Development of iterative image reconstruction for track-based multiple scattering computed tomography using a high-energy electron beam

The 6th Annual Loma Linda workshop 2020 on Particle Imaging and Radiation Treatment Planning

Daiki Hayakawa, Hendrik Jansen, Paul Schuetze
(DESY)

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

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- Test beam experiment at DESY
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- Preliminary results
- Simulation study for clinical imaging

Introduction

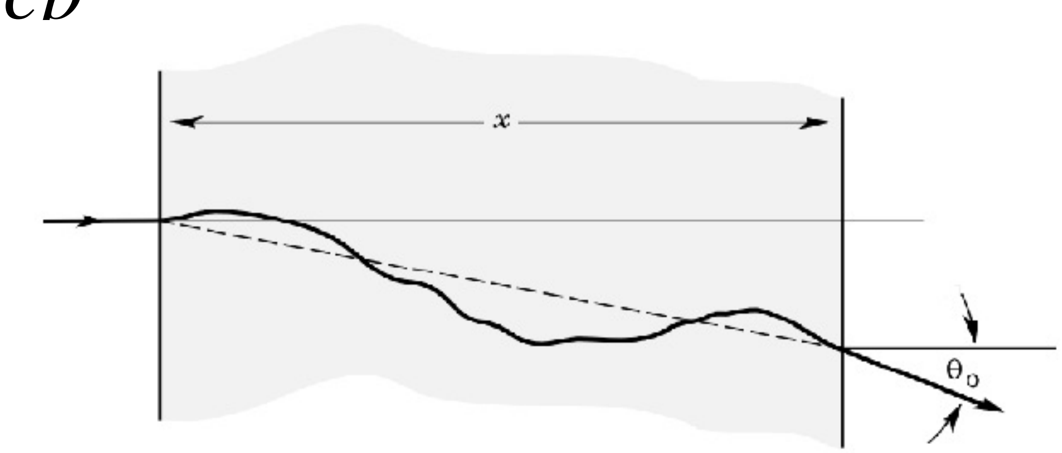
- Computed Tomography
  - Absorption: Photon (X-ray), neutron, muon, ···
  - Energy loss: Proton, ···
  - **Multiple Coulomb Scattering (MCS) with high energy electron**
    - ✦ Gaussian width of the deflection angle distribution: (Highland's approximation of the Moliere's theory)

$$\Theta_0 = \left(\frac{13.6\ \mathrm{MeV}}{\beta c p} z\right)\sqrt{\varepsilon}\,(1 + 0.038 \ln \varepsilon)$$

