SPECT Imaging of ^{155}Tb and Evaluation of the Impact of ^{156}Tb Contamination Using GATE 10

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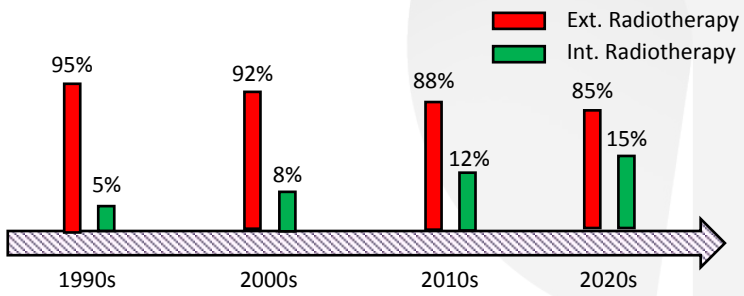
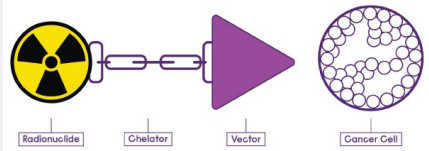
Vectorized Internal Radiotherapy and Theranostic Approach

- Vectorized Internal Radiotherapy (VIR) uses radionuclide isotopes bound to biological vectors to deliver radiation directly to tumors.
- Introduces high precision, personalized treatment and dedicated imaging instrumentation.
- Interested in theranostic (therapeutic + diagnostic) approach.

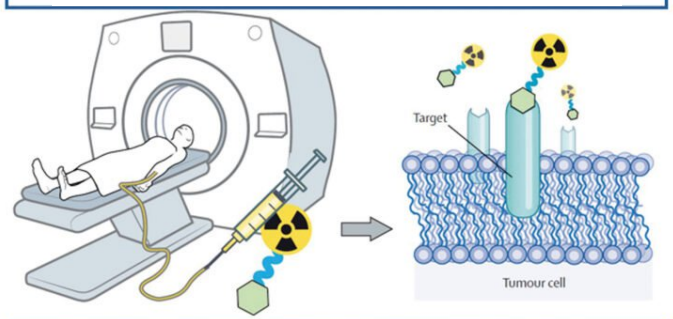
➢ Requires development of new VIR radio-pharmaceuticals.



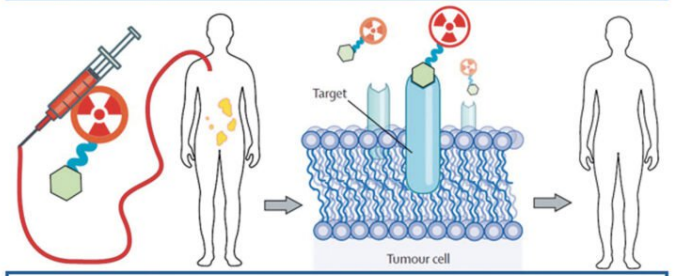
The utilization of internal vs external radiotherapy by patients in Europe and US over time[1].



Therapeutic approach in medicine



Diagnostic phase for evaluating the fixation of the radiopharmaceutical with a radionuclide for imaging purposes



Therapeutic phase with injection of a radiopharmaceutical with a radionuclide for tumoricidal purposes

[1] DIrectory of RAdiotherapy Centres (DIRAC).

La radiothérapie interne vectorisée, nouveau pilier contre le cancer, O. HUILLARD (M.D, Ph.D, E23)

Terbium Isotopes

- Terbium (Tb): promising theranostic element with four isotopes[1].

➡ Interest in ^{155}Tb-^{161}Tb potential theranostic couple (~similar $t_{\frac{1}{2}}$).

- Challenge: standard cyclotron production of ^{155}Tb induces co-production of ^{156}Tb ($t_{\frac{1}{2}}$ = 5.35 d) emitting high energy γ-rays:
  - ^{155}Tb SPECT images pollution.
  - Dosimeteric concerns.

Isotope	Diagnosis	Therapy	1/2 life
^{149}Tb	? β+14.2%, γ	✓ (α)	4.12 h
^{152}Tb	✓ (β+)		17.48 h
^{155}Tb	✓ (γ)		5.32 d
^{161}Tb	? Low energy γ	✓ (β-)	6.96 d

γ - rays energy (keV)	
^{155}Tb	^{156}Tb
86.54 (32%) 105.3 (25.1%) 180.1 (7.5%) 262.3 (5.3%)	88 (18%) 199.2 (41%) 356.3 (13.6%) 534.3 (67%) 1065.1 (10.8%) 1154.1 (10.4%) 1222.4 (31%) 1421.7 (12%)

[1] Naskar N, Lahiri S. Theranostic Terbium Radioisotopes: Challenges in Production for Clinical Application. Front Med (Lausanne). 2021 May 31;8:675014.

