SensIMed LABORATORY

Quasimodo
Quantum sensing for one-health

Politecnico di Bari

INFN BARI
Istituto Nazionale di Fisica Nucleare
Sezione di Bari

SPect for Online boron dose verification in bnCt

BA Team (WP3)

05-2025

DIPARTIMENTO INTERATENEO DI FISICA

Status

- DeepLearning reconstruction of Polimi database
  - Preprocessing and database building starting from 5 distributions provided by Polimi-Nuclear group and 2 measures samples in Pavia, and other reconstructed object with previous simulations
  - Training and test of 3 models: AutoEncoder, U-net (modificated for reconstruction and denoising), Variational AutoEncoder.
  - Results in terms of metrics: NMI, SSIM, PSNR

- Materials for mechanical support already ordered

Deep Learning framework

Pipe-line for DeepLearning reconstruction:

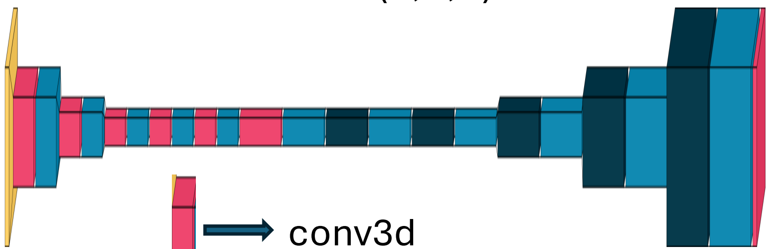
- Data are reconstructed at 50 iterations
  1. Reconstruction at 50 iterations with 6 angles projections

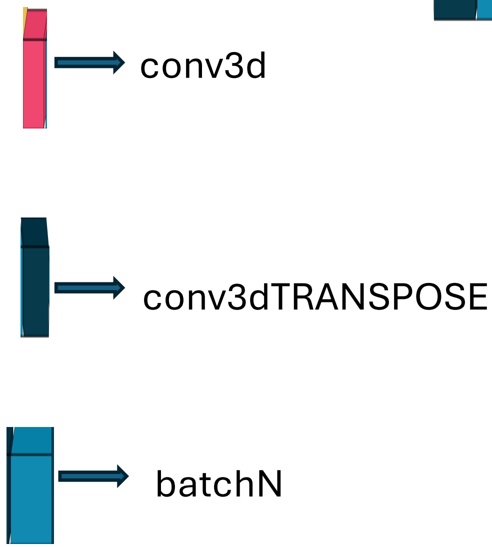
- Pre-processing
  1. Database is made by images of (128,128,128)
  2. Images are resized to (64,64,64) and cropped at center with patch (32,32,32)
  3. Bin size = 0,78 mm
  4. Database is augmented witk **Kornia.Augmentation** library: rotation, traslation, reflections, brightness, noise: 100 images for object, in total 900
  5. Database is divided into 75% of training and 25% as validation/test
  6. Cross-validated with two folds
  7. Models tested: AutoEncoder, U-net
  8. Losses: Custom
  9. Metrics: IoU, PSNR, SSIM, NMI

Deep Learning architectures

AutoEncoder (AE):

- Input tensor (32,32,32,1)
- Strides = (2,2,2)



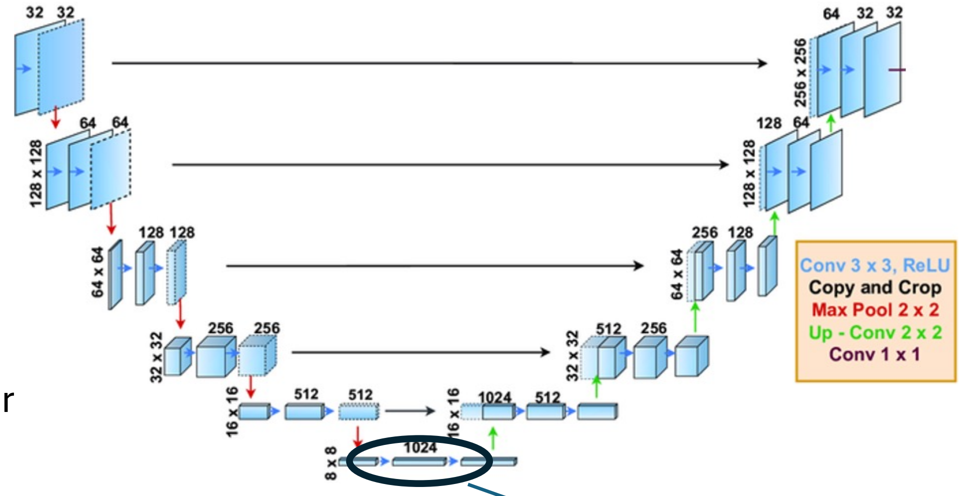


VariationalAE (VAE):

- Input tensor (32,32,32,1)
- Strides = (2,2,2)
- Regolarization of latent space with a **dense layer**

Layer (type)	Output Shape	Param #
input_layer (InputLayer)	(None, 32, 32, 32, 1)	0
conv3d (Conv3D)	(None, 16, 16, 16, 32)	896
batch_normalization (BatchNormalization)	(None, 16, 16, 16, 32)	128
conv3d_1 (Conv3D)	(None, 8, 8, 8, 64)	55,360
batch_normalization_1 (BatchNormalization)	(None, 8, 8, 8, 64)	256
conv3d_2 (Conv3D)	(None, 4, 4, 4, 128)	221,312
batch_normalization_2 (BatchNormalization)	(None, 4, 4, 4, 128)	512
conv3d_3 (Conv3D)	(None, 2, 2, 2, 256)	884,992
batch_normalization_3 (BatchNormalization)	(None, 2, 2, 2, 256)	1,024
conv3d_4 (Conv3D)	(None, 1, 1, 1, 512)	3,539,456
batch_normalization_4 (BatchNormalization)	(None, 1, 1, 1, 512)	2,048
conv3d_5 (Conv3D)	(None, 1, 1, 1, 1024)	14,156,800
batch_normalization_5 (BatchNormalization)	(None, 1, 1, 1, 1024)	4,096
conv3d_transpose (Conv3DTranspose)	(None, 2, 2, 2, 512)	14,156,288
batch_normalization_6 (BatchNormalization)	(None, 2, 2, 2, 512)	2,048
conv3d_transpose_1 (Conv3DTranspose)	(None, 4, 4, 4, 256)	3,539,200
batch_normalization_7 (BatchNormalization)	(None, 4, 4, 4, 256)	1,024
conv3d_transpose_2 (Conv3DTranspose)	(None, 8, 8, 8, 128)	884,864
batch_normalization_8 (BatchNormalization)	(None, 8, 8, 8, 128)	512
conv3d_transpose_3 (Conv3DTranspose)	(None, 16, 16, 16, 64)	221,248
batch_normalization_9 (BatchNormalization)	(None, 16, 16, 16, 64)	256
conv3d_transpose_4 (Conv3DTranspose)	(None, 32, 32, 32, 32)	55,328
batch_normalization_10 (BatchNormalization)	(None, 32, 32, 32, 32)	128
conv3d_6 (Conv3D)	(None, 32, 32, 32, 1)	865

Deep Learning architectures



Unet with bottleneck (Unet3D):

INPUT = (1,32,32,32)

Each Downward Block: 2-(3D) convolutions with BatchNor + LeakyReLU.

Each Downsample Block: Conv3D with stride 2 → halves the spatial dimensions.

Upsample Block: Upsample + Conv3D(1x1) to raise the resolution.