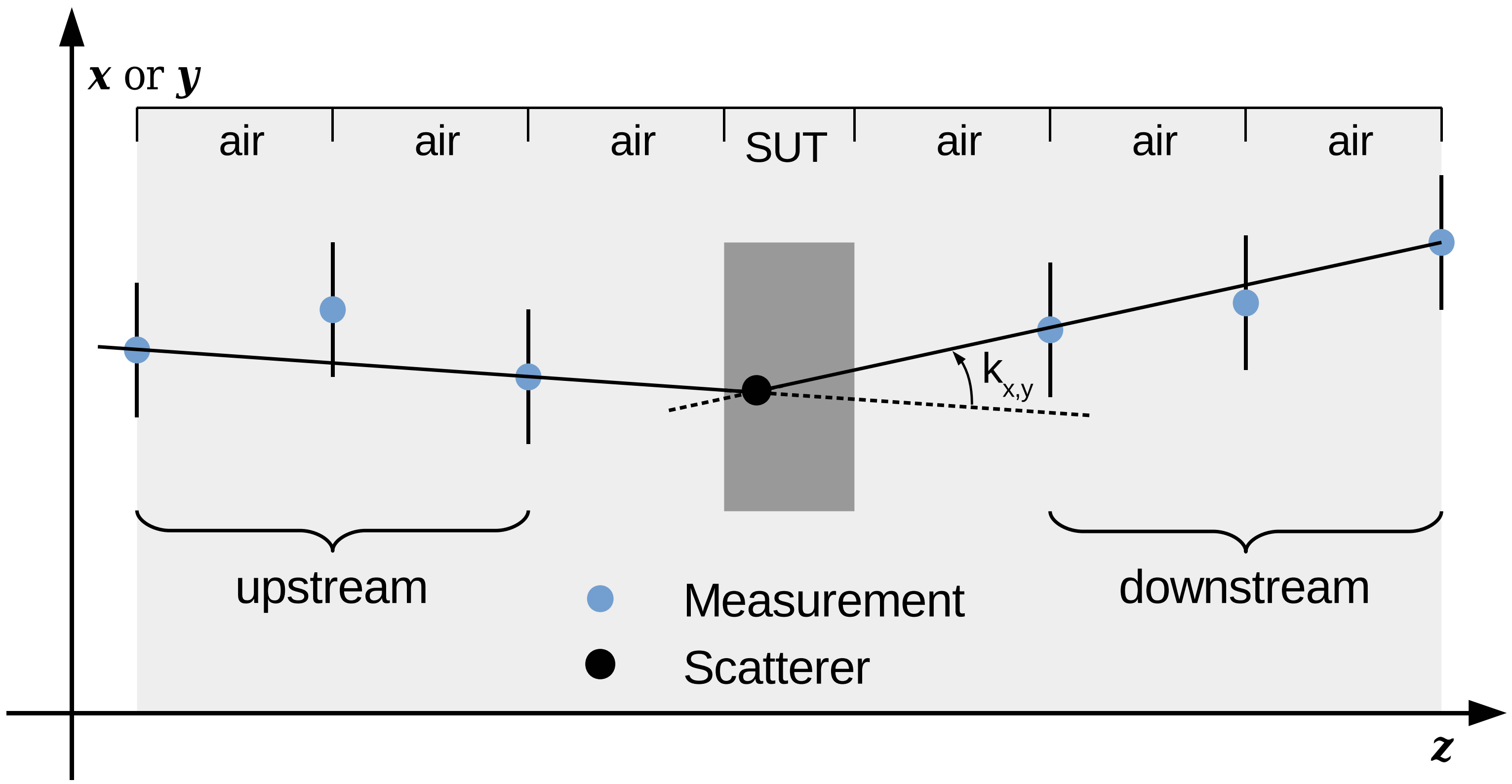
path length

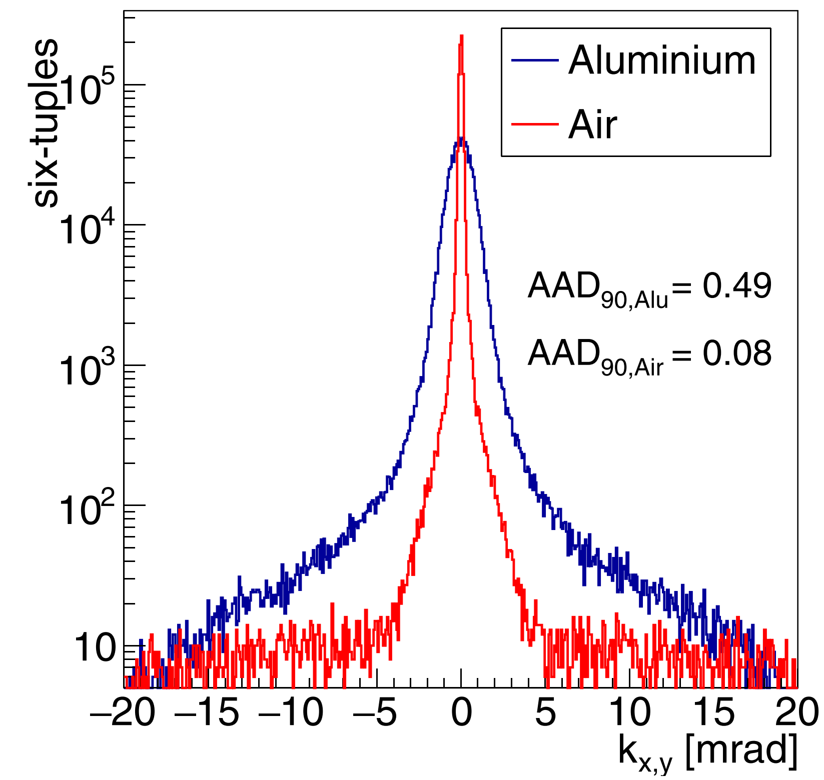
$$\left(\varepsilon = \frac{x}{X_0}\right)$$

radiation length



Track-based multiple scattering tomography





- Measure the hit positions of individual electrons on sensor planes upstream and downstream of the sample under test (SUT)