Objective and Methodology

- Evaluate by simulation the impact of contamination of ^{156}Tb on ^{155}Tb SPECT images in order to determine acceptable contamination limit.

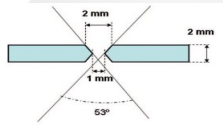
How?

- SPECT imaging Monte Carlo (MC) simulation of ^{155}Tb phantom contaminated with 0-10% ^{156}Tb of two cameras :
  1. ALBIRA (BRUKER).
  2. THIDOS (homemade high performance camera).

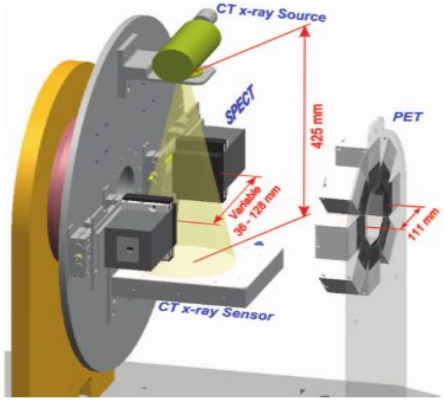
Experimental setup

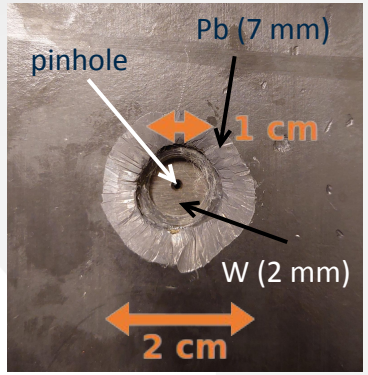
SPECT Cameras

- **ALBIRA**[1] S108 small animal PET/SPECT/CT imaging system, at CHUV, Lausanne .



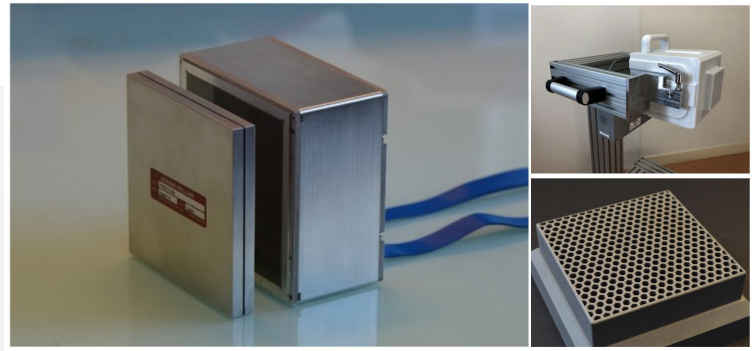
  - 2 rotating SPECT heads, 30 positions
  - 2 mm diameter tungten single pinhole collimator.
  - 7 mm thick lead shielding.
  - Intrinsic spatial resolution (FWHM) : 1.5 mm.
  - Energy resolution (FWHM): 17% at 140 keV.





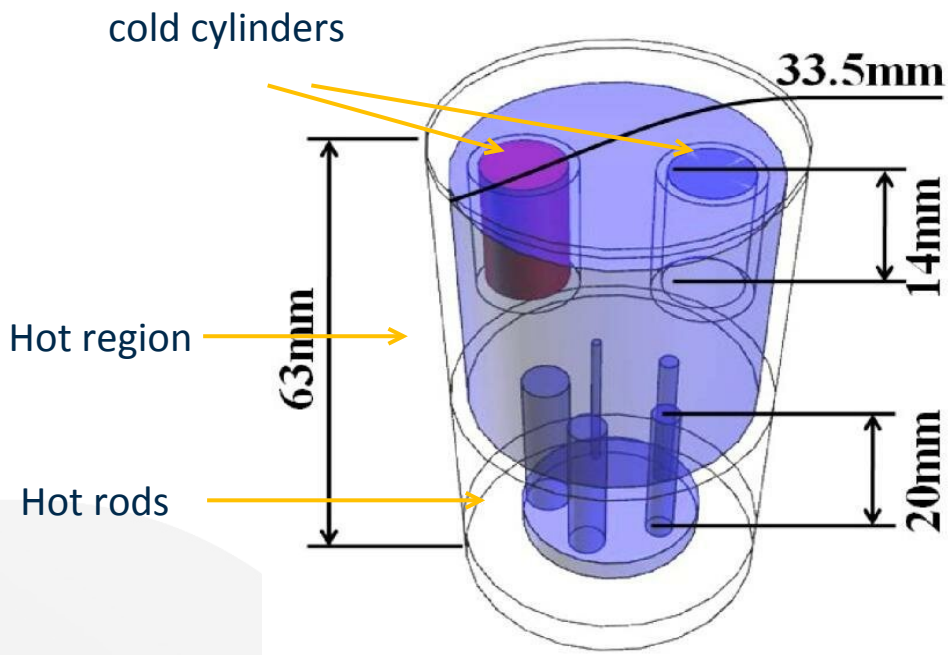
[1] Sánchez et al. Med. Phys, 40, No. 5, May 2013.