Skip connections: Addition (not concatenation) between the upsampled output and the one from the encoding path.

Final Block: Set the number of channels to 1 for the output

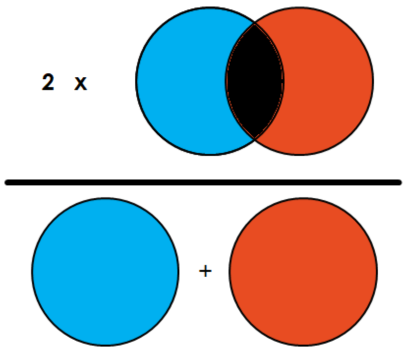
Deep Learning losses and metrics

1. **Mean Squared Error** (**MSE**):
   $(y_{true} - y_{pred})^2$
2. **1 - Dice**

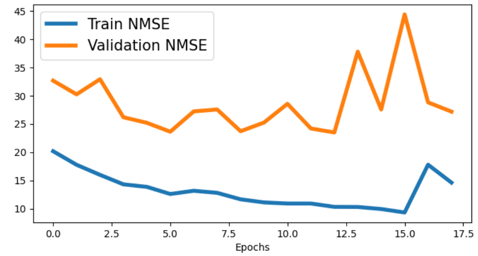
Loss = ½ (1-Dice) + ½ (MSE)

1. **NMI**: normalized mutual information
2. **IoU**: intersection over unit
3. **SSIM**: structure similarity index metrics
4. **PSNR**: peak signal to noise ratio

$$\text{Dice} = \frac{2 \cdot \text{Area of overlap}}{\text{Area 1} + \text{Area 2}}$$



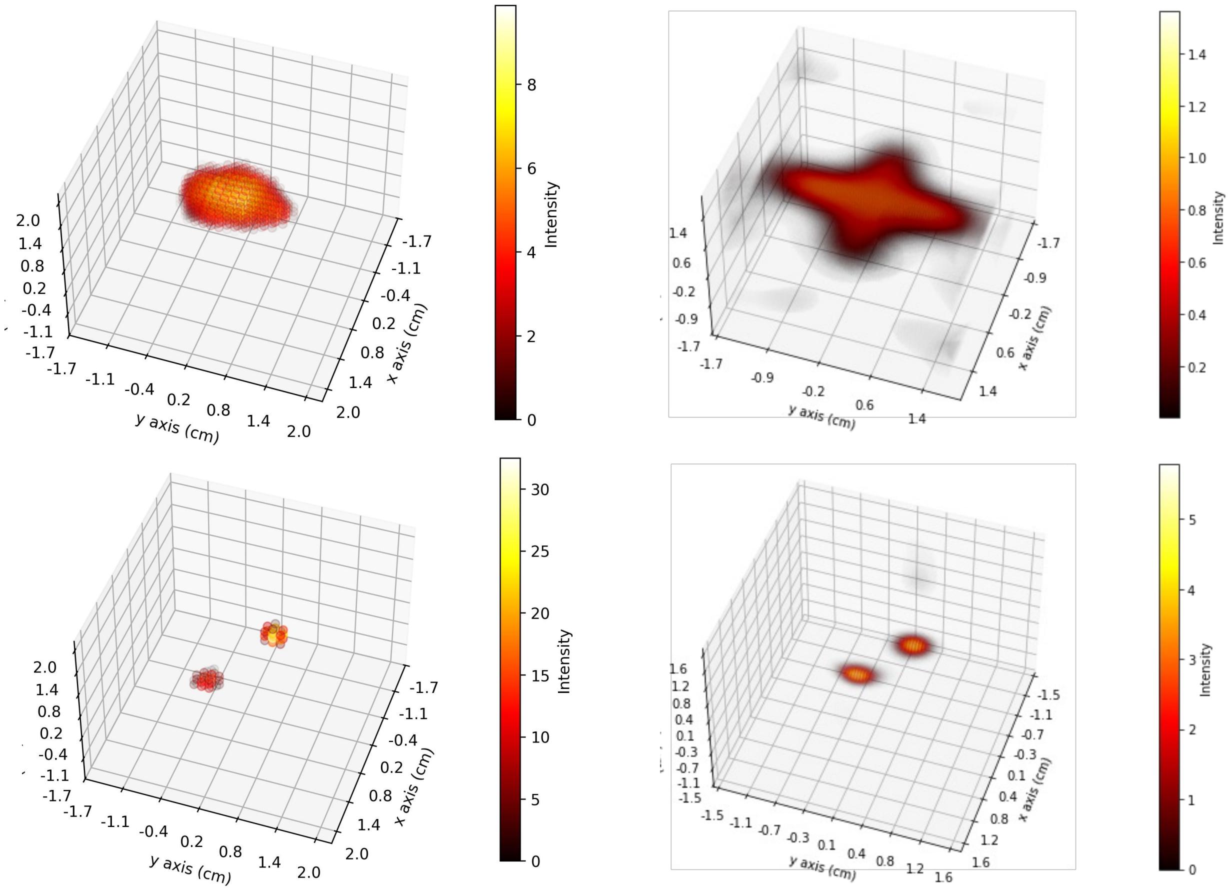
AE results (fold 1)



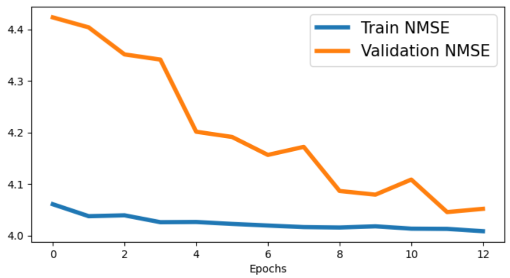
VAE:
- IoU: 5%
- SSIM: 0.43 +/- 0.02
- PSNR: 10 +/- 2
- MSE: 0.10
- NMI: 1.02

VAE:
- IoU: 20%
- SSIM: 0.6 +/- 0.07
- PSNR: 32 +/- 4
- MSE: 0.05
- NMI: 1.4

IMAGE LABEL



AE results (fold 2)