- Reconstruct the tracks and calculate the scattering angle ($k_{x,y}$)

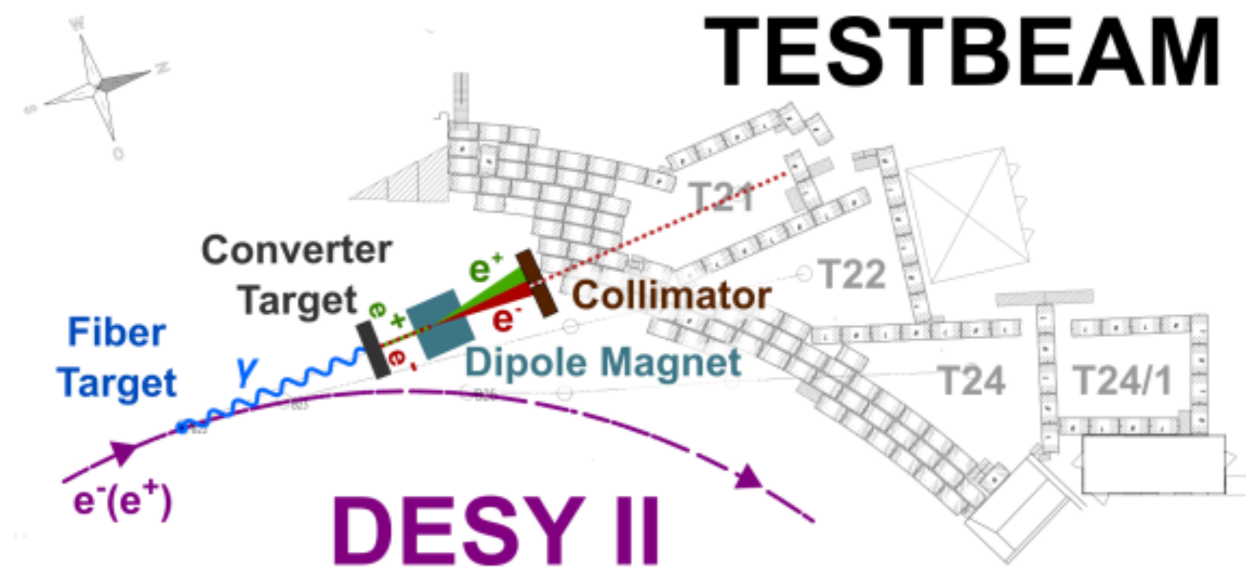
- We use absolute deviation of the distribution's inner 90% quantile (<u>AAD_{90}</u>) to calculate Θ_0

Potentials of Material Budget Imaging

- Potentials
  - Non-destructive imaging of <u>high-Z</u> materials [>1 GeV electron]
  - Medical imaging for treatment planning [O(100) MeV electron]
    - ✦ Low dose, better spatial/density resolution, less metal artifacts
- Challenges
  - Statistics: high rate data acquisition and beam rate
  - Detector size