- **THIDOS**[2] is a medium-energy γ-camera developed at IJCLab for dosimetry control during internal radiotherapy.
  - Tungsten parallel-hole collimators:
    - L=58.7 mm, d=1.8 mm, t=0.84 mm
  - Optimized for 364 keV (^{131}I).
  - Intrinsic spatial resolution (FWHM) : 1.15 mm.
  - Energy resolution (FWHM): 8% at 356 keV.



[2] Théo Bossis et al, A High-Resolution Portable Gamma-Camera for Estimation of Absorbed Dose in Molecular Radiotherapy.

- **Phantom**: NEMA NU 4-2008, a standard small-animal imaging phantom designed for quantitative performance evaluation.[1]
  - Includes rods (1–5 mm) for spatial resolution testing.
  - Cold and uniform regions for contrast, uniformity, and SNR analysis.



[1] NEMA Standards Publication NU 4-2008 Performance Measurements of Small Animal Positron Emission Tomographs National Electrical Manufacturers Association 1300 N. 17th Street, Suite 1752 Rosslyn, VA 22209.

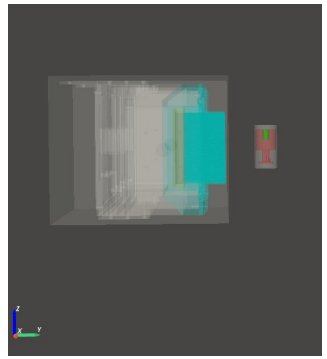
GATE 10 Simulation

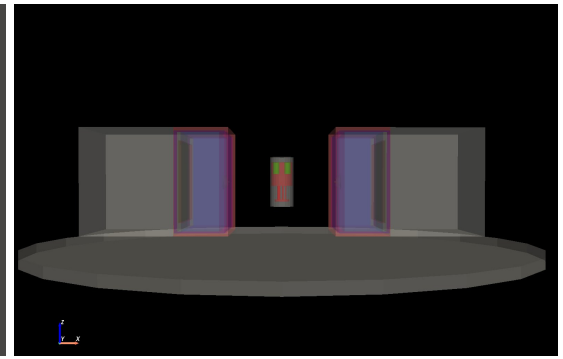
- Reproducing phantom, camera parts and movement, phantom and all sources (isotopes and contaminants → dissemble rays contribution).

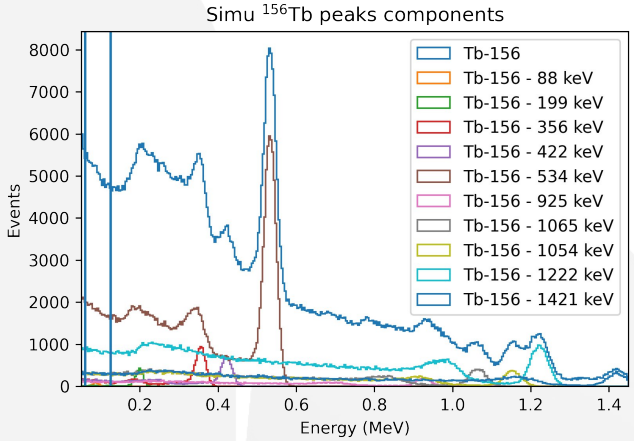
- Used PHID source (Photon from Ion Decay).
  - PHID files of ^{154}Tb, ^{155}Tb, ^{156}Tb, ^{161}Tb and ^{139}Ce (atomic relaxation and isomeric transition) were created.

