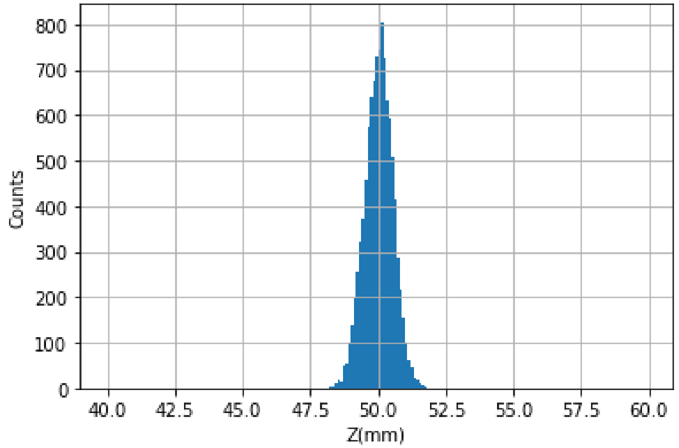




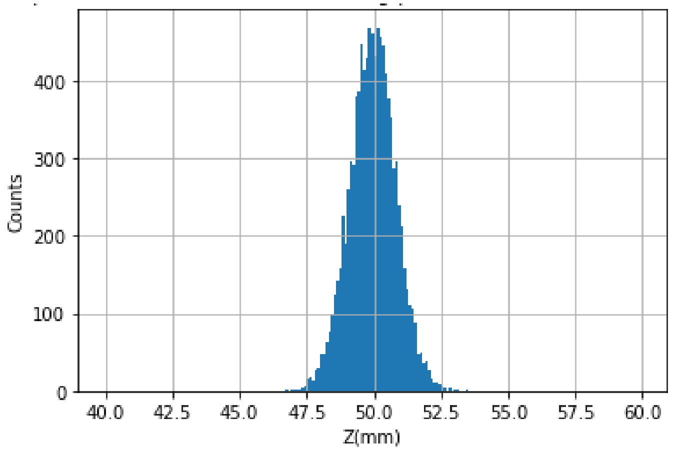
Imaging using Compton scattering

Imaging of a simulated source located at (0,0,50)mm in the sphere of AGATA

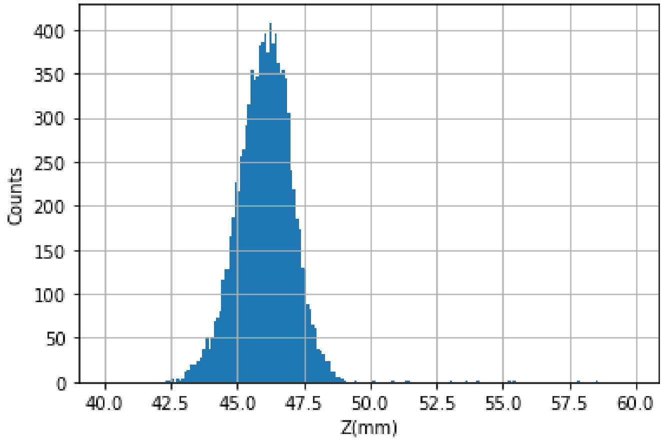
Experimental position error



Two times the experimental position error



Experimental position error with bad tracking



FWHM 1.3mm 2mm 2.4mm

Conclusions and prospects.

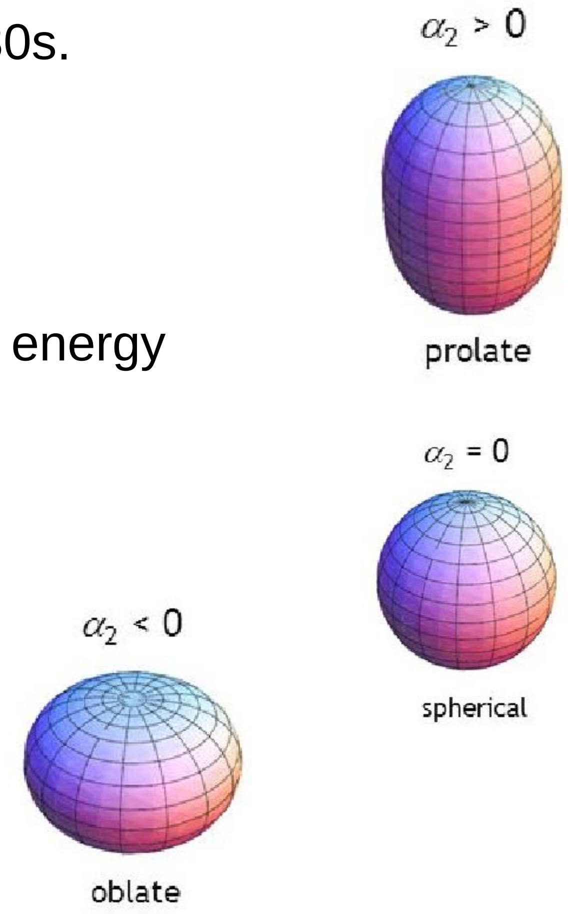
- The neural network 12 hours for training and 2 hour to process the two scans compared to 5 day.
- Since we can’t know what is the exact position of a signal, it’s complicated to determine which method is more accurate.
- We developed a fast imaging method using Compton scattering to characterize the PSA.
- The imaging method will be used to characterize the results of the neural network.
- This work can open the door for neural network PSA.

Niobium analysis: Overview

- Nuclear structure models.
  - Collective models.
  - Single particle excitation model.
- Experimental setup.
- Nuclear structure phenomena in the N=60 and A~100 region.
  - Shape coexistence.
  - Abrupt deformation.
- 99Nb analysis.
- Prospects.

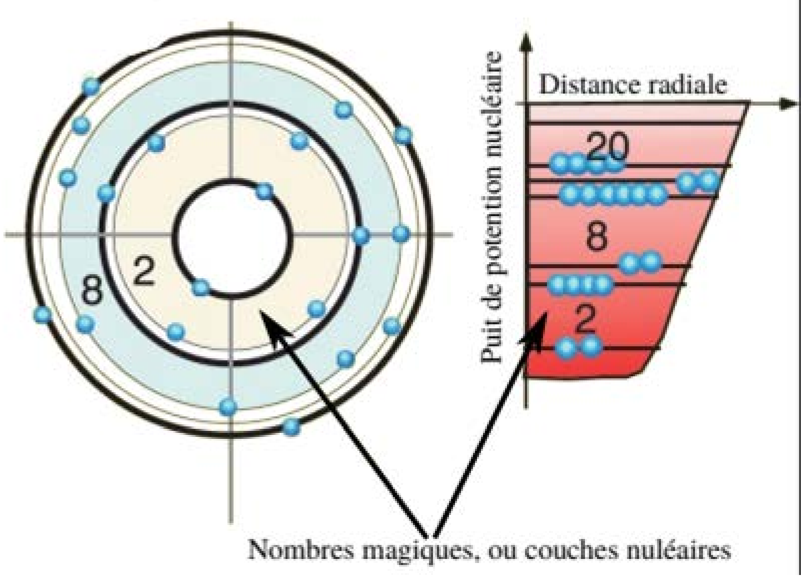
Collective nuclear structure model: Liquid drop model

- Proposed by George Gamow and Carl Friedrich von Weizsäcker in the 1930s.
- Treats the atomic nucleus as a liquid drop.
- Assumes that the nucleons are in a potential well with an average binding energy per nucleon.
- The model explains:
  - ✓ The overall binding energy of the nucleus.
  - ✓ The fission process of heavy nuclei.
  - ✓ The collective motion of nucleons.
- Limitations:
  - ✓ Does not explain the magic numbers or nuclear shell structure.
  - ✓ Cannot predict the stability of individual isotopes.



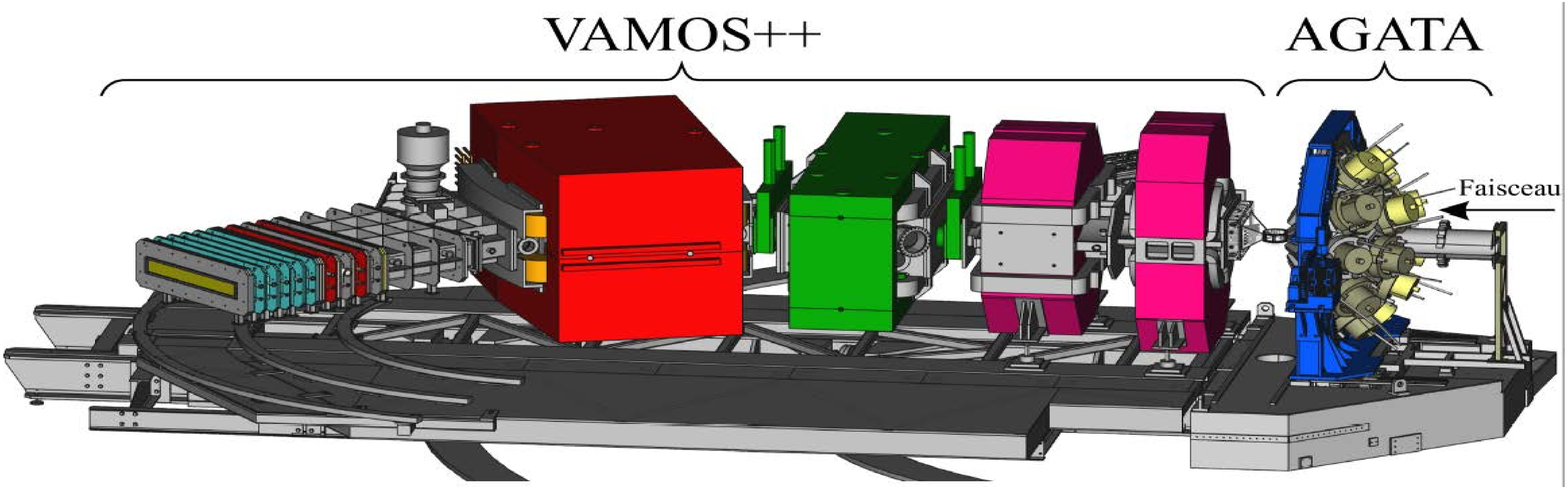
Single particle nuclear structure model: Shell model