Test beam Experiment at DESY

Hamburg-Bahrenfeld

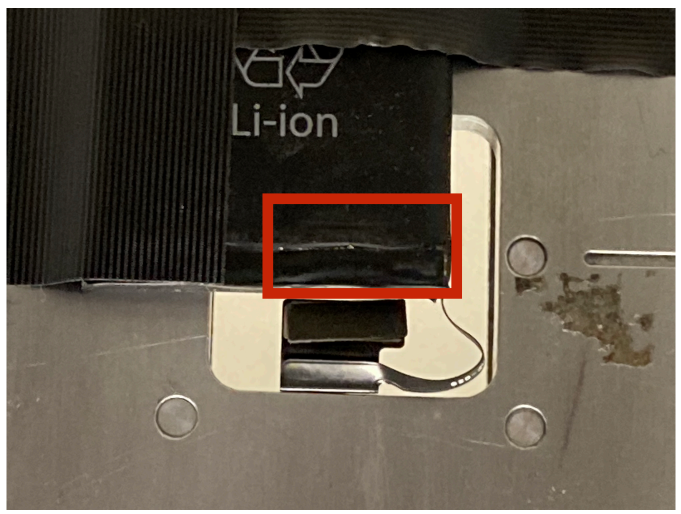


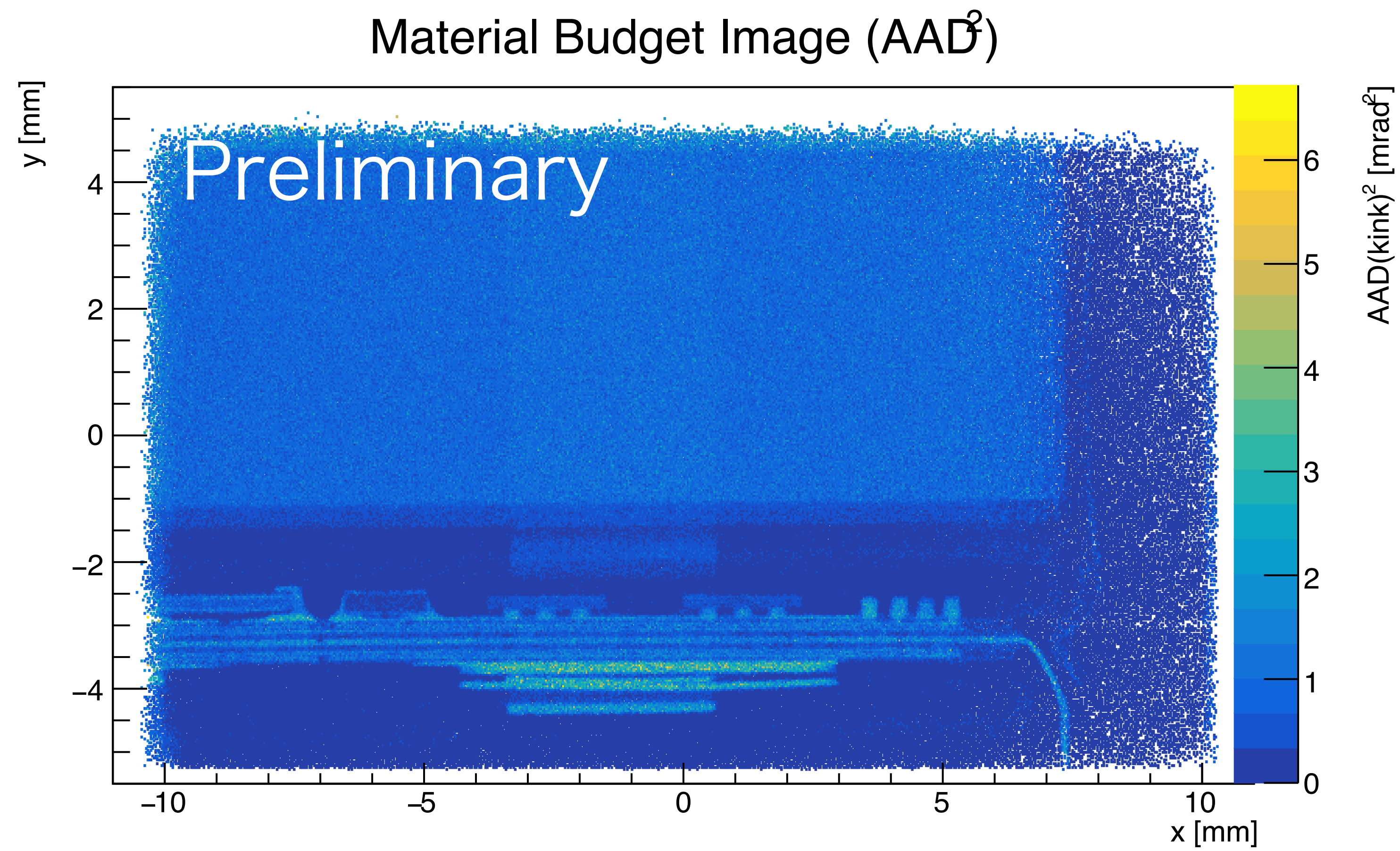
- We performed test beam experiment on June 2020
- Independent electron beam at DESY II synchrotron
- User selectable energy: O(100) MeV ~ 6 GeV