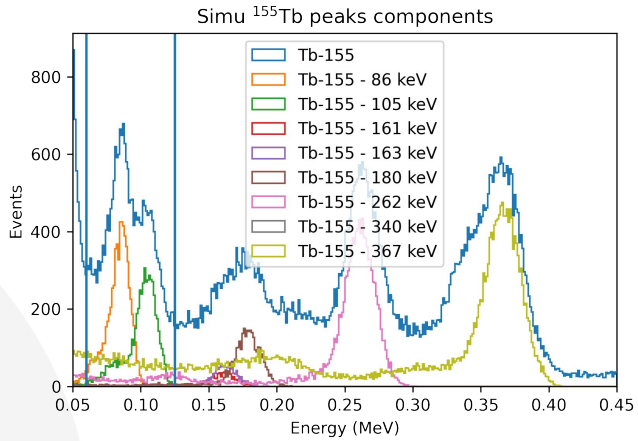
- Used (add_dynamic_parametrisation) for cameras rotation and translation.

- Used actors:
  - Digitizer Hits Collection Actor for “hits”.
  - Digitizer Adder Actor for “singles”.
  - Digitizer Spatial Blurring Actor.
  - Digitizer Blurring Actor.
  - Digitizer Energy Windows Actor.
  - Digitizer Projection Actor.





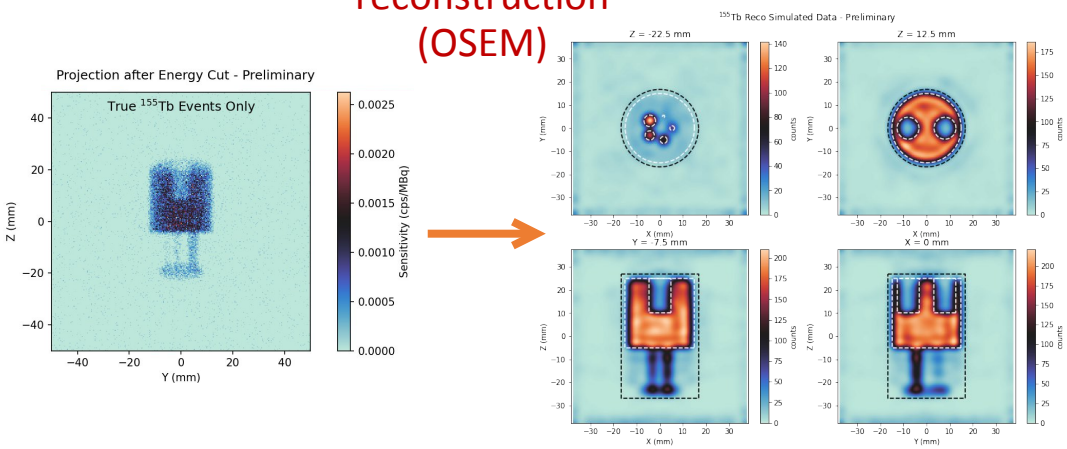


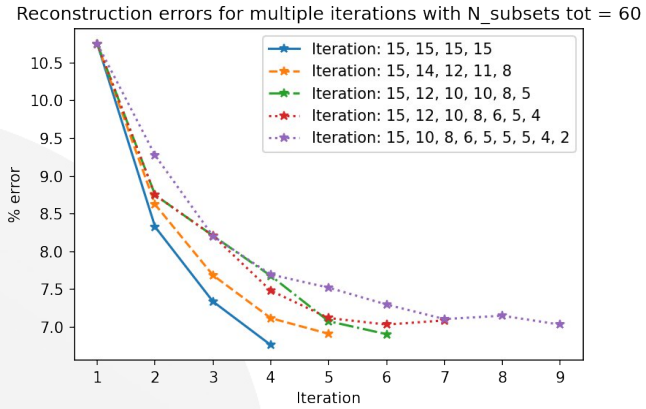


Tomographic Reconstruction

- **Tomographic SPECT reconstruction** performed using CASToR platform.[1]
- Data converted from GATE 10 form to CASToR form, starting from projections or singles.
- Ordered Subset Expectation Maximization (OSEM) algorithm, a Faster MLEM variant used for reconstruction.
- Camera geometry defined and correction added.
- CASToR parameters were optimized.
  - 16 iterations, subsets decreases gradually.
  - PSF function and standard deviation : Gaussian (3.5, 3.5, 3) mm.
  - Convolution (Sieve): apply convolver forward, backward and at the end of each iteration.