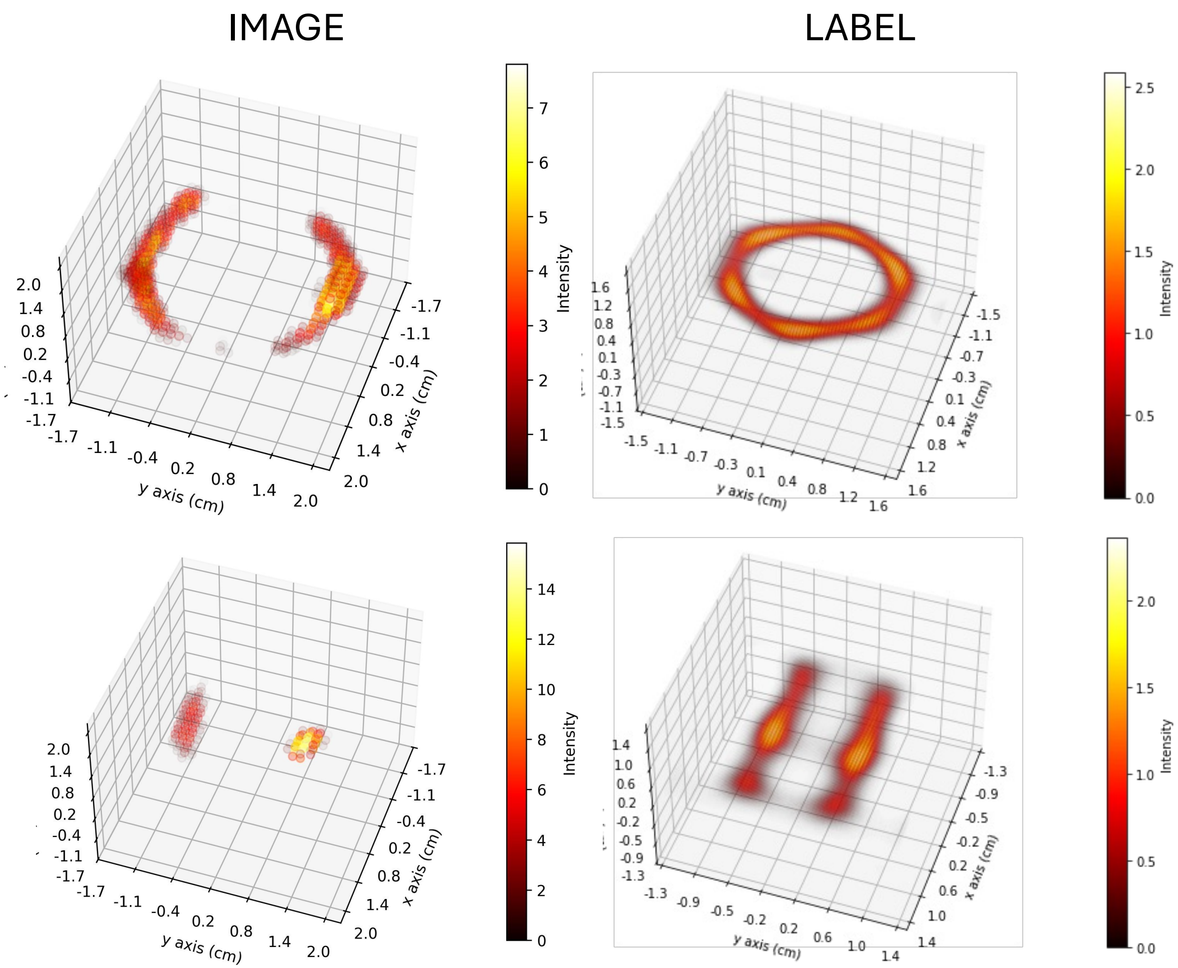


VAE:

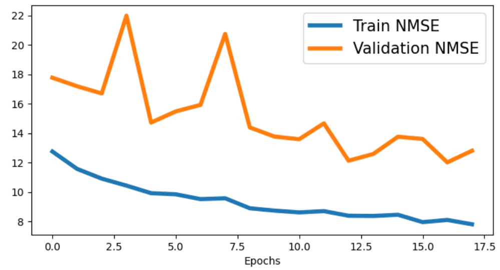
- IoU: 70%
- SSIM: 0.65 +/- 0.09
- PSNR: 12 +/- 2
- MSE: 0.09
- NMI: 1.04

VAE:

- IoU: 8%
- SSIM: 0.45 +/- 0.1
- PSNR: 15 +/- 3
- MSE: 0.12
- NMI: 1.02

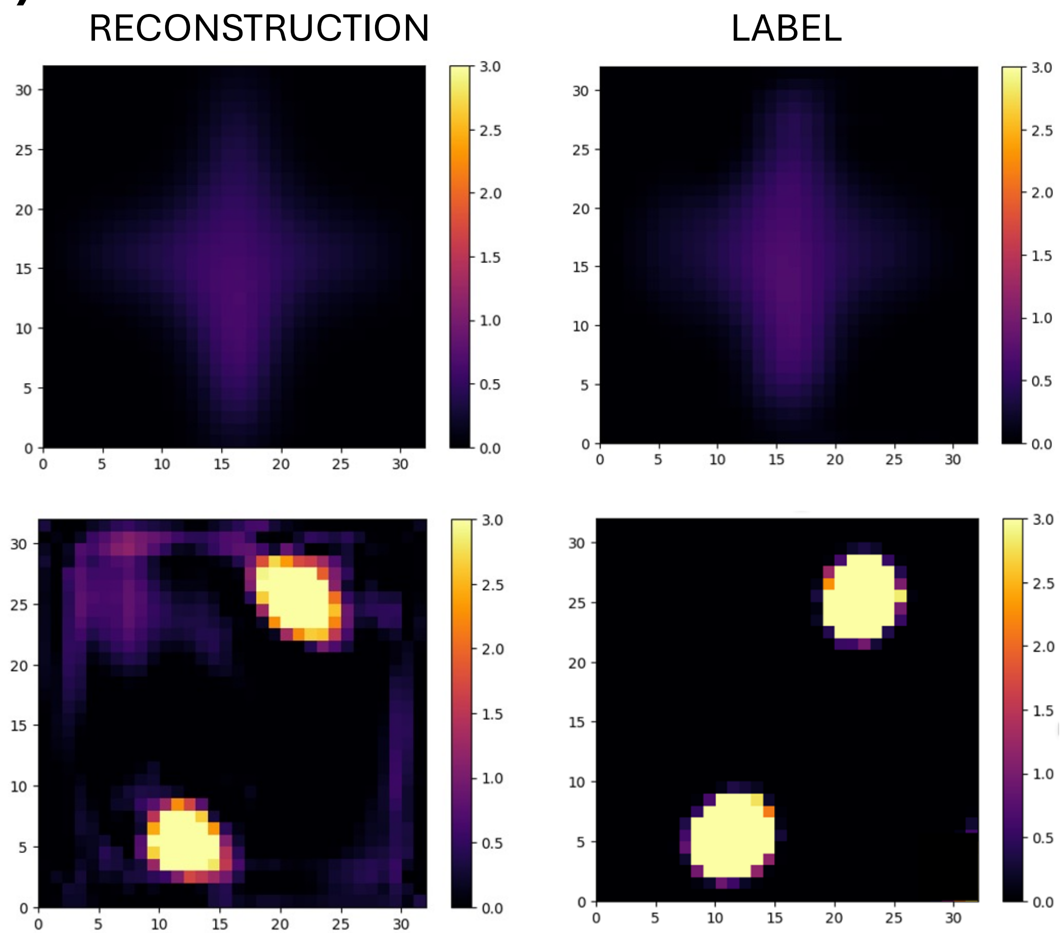


U-Net results (fold 1)