EUDET-type Telescope

- 6 silicon pixel sensors (MIMOSA26)
  - Pitch: 18.4 μm × 18.4 μm
  - Area: 10.6 mm × 21.2 mm
  - Intrinsic sensor resolution: > 3.24 μm
- 4 PMTs for coincidence trigger

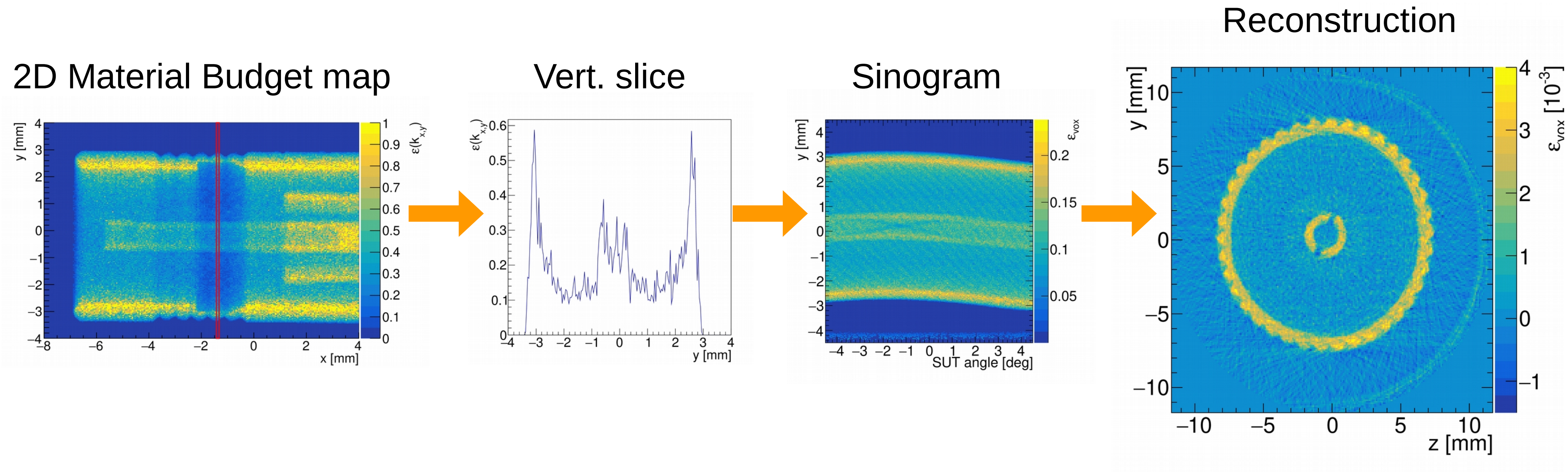
2D Material Budget Imaging





- SUT: small Lithium-ion battery
- The AAD^2 distribution shows the fine inner structure of the battery

Electron CT



(Ref: APPLIED PHYSICS LETTERS 112, 144101)

- Measurement with different rotation angles to create a sinogram
- Reconstruction algorithm
  - Filtered back projection (FBP)
  - Iterative reconstruction?

Iterative Image Reconstruction

$$\vec{y} \Rightarrow \vec{y} = A\vec{x} \Rightarrow \vec{x}$$

Data

Model

Image (Truth)

Suppose that: $\vec{y} = A\vec{x} + \vec{n}$

noise

$$J(\vec{x}) = \|A\vec{x} - \vec{y}\|^2$$

$$A^T A\vec{x} = A^T\vec{y} \quad (\text{minimize } J(\vec{x}) \to \partial J(\vec{x})/\partial \vec{x} = 0)$$