2D Projection | 3D image reconstruction (OSEM) | 3D reco. image





[1] CASToR: a generic data organization and processing code framework for multi-modal and multi-dimensional tomographic reconstruction, Thibaut Merlin et al., 2018.

- To quantify the reconstructed images, multiple factors were calculated:

- Integral uniformity [%]: $IU = \frac{\sigma_N}{\bar{N}}$

  σ_N: Standard deviation of voxels values in ROI.
  $\bar{N}$: Sum of counts in ROI averaged by # of voxels.

- Signal to noise ratio: $SNR = \frac{|N_s - N_n|}{N_n}$

  N_s: # of counts considered as signal in ROI.
  N_n: # of counts considered as noise in ROI.

- Contrast factor of the cold cylinders [%]: $Q_{cold} = [1 - \frac{\bar{S}_{cold}}{\bar{S}_{Phantom}}]$

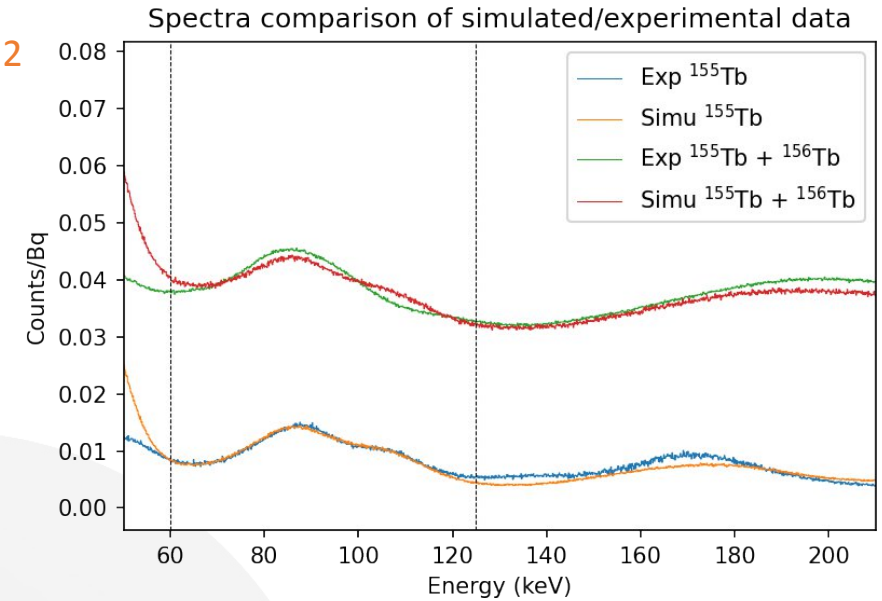
  $\bar{S}_{cold}$: average counts in the cold cylinder.
  $\bar{S}_{Phantom}$: average counts in the ROI of the phantom.

Simulation Validation : Spectra

- Two measurments performed to validate ALBIRA simulation at CHUV, Lausanne, Switzerland :
  - Pure ^{155}Tb measurement (6 MBq + 12 MBq ^{139}CeO).
  - Contaminated ^{155}Tb (28.7 MBq) with ^{156}Tb (2.5 MBq) measurement (+ 1.2 MBq ^{154}Tb).

- Experimental observations :
  - 79.8% 156Tb detected counts in [60, 125] keV for 8% activity contamination.

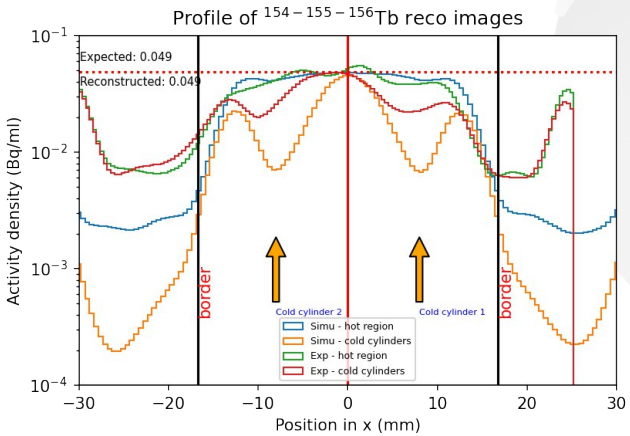
- Simulation validation :
  - Good agreement between spectra in [60, 125] keV window.