- Proposed by Maria Goeppert-Mayer and J. Hans D. Jensen in the early 1950s.
- Treats nucleons as independent particles moving in a central potential.
- Assumes that nucleons fill energy levels or "shells" within the nucleus.
- The model explains:
  - ✓ The magic numbers and nuclear shell structure.
  - ✓ The stability and energy levels of individual isotopes.
- Limitations:
  - ✓ Does not account for collective motion or correlations between nucleons.
  - ✓ Cannot fully explain the properties of heavy nuclei.



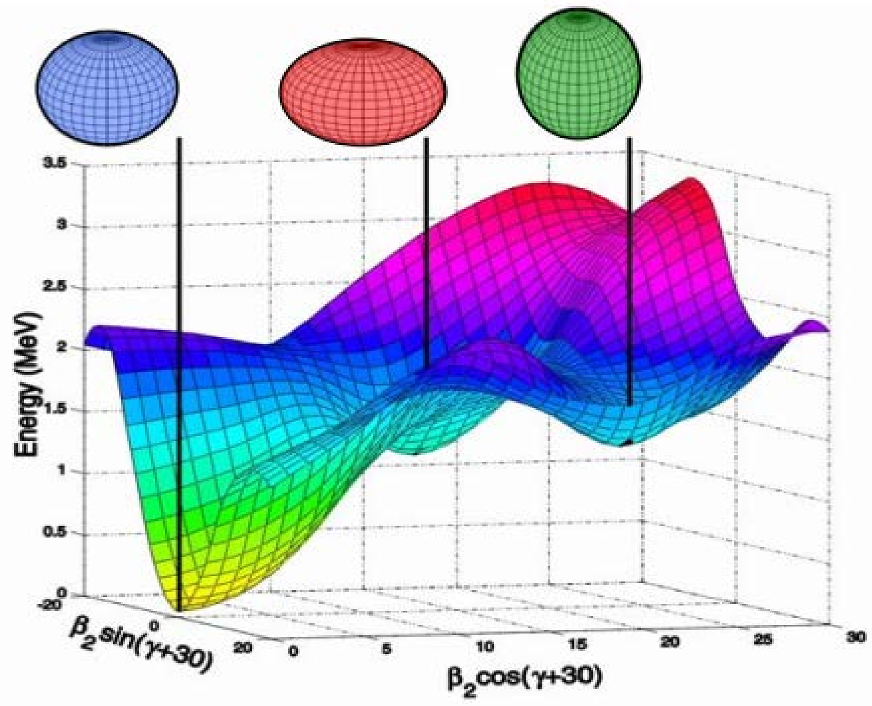
Experimental setup: Fusion and fission experiment

- Reaction : Fission induced by fusion:
  - 238U@6.2 MeV/u + 9Be (1.85 mg/cm2), I~6 10^9 pps.
- Detectors:
  - AGATA: Identification of Gamma-ray transitions.
  - Vamos++: Identification(A,Z) of the fission fragments.



Nuclear structure phenomena: Shape coexistence

- Observed in the region with N around 60 and A around 100.
- Shape coexistence refers to the presence of multiple stable or quasi-stable nuclear shapes in the same nucleus.
- Shape coexistence can arise due to competing nuclear forces and the interplay between the single-particle and collective degrees of freedom.
- Experimentally observed through various spectroscopic techniques, such as Coulomb excitation, transfer reactions, and gamma-ray spectroscopy.

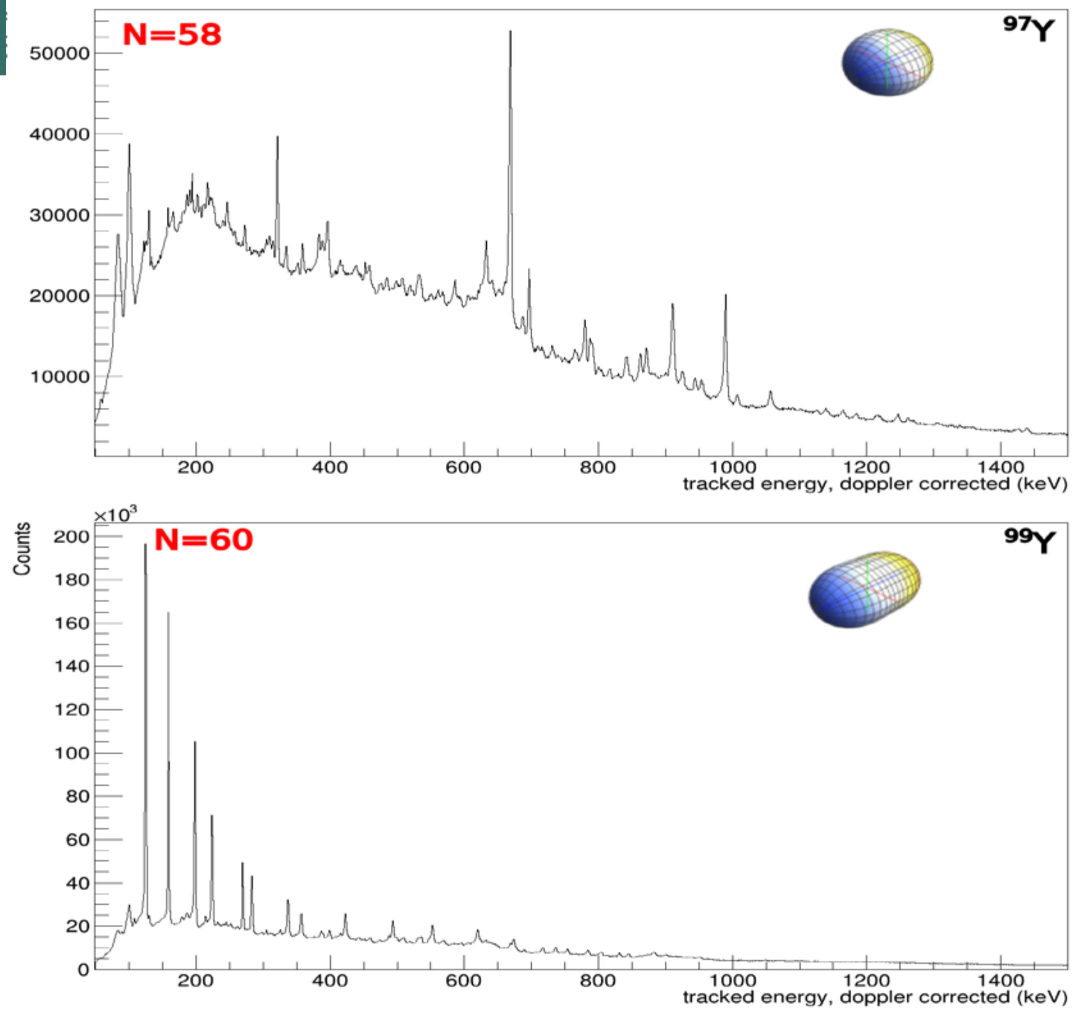


Potential Energy Surface for ^{186}Pb

A. Andreyev et al., Nature 405 (2000) 430

Nuclear structure phenomena: Abrupt deformation at N=60 and A~100

- An abrupt transition from single-particle excitation to collective behavior.
- It appears at Neutron number equal 60 and around atomic number of 100.
- It appears in the gamma-ray spectra as a change in the order of transitions with respect to the energy and intensity.