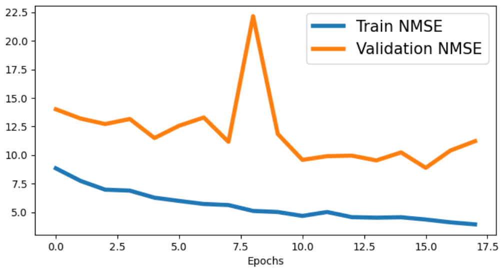


U-Net:
- IoU: 58%
- SSIM: 0.71 +/- 0.05
- PSNR: 27 +/- 0.7
- MSE: 0.06
- NMI: 1.08

U-Net:
- IoU: 71%
- SSIM: 0.82 +/- 0.01
- PSNR: 33 +/- 1
- MSE: 0.07
- NMI: 1.21

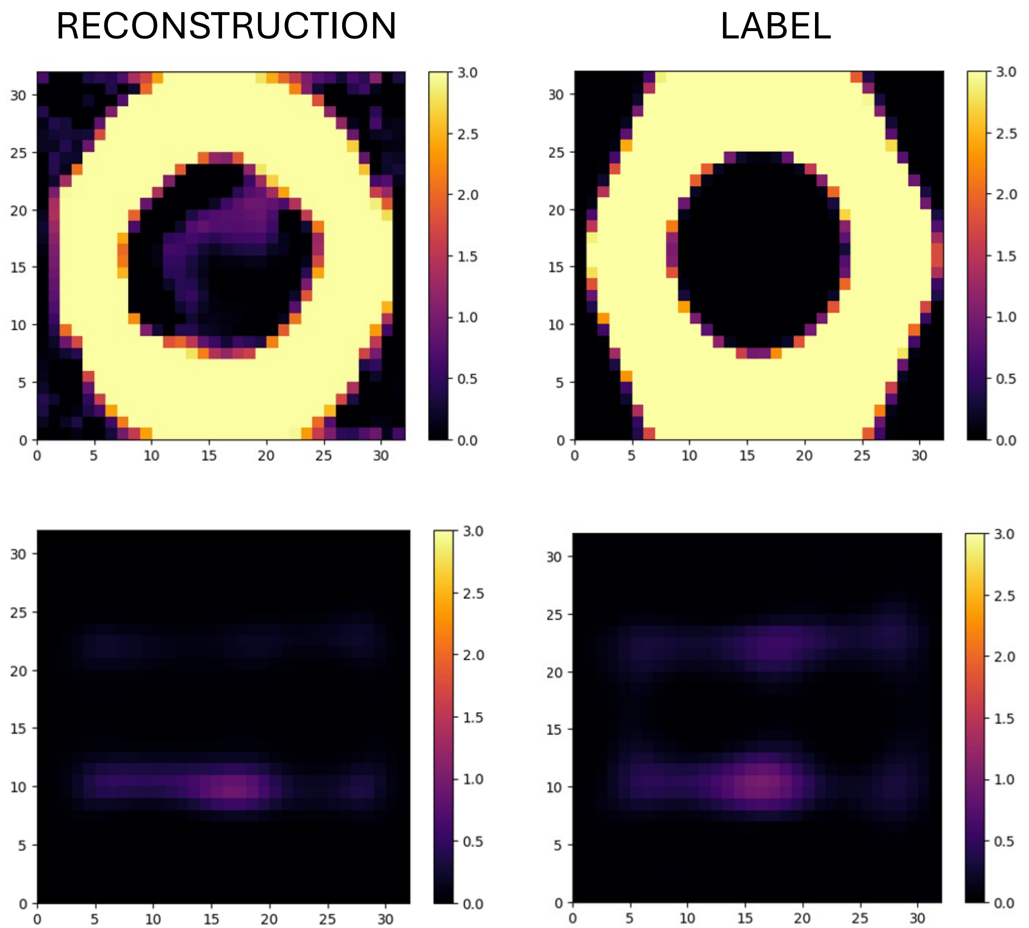


U-Net results (fold 2)

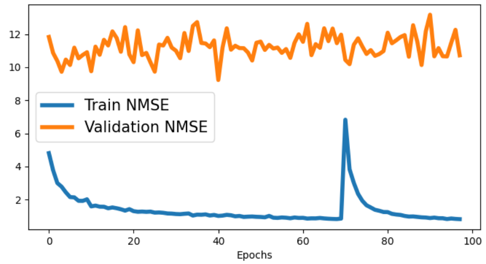


U-Net:
- IoU: 89%
- SSIM: 0.88 +/- 0.02
- PSNR: 28 +/- 3
- MSE: 0.05
- NMI: 1.62

U-Net:
- IoU: 81%
- SSIM: 0.86 +/- 0.03
- PSNR: 31 +/- 3
- MSE: 0.11
- NMI: 1.37



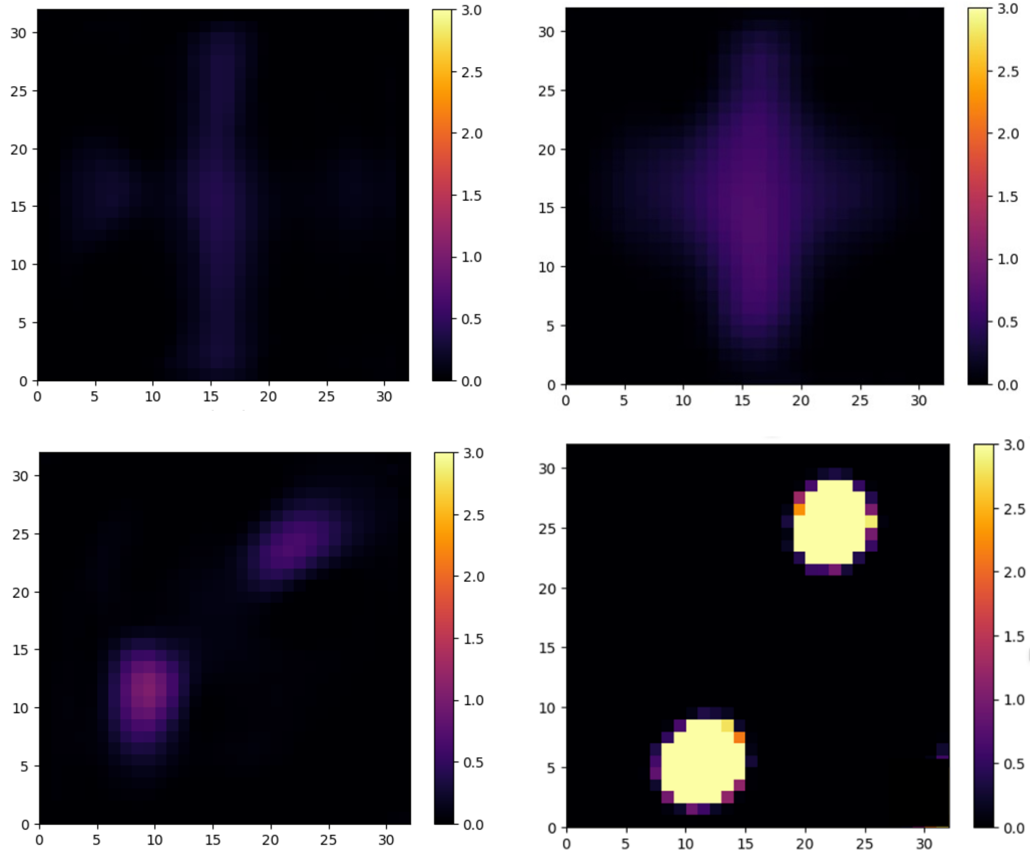
VAE results (fold 1)



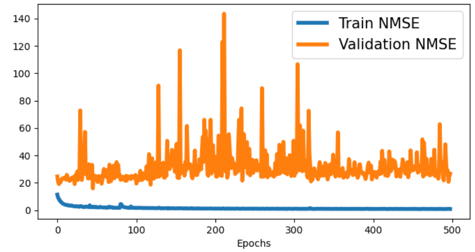
VAE:
- IoU: 32%
- SSIM: 0.21 +/- 0.1
- PSNR: 14 +/- 1
- MSE: 0.8
- NMI: 1.07