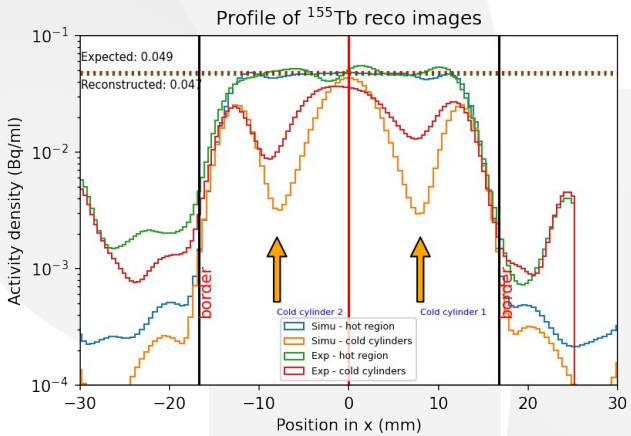


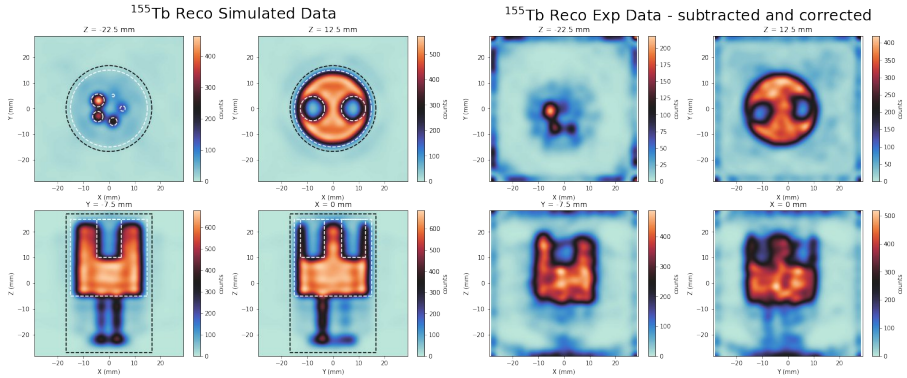
Simulation Validation : Reconstructed images

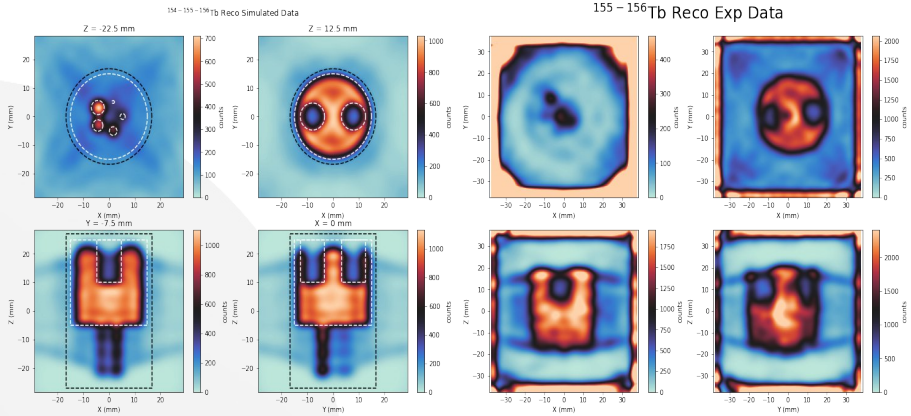
- Experimental observations : Reconstructed images strongly impacted by ^{156}Tb contamination.
- Simulation validation : Some discrepancies between experiment and simulation are under investigations.

Quant. factor	^{155}Tb exp	^{155}Tb +8% ^{156}Tb exp	^{155}Tb simu	^{155}Tb+8% ^{156}Tb simu
SNR	50.86	7.12	103.9	15.86
IU (%)	8.39	7.54	4.49	4.08
Q_{cold} (%)	84.48	63.19	89.73	83.93