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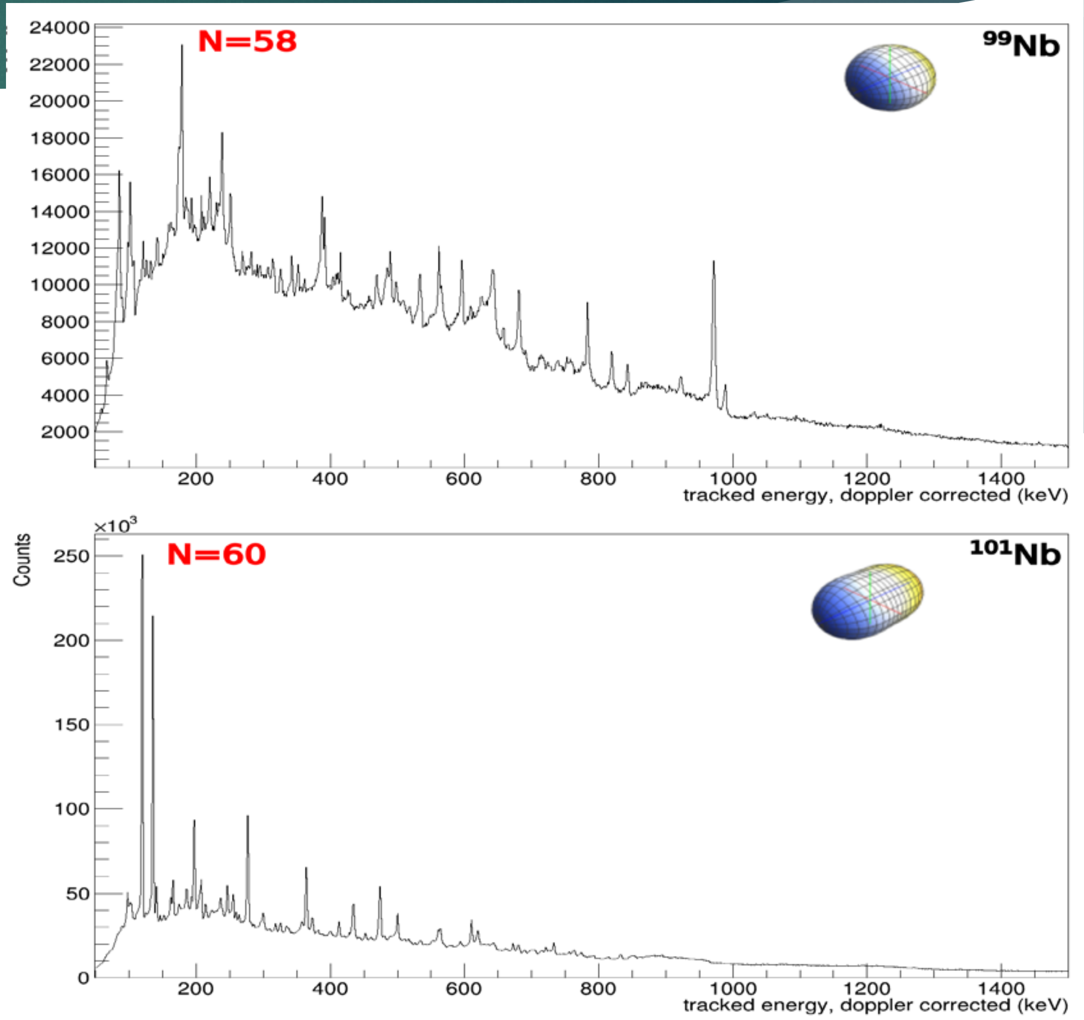
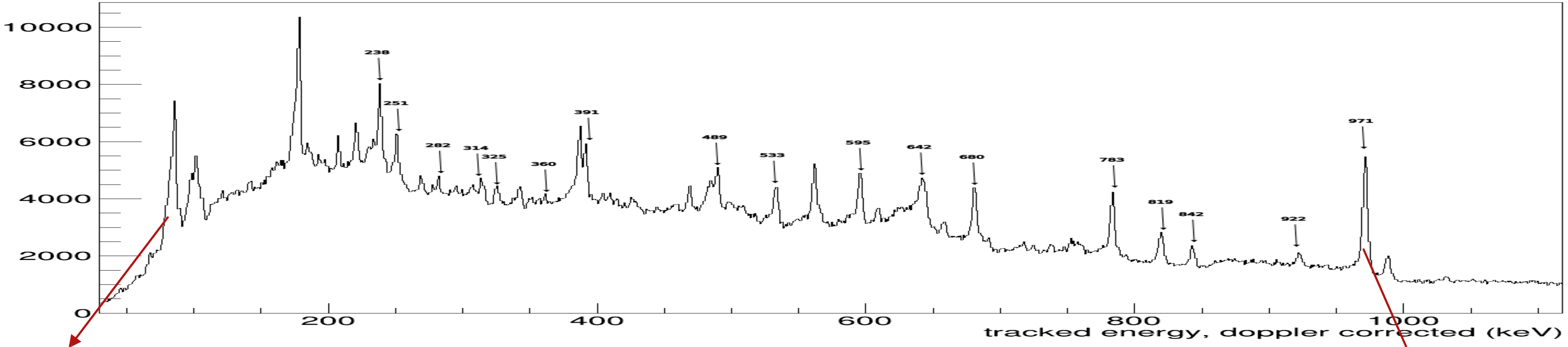
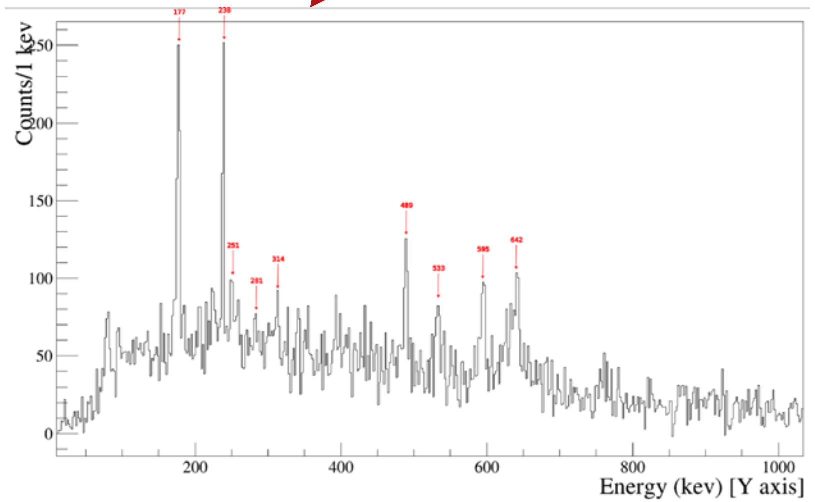
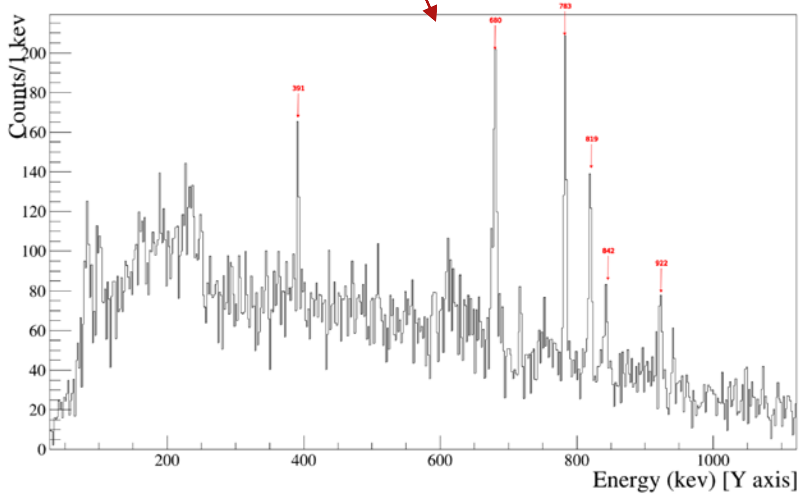