Landweber method:

$$\vec{x}^{(k+1)} = \vec{x}^{(k)} + \alpha A^T(\vec{y} - A\vec{x}^{(k)})$$

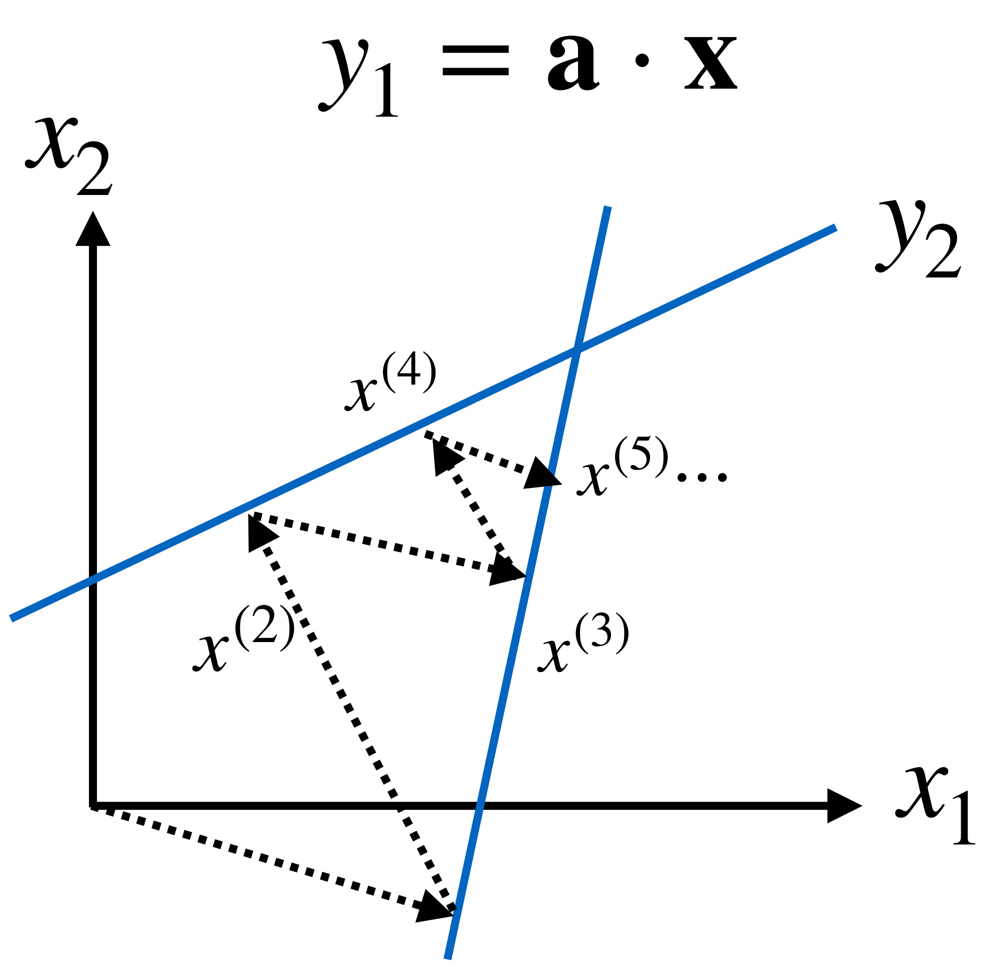
$$\vec{x}^{(k+1)} = \vec{x}^{(k)} + \sum_{i=1}^{I} \alpha \|\vec{a}_i\|^2 \frac{y_i - \vec{a}_i \cdot x_i^{(k)}}{\|\vec{a}_i\|^2}\vec{a}_i$$

Simultaneous iterative reconstruction technique (SIRT)

Projection method

$$\overrightarrow{x}^{(k+1)} = \overrightarrow{x}^{(k)} + \cancel{\sum_{i=1}^{I} \alpha \|\overrightarrow{a_i}\|^2} \frac{y_i - \overrightarrow{a_i} \cdot x_i^{(k)}}{\|\overrightarrow{a_i}\|^2} \overrightarrow{a_i}$$