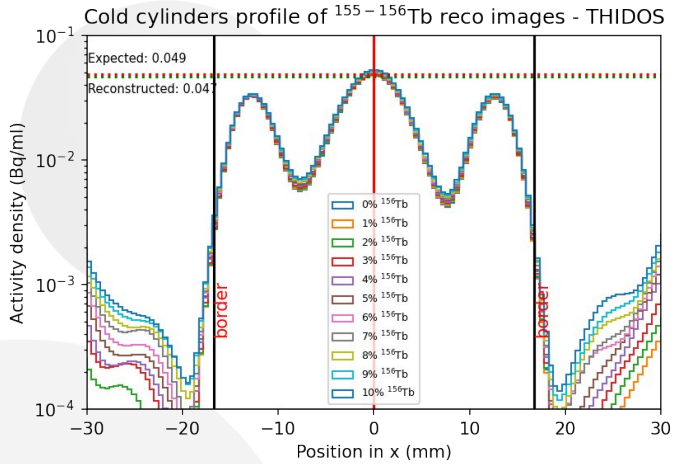
Results

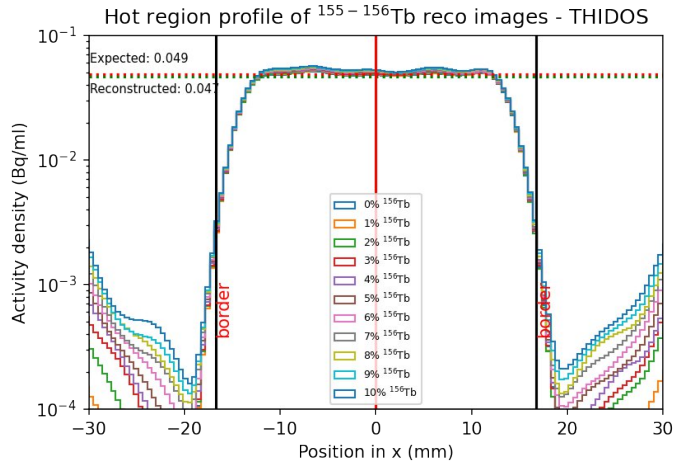
Images Profiles

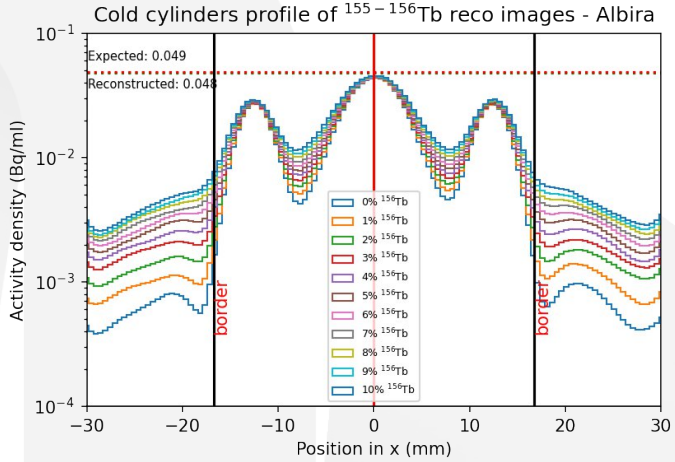
- At 8% ^{156}Tb → ALBIRA = 72%, THIDOS = 30% of detected counts from ^{156}Tb.

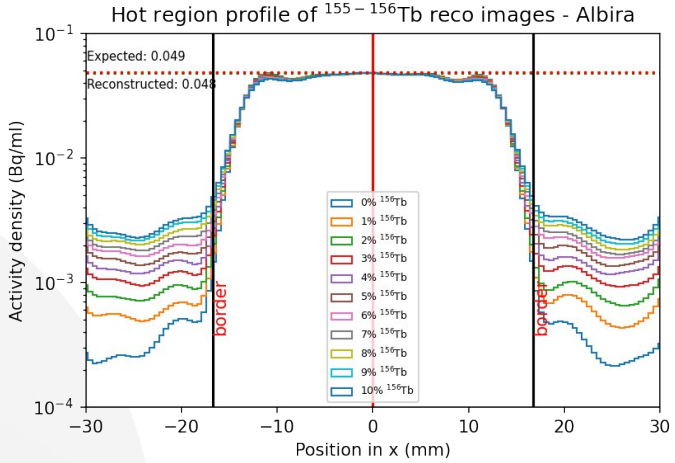
➡ Contamination limit strongly depends on collimator/shielding.

➡ Better collimation improves image quality but it is a trade-off with sensitivity.