^{99}Nb: Spectrum

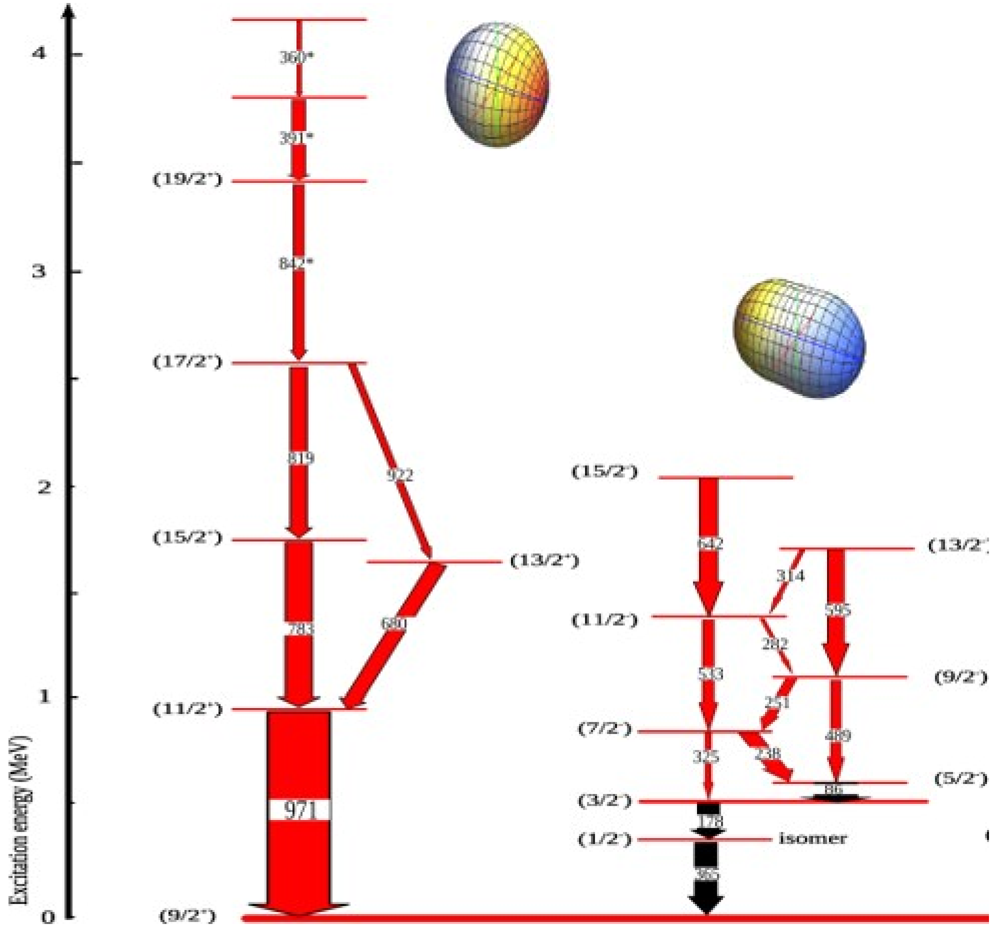






^{99}Nb: Level Scheme

- Level scheme was built for 99Nb using the coincidence between the transitions.
- The level scheme indicates that there is shape coexistence.
- Theoretical calculation and interpretation is needed to confirm the shape coexistence.
- We are currently collaborating with a team from Vanderbilt University in the US to do these calculations.



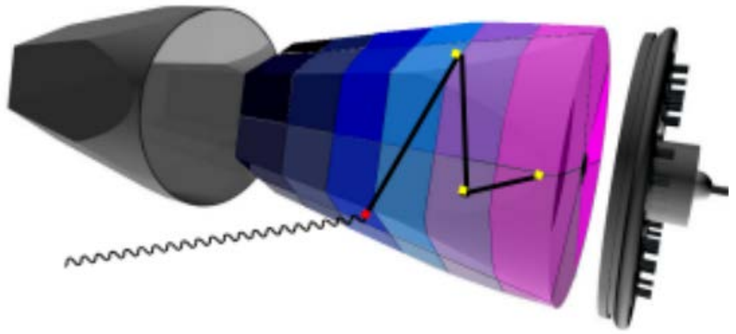
Prospects

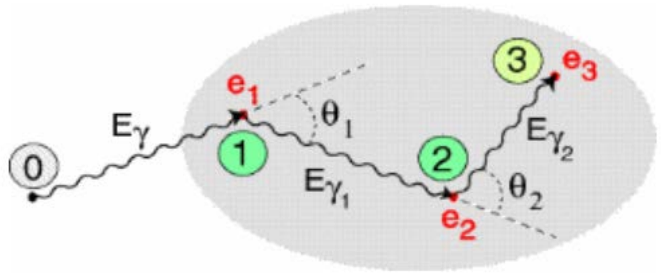
- Obtain the theoretical calculations for the Nb isotopic chain.
- Finalize the analysis of 102,104,105,106,107 Nb.
- Advance the collaboration with the team of Vanderbilt University.

Thank you for your attention ☺

The tracking of the gamma ray

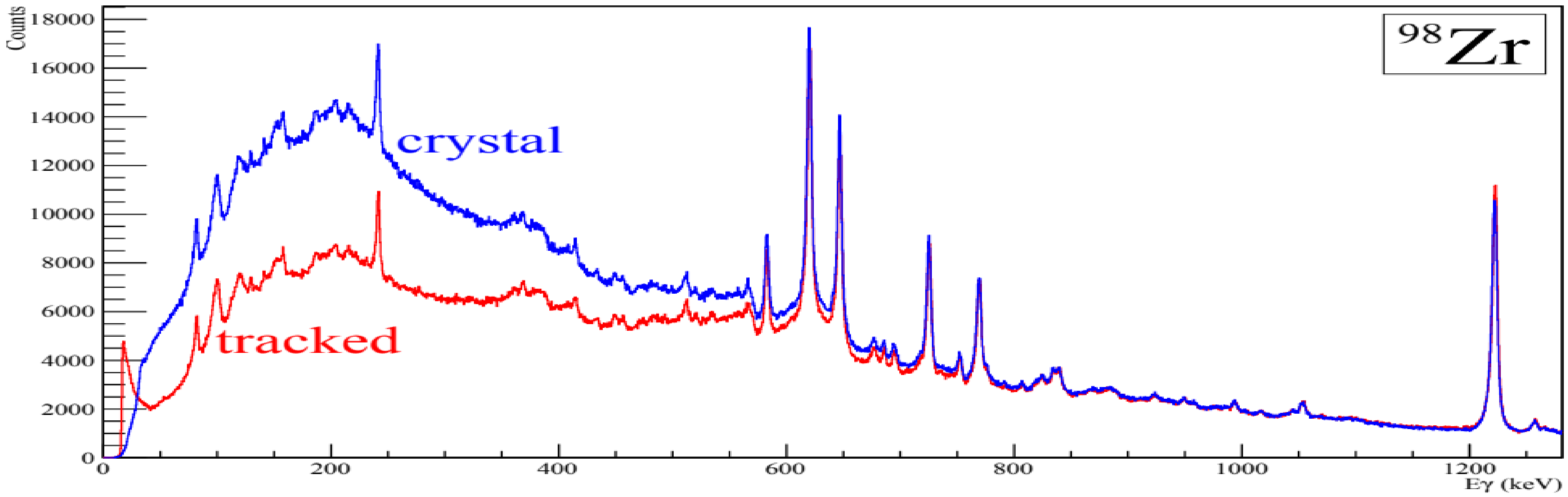
- Gamma-ray are tracked back to the source using Compton diffusion formula.
  - ✓ Allows for the determination of the first interaction point.
    - ✓ Accurate Doppler correction.
  - ✓ Improve the photopeak to background ratio.



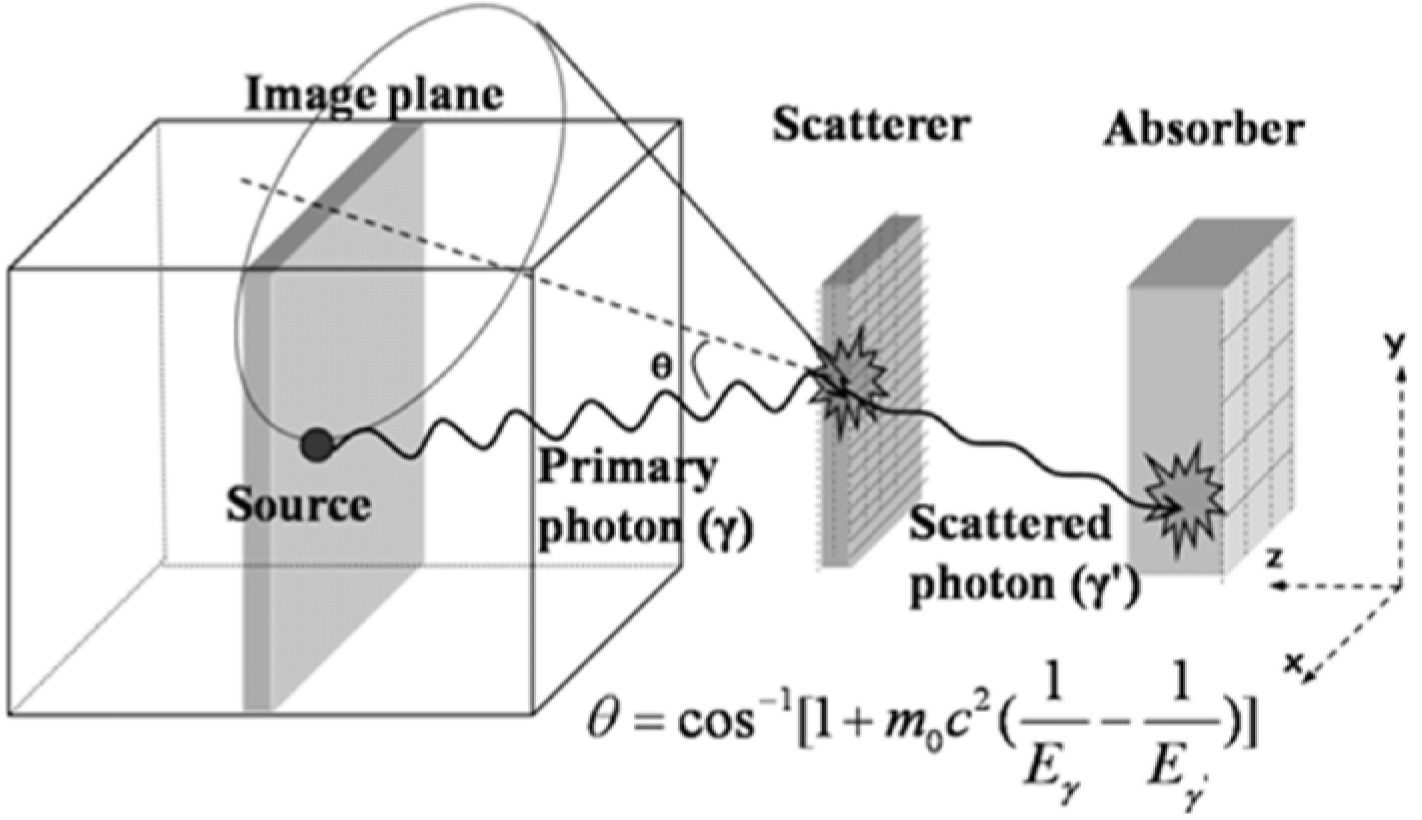


AGATA capabilities

- The tracking method reduces the low energy background significantly.