VAE:
- IoU: 45%
- SSIM: 0.42 +/- 0.2
- PSNR: 22 +/- 3
- MSE: 0.7
- NMI: 1.01

RECONSTRUCTION LABEL

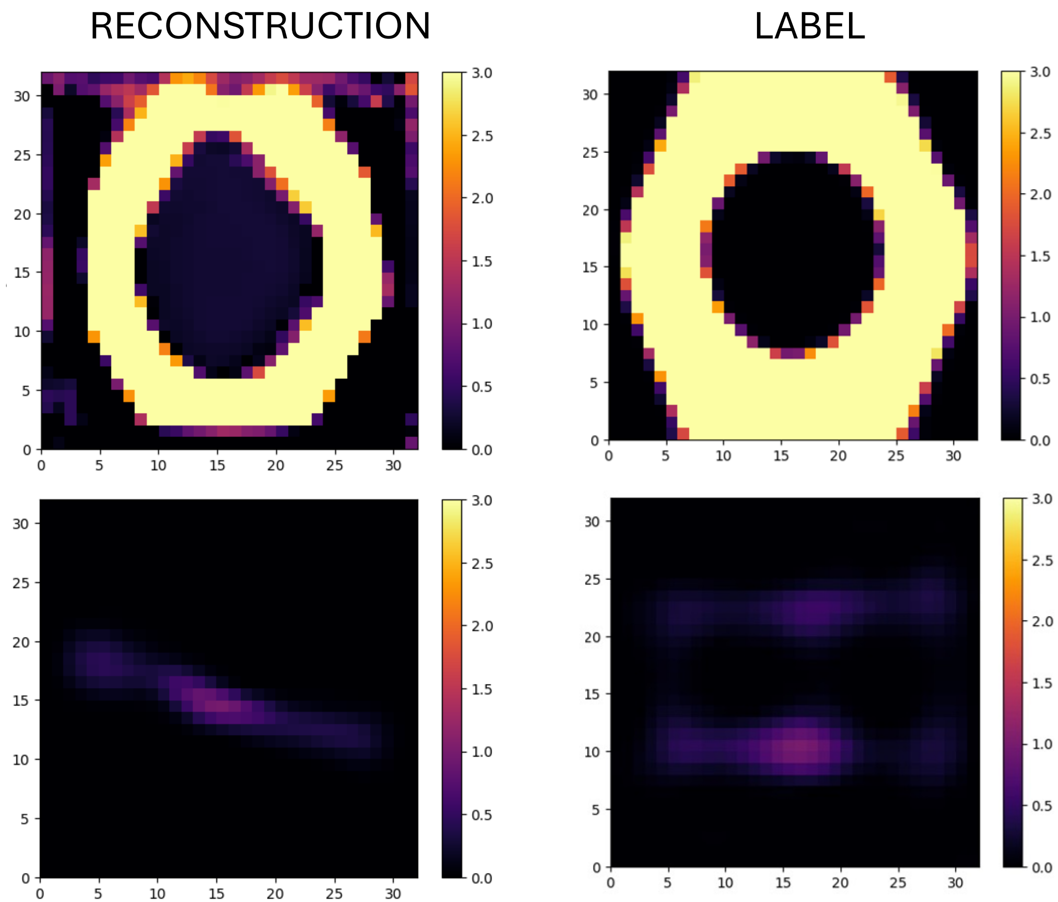


VAE results (fold 2)



VAE:
- IoU: 79%
- SSIM: 0.73 +/- 0.07
- PSNR: 24 +/- 0.9
- MSE: 0.13
- NMI: 1.05

VAE:
- IoU: 14%
- SSIM: 0.3 +/- 0.07
- PSNR: 19 +/- 2
- MSE: 0.53
- NMI: 1.02



Thanks

BA Team @ Collaboration meeting

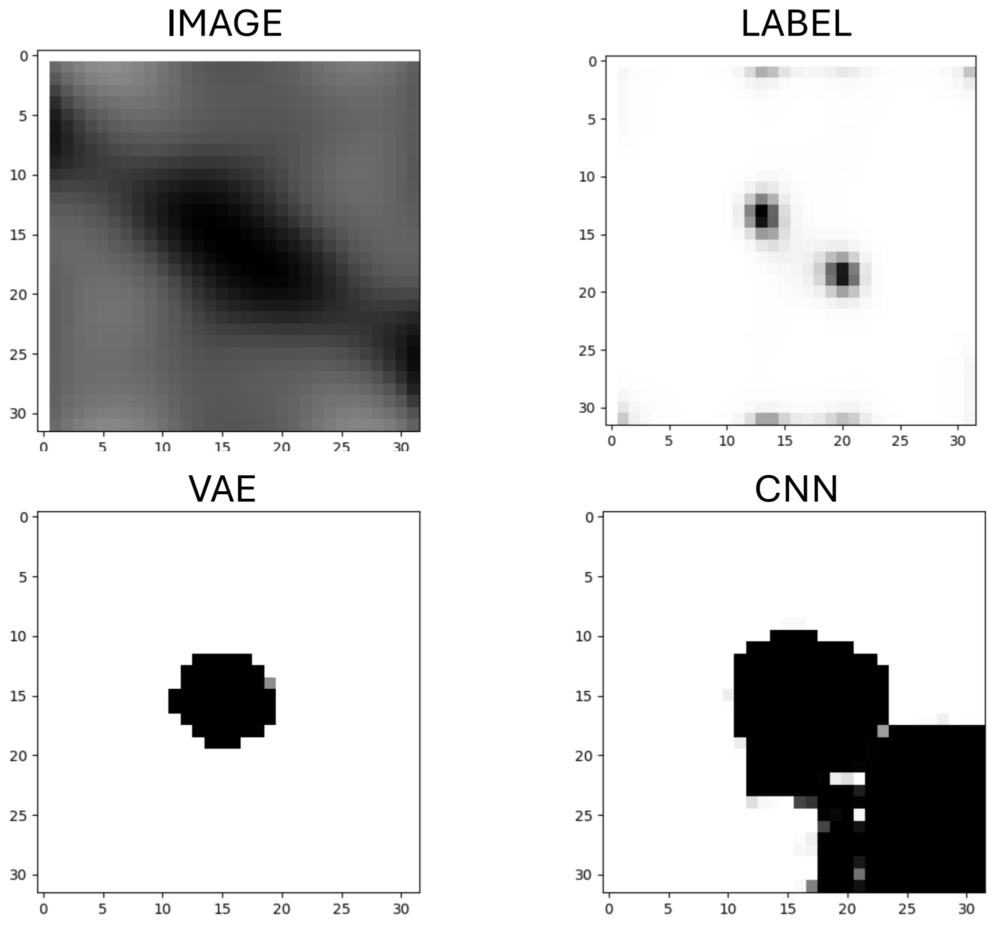
Backup slides

BA Team @ Collaboration meeting

Deep Learning results

VAE:
- IoU: 20%
- SSIM: 0.89 +/- 0.07
- PSNR: 32 +/- 4
- MSE: 1.09

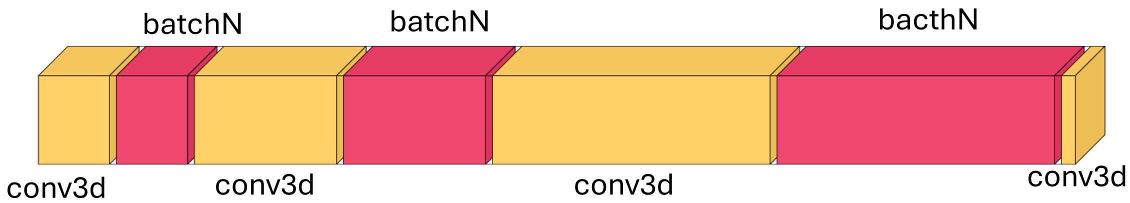
CNN:
- IoU: 9%
- SSIM: 0.74 +/- 0.09
- PSNR: 15 +/- 2
- NMI: 1.01