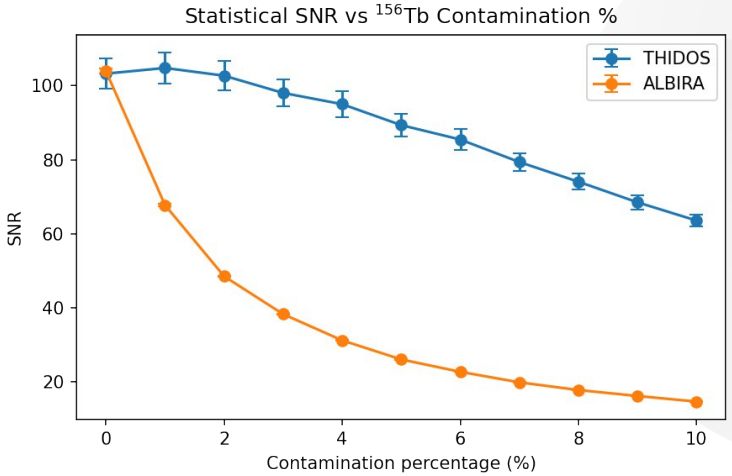


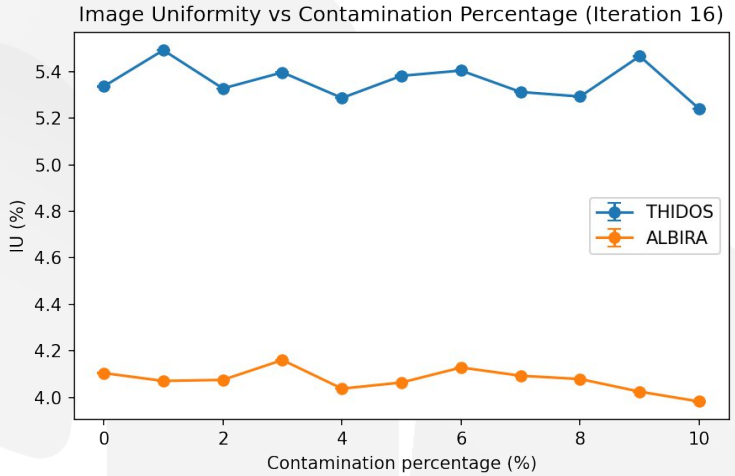


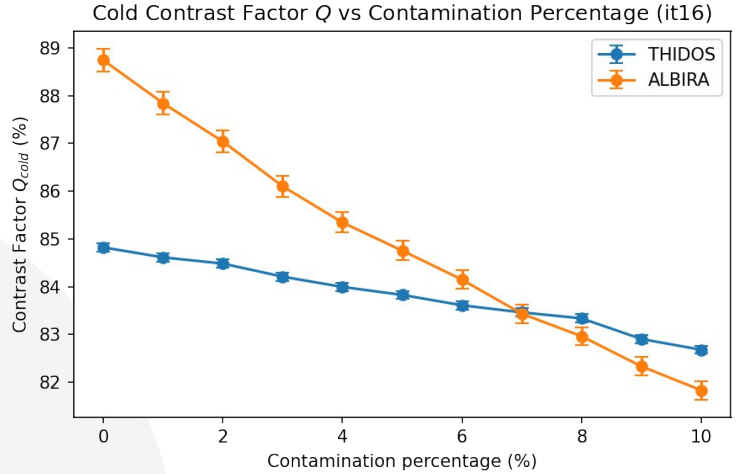


Images Quantification

- At 10% contamination → SNR drops 40% for THIDOS vs >80% for ALBIRA.
  - ➢ For a low energy configuration : contamination limit must be < 2% to limit SNR reduction < 50%.
- Better ALBIRA IU (only 1% difference) → effect of THIDOS collimator?
- Q_{cold} for ALBIRA decreases faster than THIDOS as contamination (%) increases.







Summary and Perspectives

- Simulations of the ALBIRA and THIDOS cameras were performed.
- ALBIRA was validated with two experiments: (i) a pure ^{155}Tb measurement (6 MBq), and (ii) a contaminated ^{155}Tb measurement (28.7 MBq) containing ^{156}Tb.
- Contamination acceptable limit depends on instrumentation, not only isotope ratio.
  - For a low energy configuration : contamination limit must be < 2% to limit SNR reduction < 50%.
- THIDOS significantly reduced contamination with dedicated collimation and shielding.
- ^{155}Tb imaging feasible ; ^{156}Tb contamination overwhelms images with current SPECT cameras.

- Next steps :
  - Optimize THIDOS collimation for ^{155}Tb imaging contaminated with ^{156}Tb.
  - Evaluate impact of ^{156}Tb contamination on dosimetry.
  - Study subtraction method for contamination removal.

Thank You

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Thanks to C. Duchemin[a],N. van der Meulen[b], Z. Talip[b]

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a: MEDICIS, CERN.
b: Paul Scherrer Institute PSI.