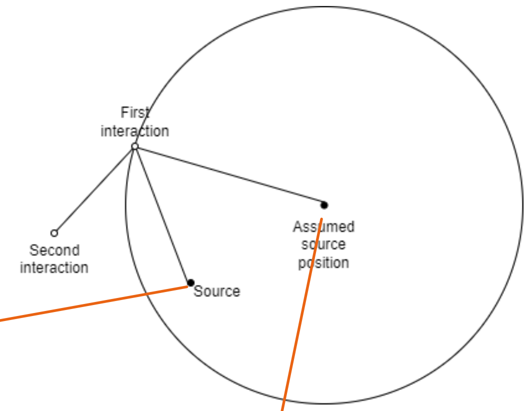


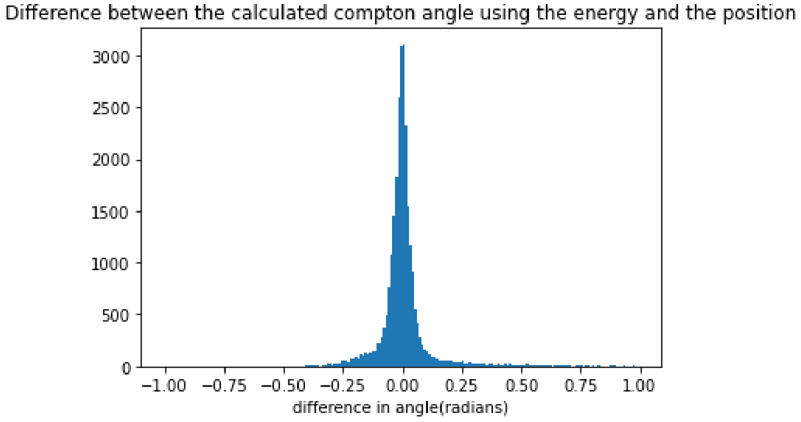
Imaging using Compton scattering

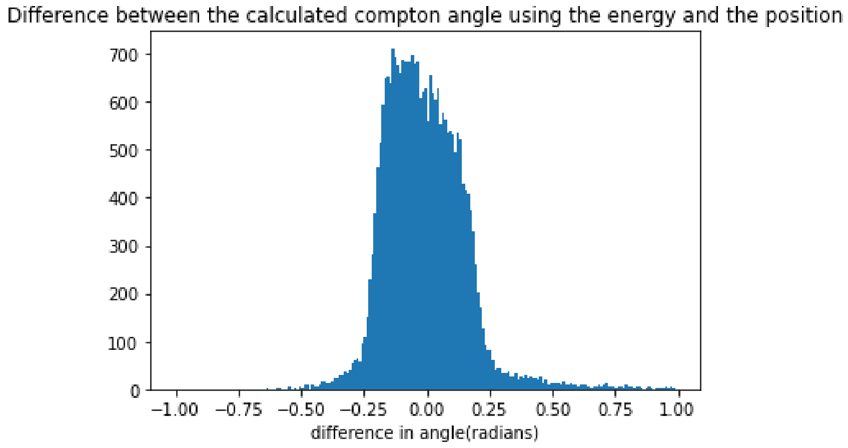


Imaging using an optimizer

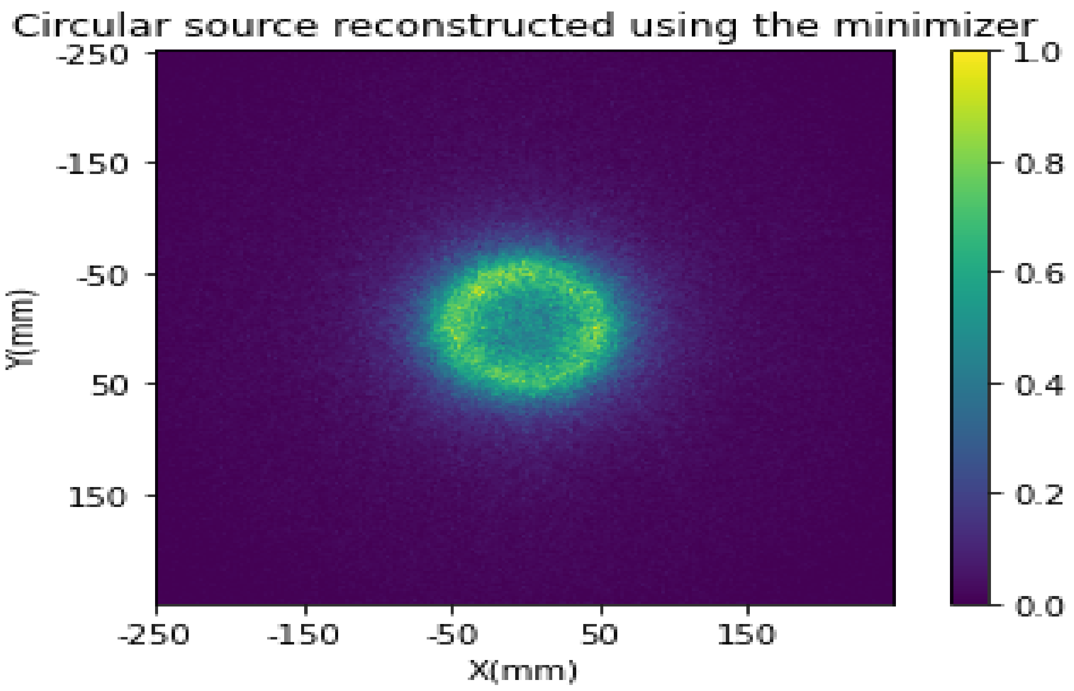
- The scattering angle can be calculated from the energy and from the position.
- Minimizing the difference between the two will give the source position