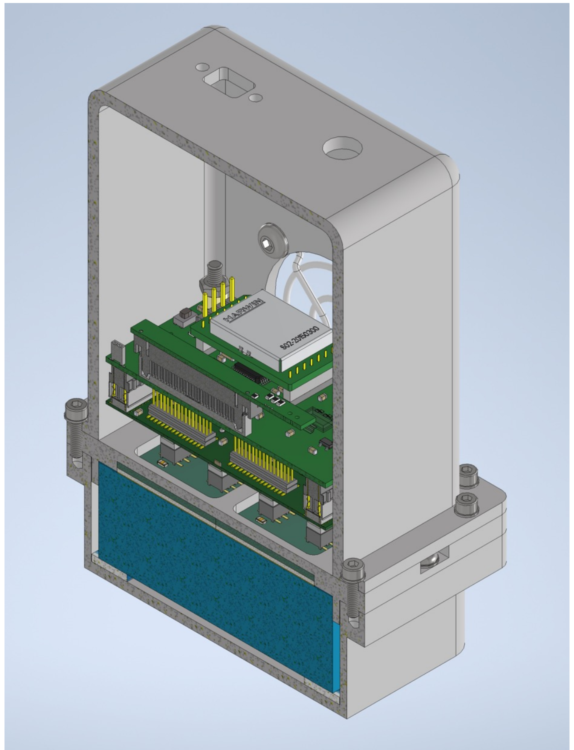
Deep Learning architectures

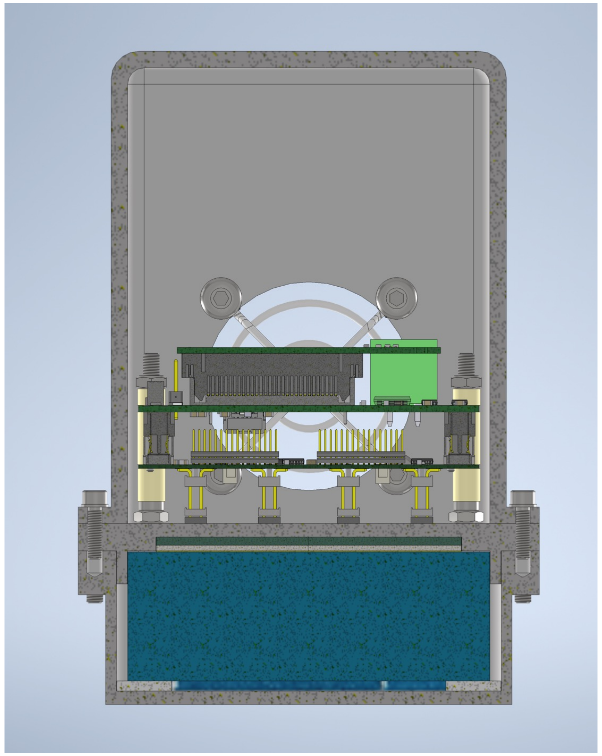
1. Convolutional Neural Network (CNN):
    - Input tensor (32,32,32,1)
    - No strides

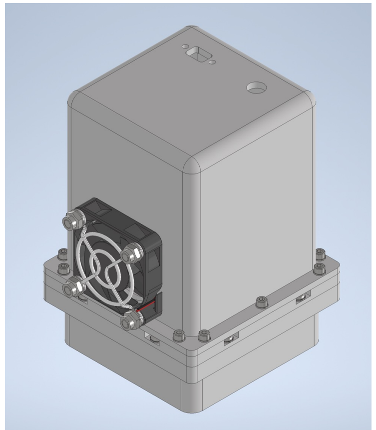
Layer (type)	Output Shape	Param #
conv3d_7 (Conv3D)	(None, 32, 32, 32, 32)	896
batch_normalization_11 (BatchNormalization)	(None, 32, 32, 32, 32)	128
conv3d_8 (Conv3D)	(None, 32, 32, 32, 64)	55,360
batch_normalization_12 (BatchNormalization)	(None, 32, 32, 32, 64)	256
conv3d_9 (Conv3D)	(None, 32, 32, 32, 128)	221,312
batch_normalization_13 (BatchNormalization)	(None, 32, 32, 32, 128)	512
conv3d_10 (Conv3D)	(None, 32, 32, 32, 1)	3,457

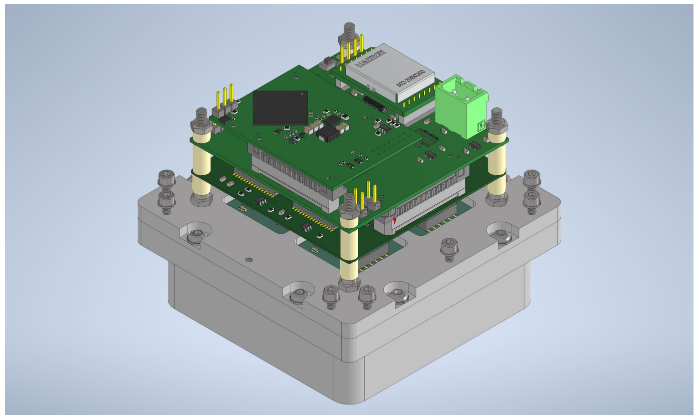


Mechanical layout for detector case





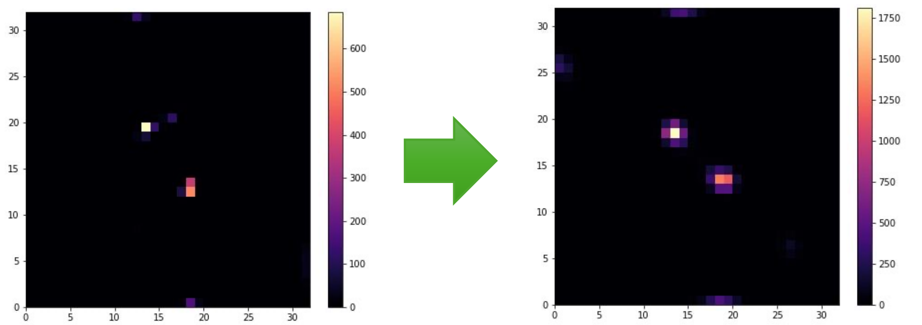




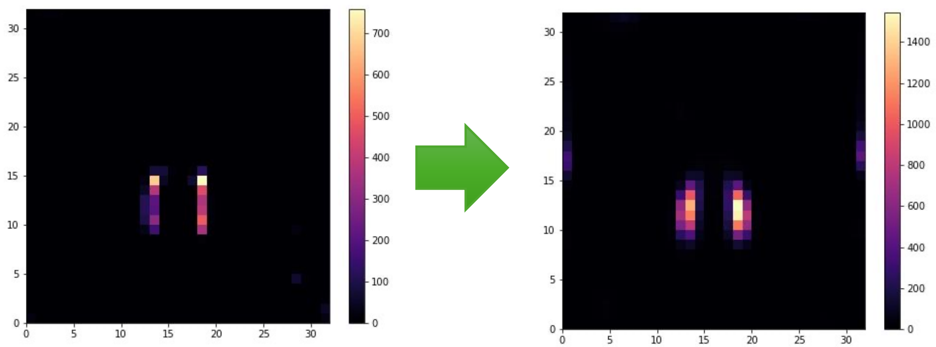
Vials reconstruction corrected

- Correction parameters: ɑ = 0.85, 0.95, 0.99, 0.85 (0-180 deg)
- Projection image correction: $I = I_0 - \alpha \cdot I_{background}$