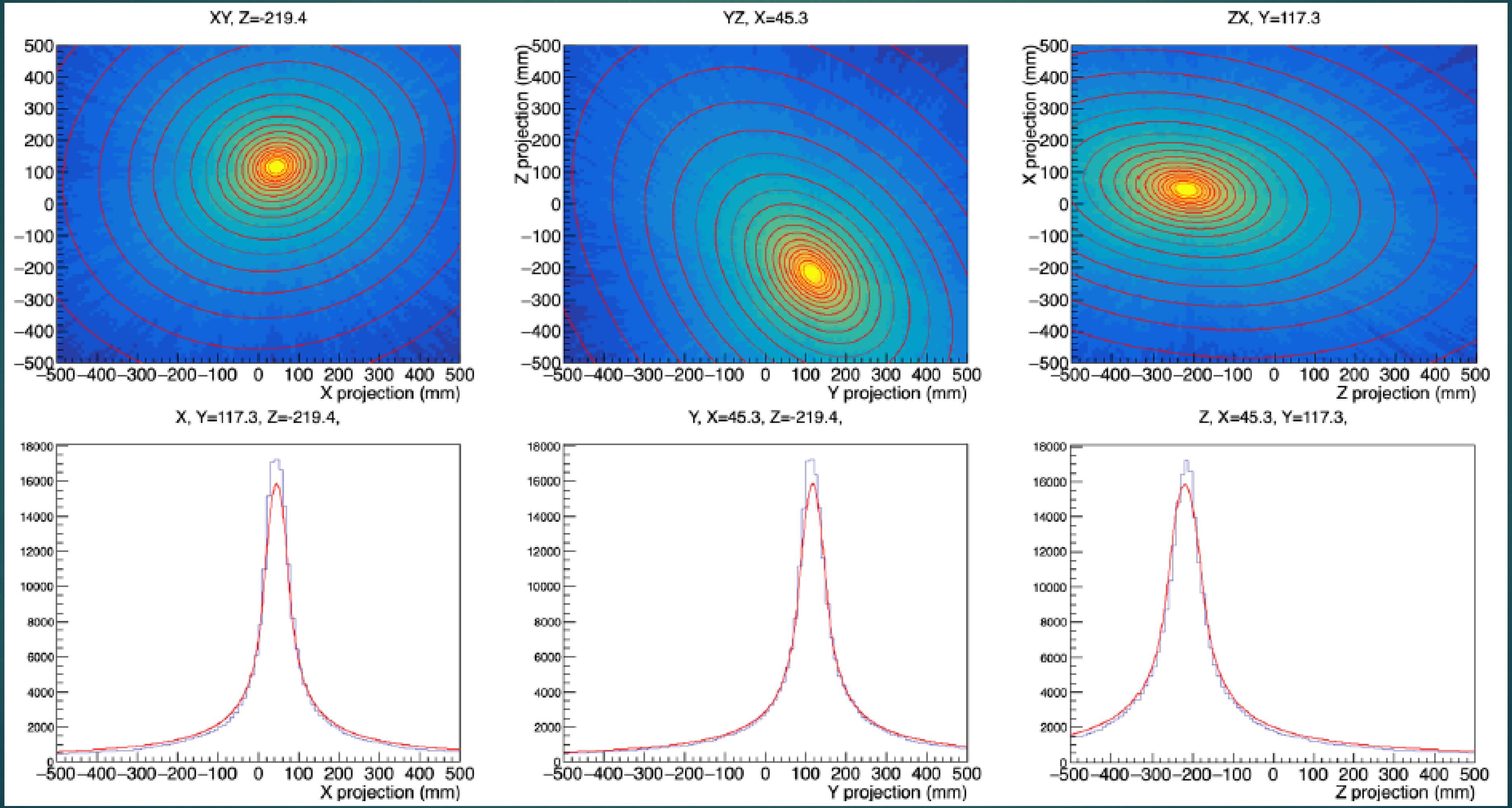




Imaging using Compton scattering



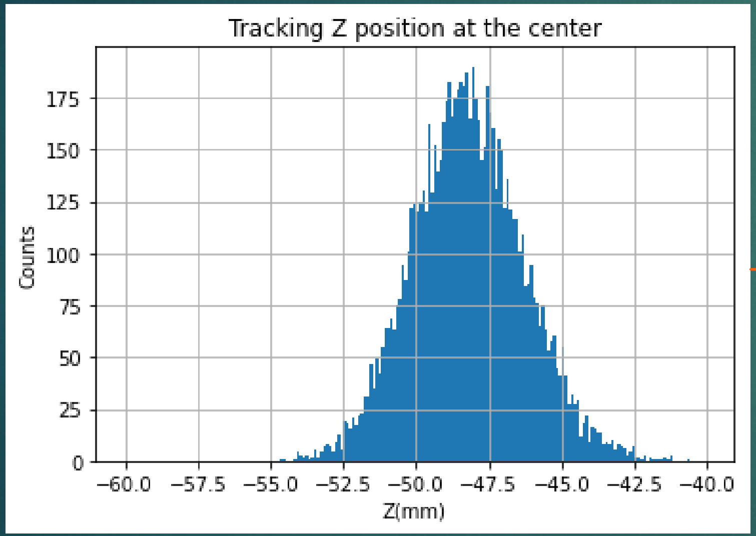
Imaging using 3D histograms



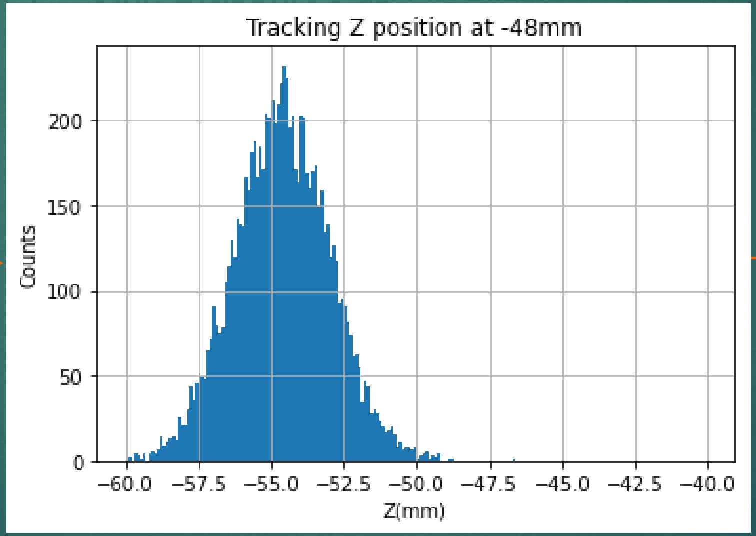
Results of the minimizer with experimental data

- This source run was conducted during GANIL campaign in the autumn of 2021.
- The source used is Eu located at (0,0,-55)mm.

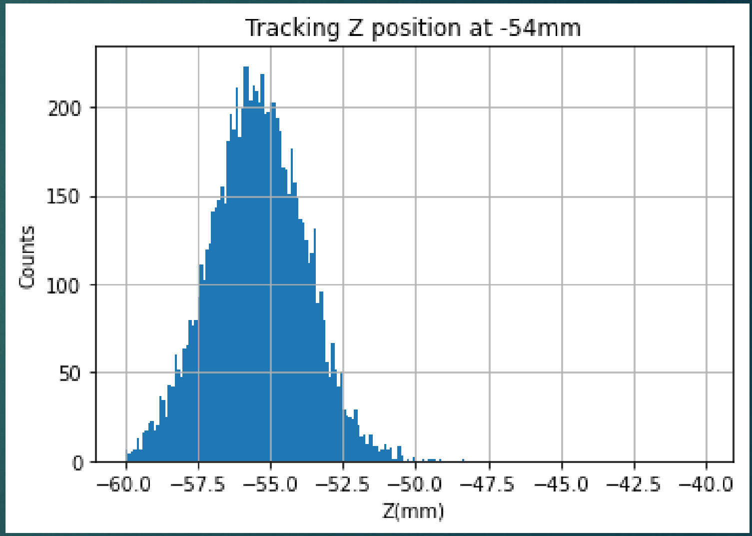
[-3.63   0.55 -48.23]



[-3.8   0.5 -54.58]



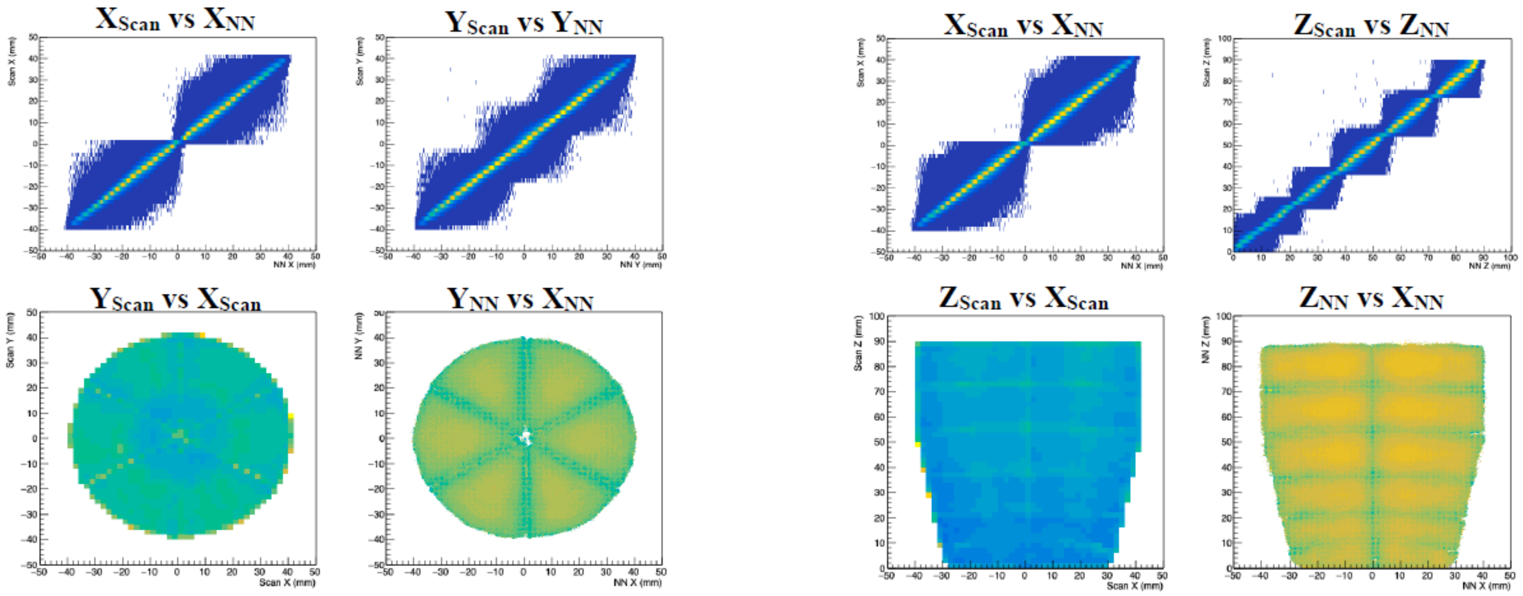
[-3.71   0.52 -55.46]



FWHM: 4.5mm 3.83mm 3.78mm

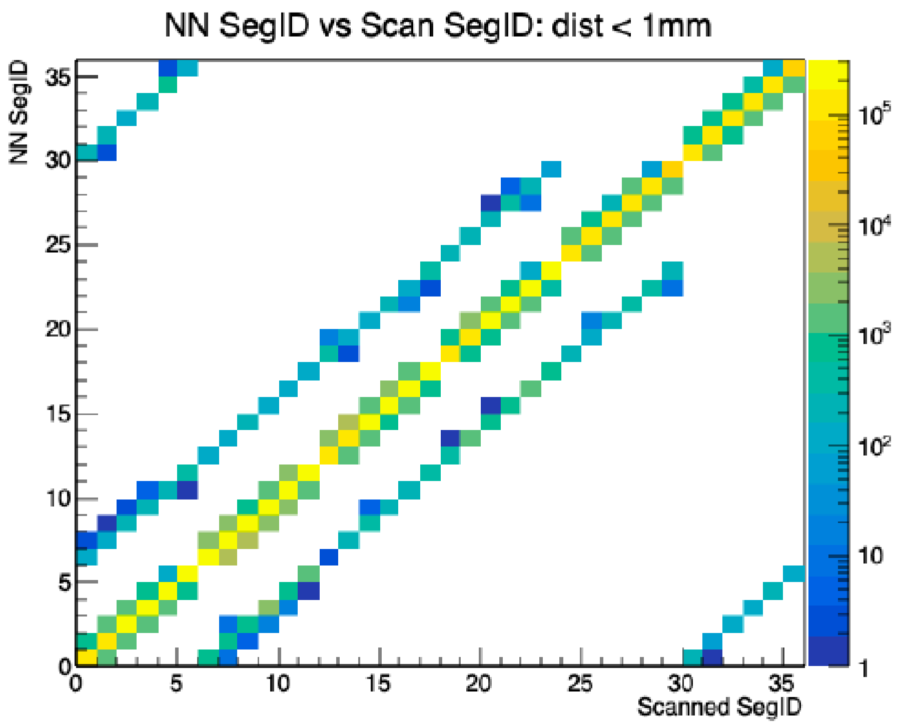
Analysis of neural network results

- The two known axis are compared with the predictions of the network.
- Only the predictions with error on the known axis of less than 1mm are kept.

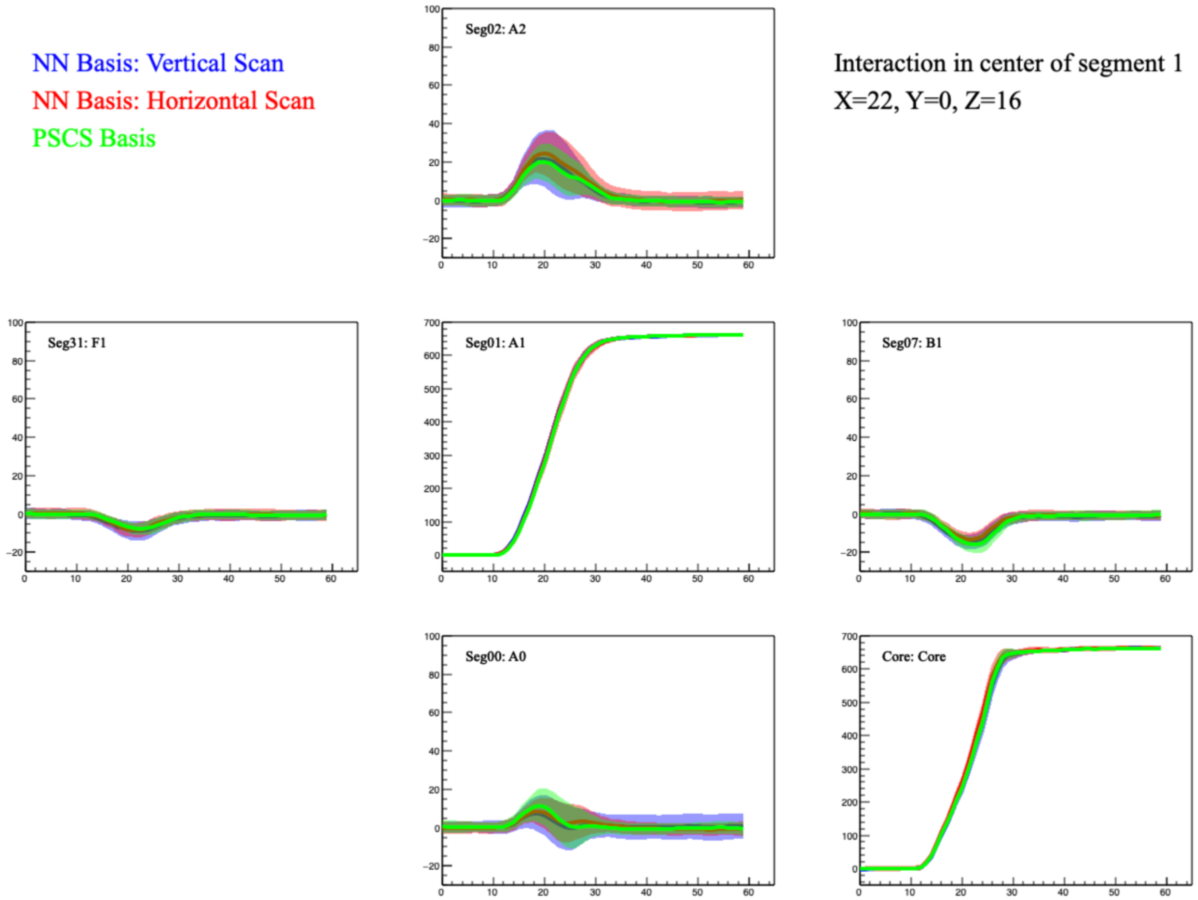


Analysis of neural network results

- Only 2% of the predicted segments were wrong.