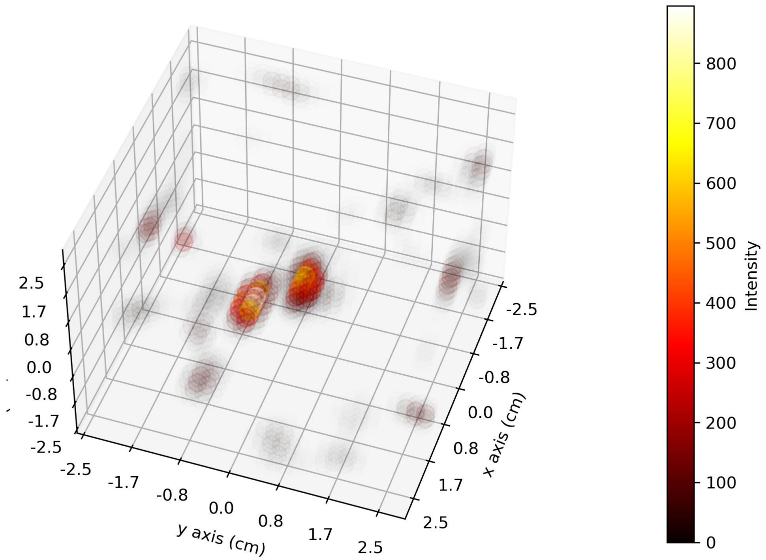
XZ-PROJECTION



YZ-PROJECTION



CORRECTED TOMOGRAPHY



- Pixel side: 1.56 mm
- Vials reconstructed with ∽ **12-14 mm distance**

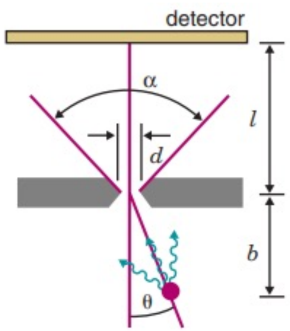
Tomography reconstruction

- Method: Ordered Subset Expectation Maximizaion (**OSEM**) GPU accelerated (already implemented in Pytomography) widely used for SPECT tomography*

$$\lambda(\text{new})_j = \frac{\lambda(\text{old})_j}{\sum_{D_n}\sum_{D_m}\sum_{i\in S_L} C_{ij(nm)}} \times \sum_{D_n}\sum_{D_m}\sum_{i\in S_L} C_{ij(nm)} \left(\frac{Y_{i(nm)}}{\sum_K C_{ik(nm)}\lambda(\text{old})_k} \right),$$

where λ = image variable, C_{ij} = system matrix, Y_i = Count number of photon, D_n = GPU domain length (horizontal thread number), and D_m = GPU domain length (vertical thread number).

- Collimator resolution function :



Pinhole

$$R_{\text{coll}} \approx d_{\text{eff,R}}(l+b)/l$$

$$d_{\text{eff,R}} = d + \frac{\ln(2)}{\mu}\tan\left(\frac{\alpha}{2}\right)$$

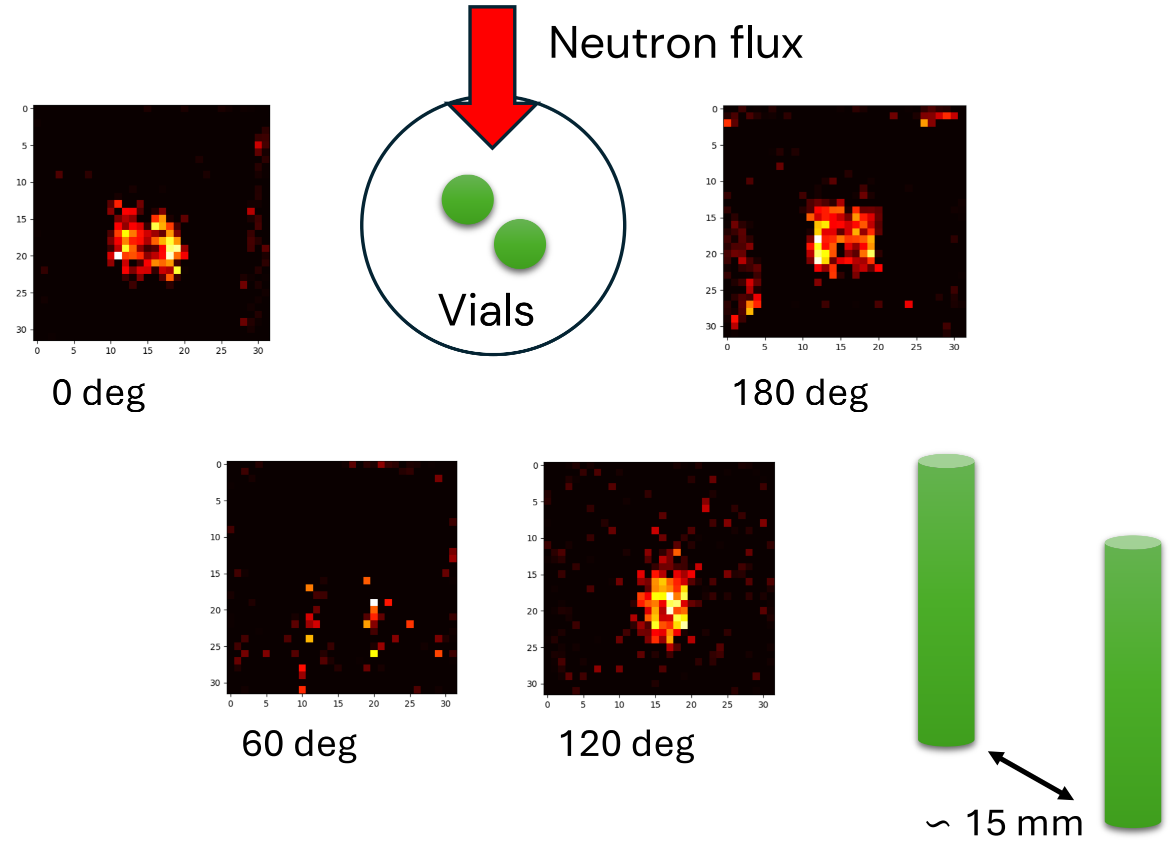
New function!!!

$$R_{coll} = \left(\frac{x}{f}\right)\sqrt{R_d^2 + \left(\frac{f+x}{x+\frac{CH}{2}}\right) * d_e^2}$$

R_d = 3.0 mm, intrinsic resolution
f = 30 cm, distance collimator-detector
x = 30 cm, distance collimator-source
d_e = 5 mm, pinhole diameter
CH = 48.04 mm, channel length

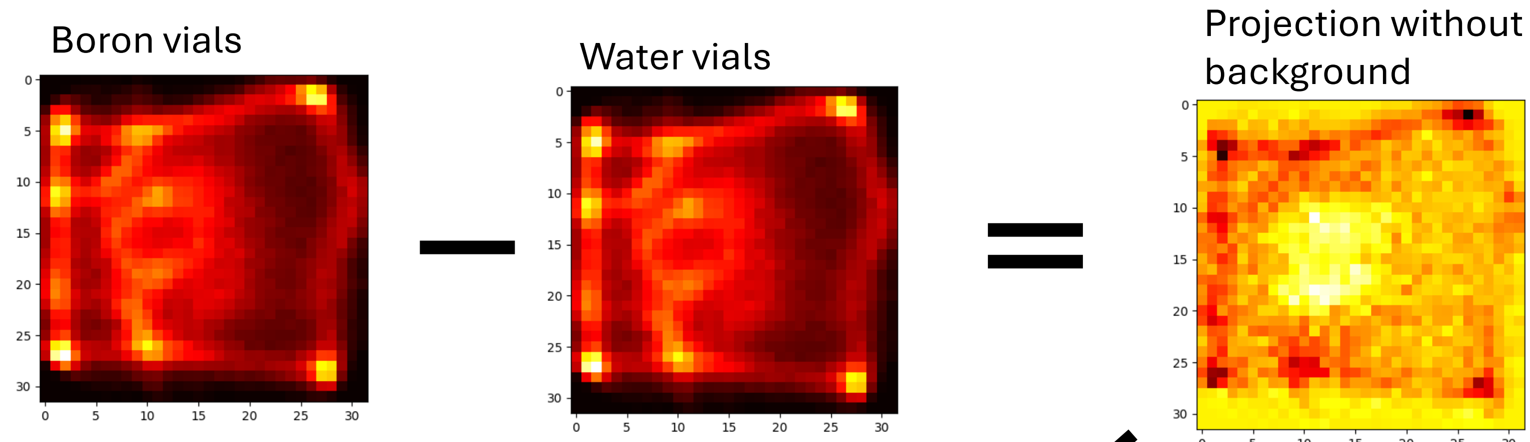
* GPU-based prompt gamma ray imaging from boron neutron capture therapy
** Physics in Nuclear Medicine. Simon R. Cherry, James A. Sorenson and Michael E. Phelps

LENA beam test set-up

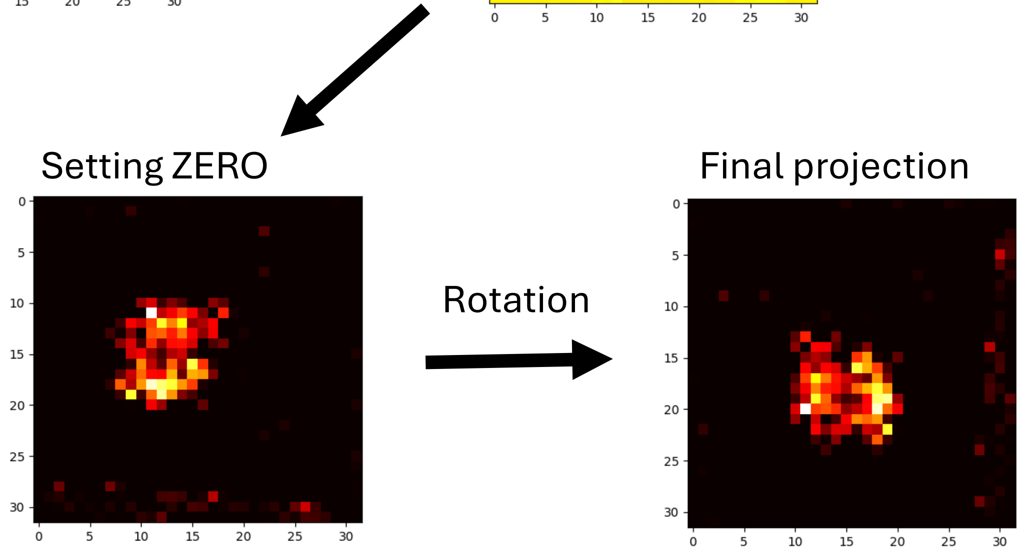


- 4 projections [0, 60, 120, 180 deg]
- Projections obtained by difference between boron sample and water sample (see next slide)
- Boron vials concentration 7371 ppm @ 70 kW reactor power
- Pytomography algorithm for tomography reconstruction

Data preprocessing

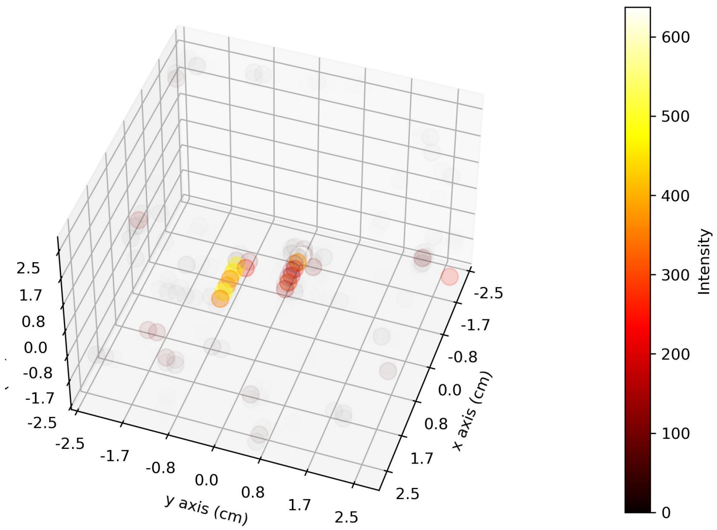


- Projections of Boron-vials and Water-vials are the output from detector Neural Network
- Once removed background (Water-vials) from projections of Boron-vials, the negative values were set to ZERO

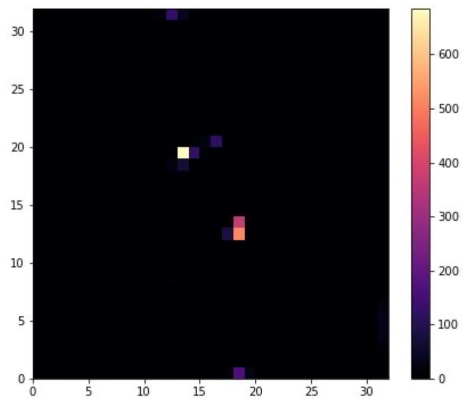


Vials reconstruction results

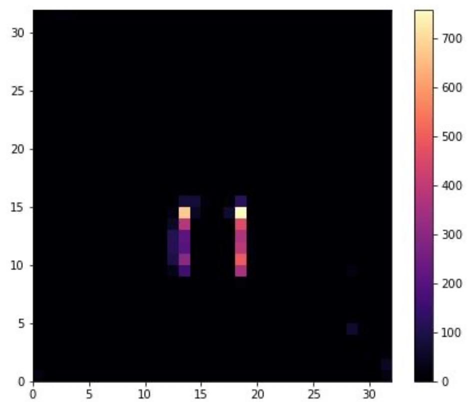
- iterations: 50, subsets: 3
- Pixel side: 1.56 mm
- Vials reconstructed with ∽ **15-17 mm distance**
- **Higher dose on vial nearest to beam port**



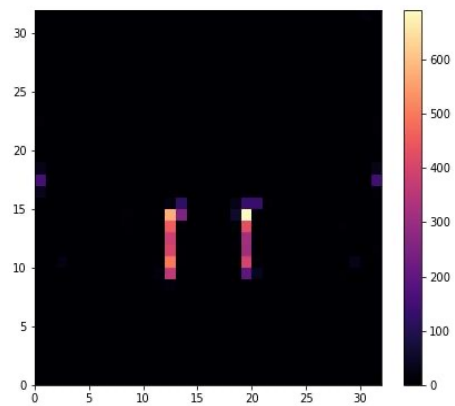
XZ-PROJECTION



YZ-PROJECTION



XY-PROJECTION



Vials reconstruction results corrected

- iterations: 20, subsets: 3
- Pixel side: 1.56 mm
- Vials reconstructed with ∽ **12-14 mm distance**
- **Corrected images with Polimi attenuation factors**