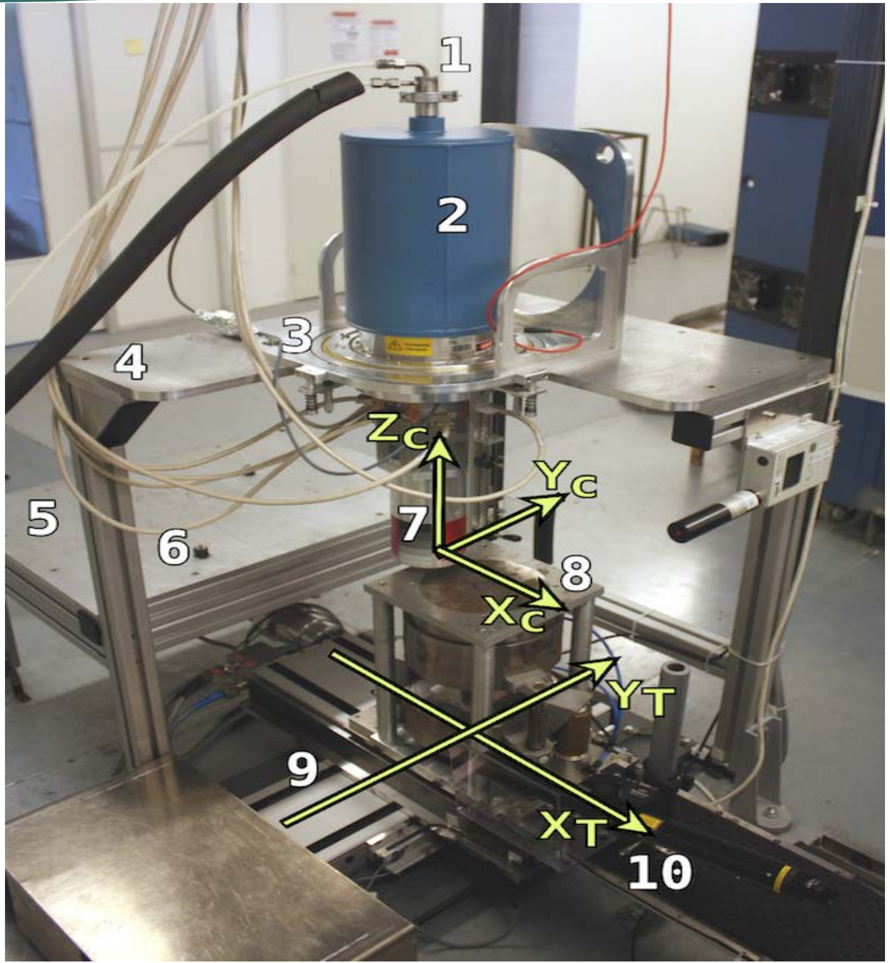


Neural network results

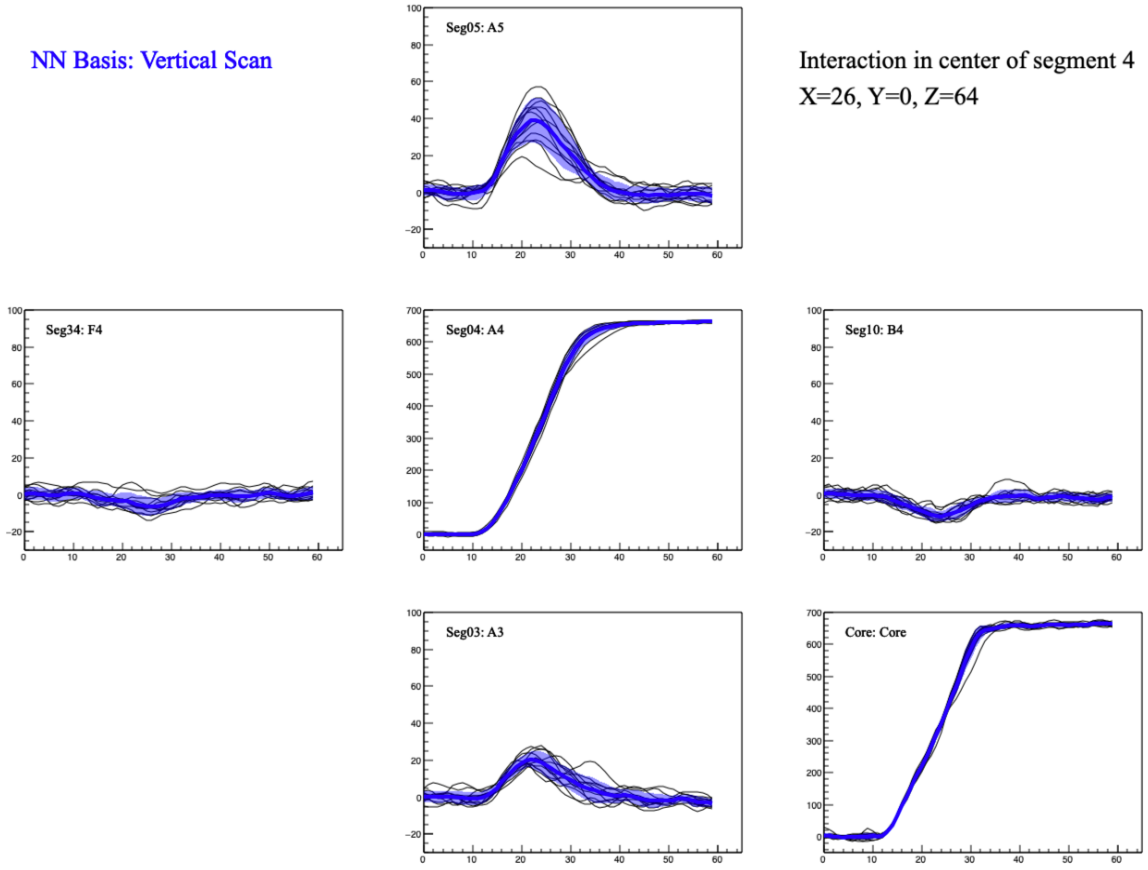


The Strasbourg scanning tables

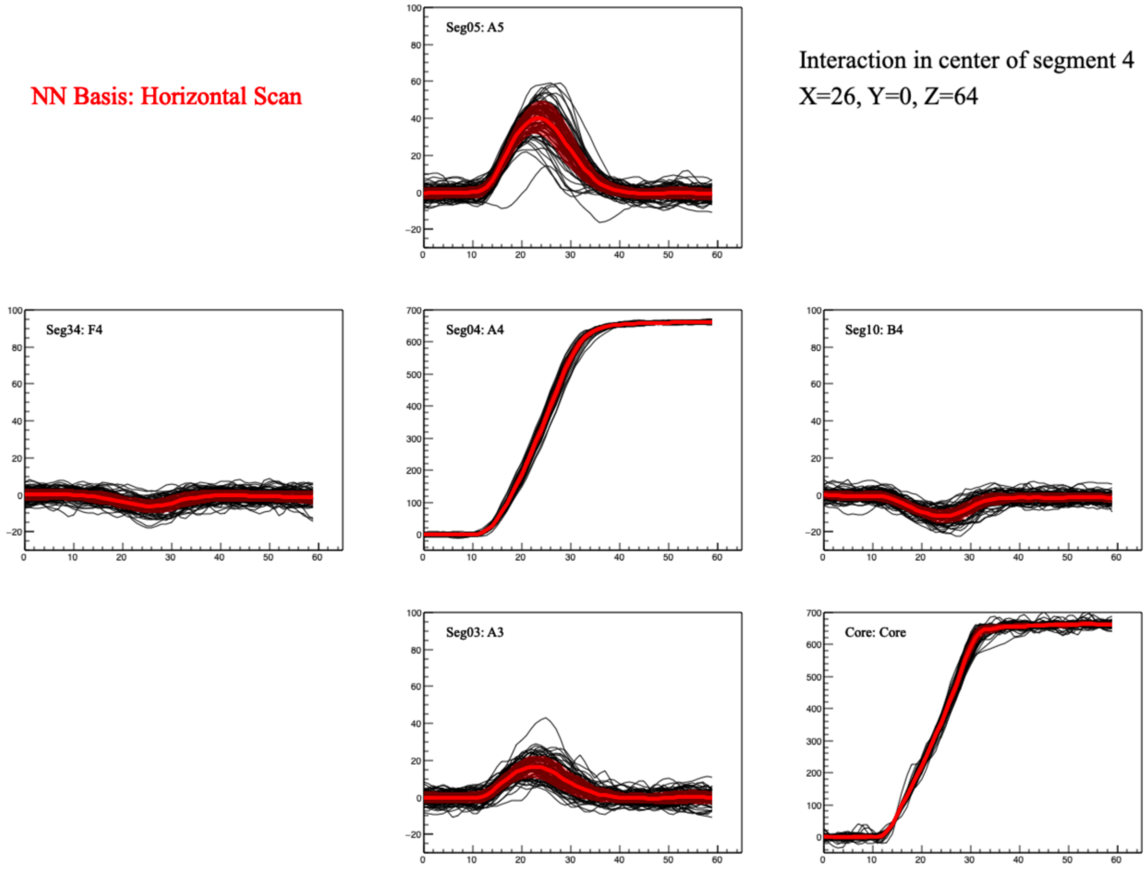
- A motorized collimator with a $10\mu m$ precision.
- A system allowing the placement of the detector in vertical and horizontal positions.
- A laser alignment system.
- Detector scanned in this work: the symmetric S001 crystal, with a 137Cs source.



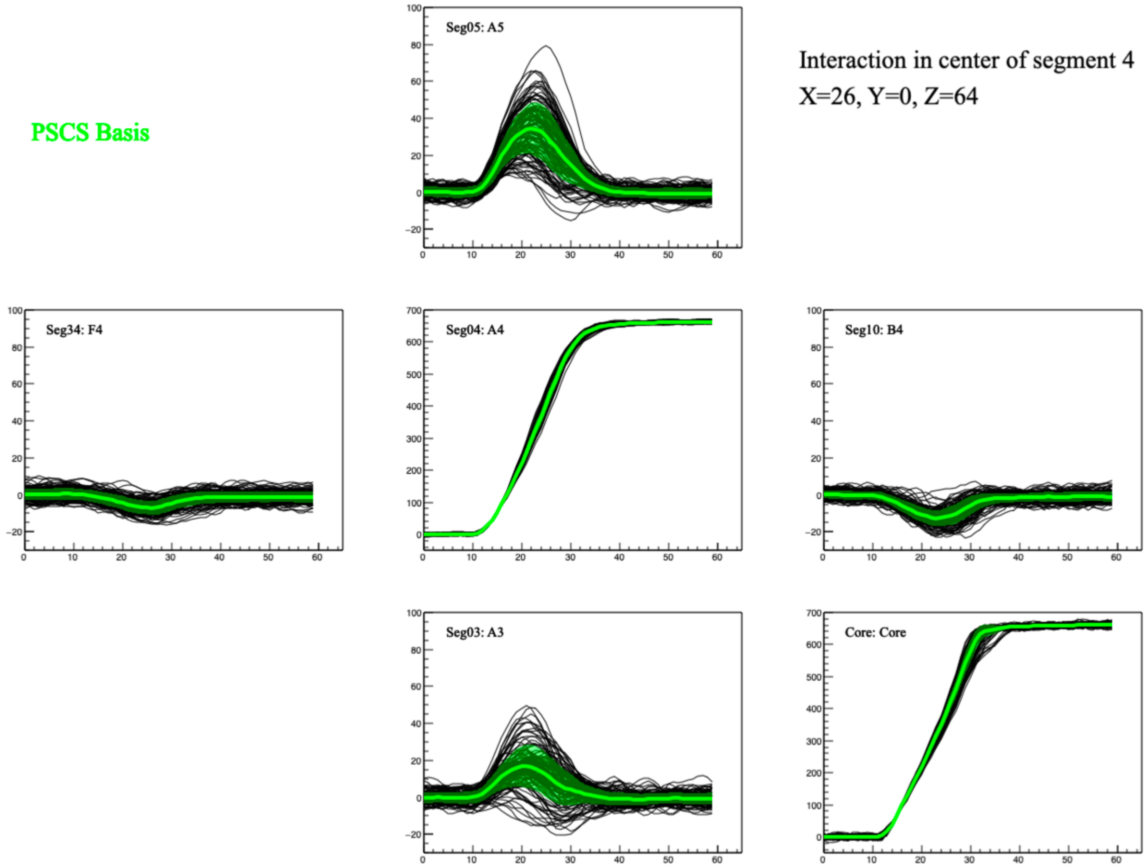
Neural network results: Vertical Signals



Neural network results: Horizontal signals



PSCS method signals



Neural network Vs PSCS