= 1 → Algebraic reconstruction technique



$$\mathbf{y} = (y_1, y_2)^T$$

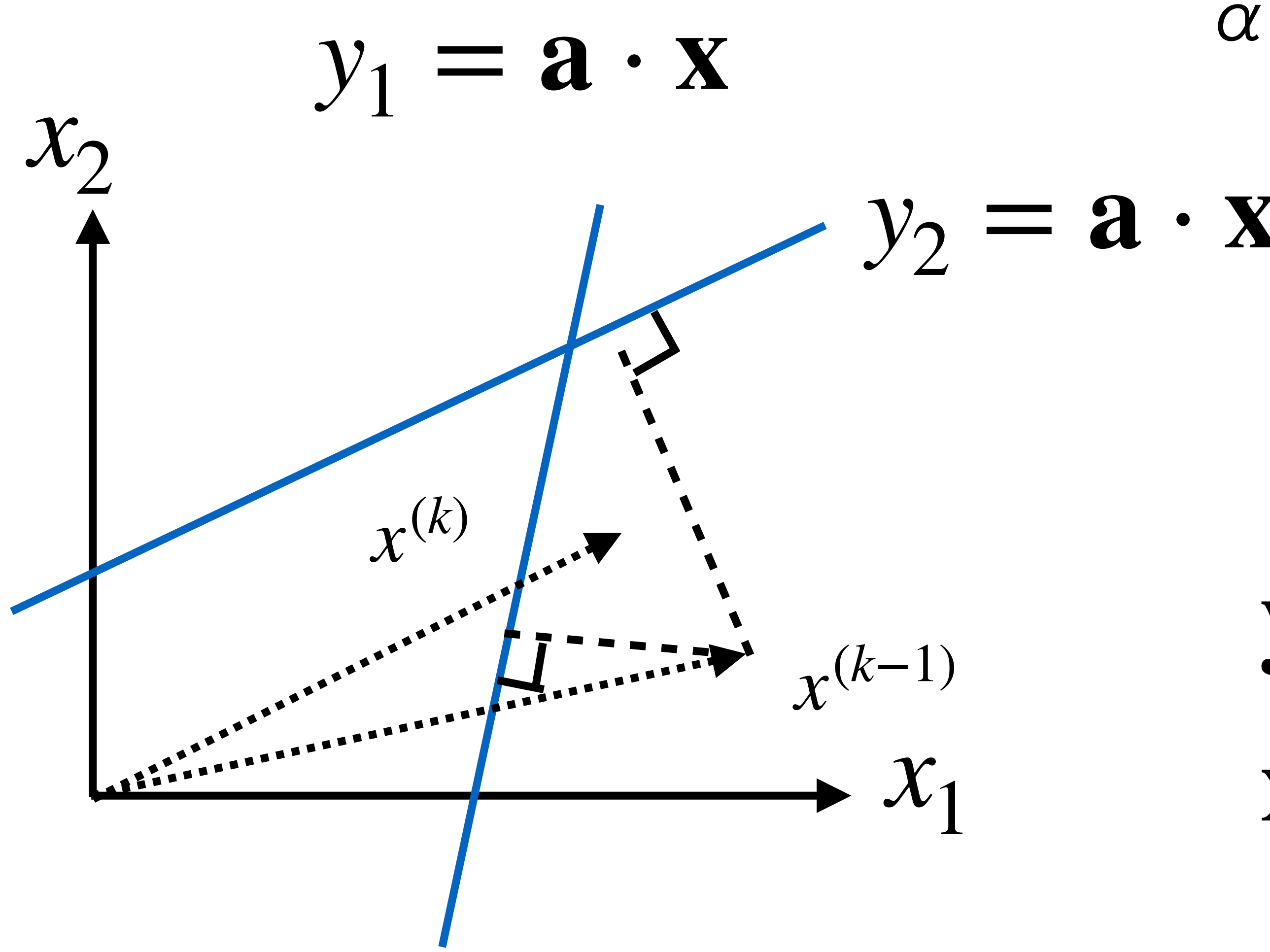
$$\mathbf{x} = (x_1, x_2)^T$$

SIRT Projection

$$\overrightarrow{x}^{(k+1)} = \overrightarrow{x}^{(k)} + \sum_{i=1}^{I} \alpha \|\overrightarrow{a_i}\|^2 \frac{y_i - \overrightarrow{a_i} \cdot x_i^{(k)}}{\|\overrightarrow{a_i}\|^2} \overrightarrow{a_i}$$

Simultaneous projection with weighting $\sum_{i=1}^{I} \alpha \|\overrightarrow{a_i}\|^2$

α: step size (free parameter)



$$\mathbf{y} = (y_1, y_2)^T$$

$$\mathbf{x} = (x_1, x_2)^T$$

Comparison between FBP

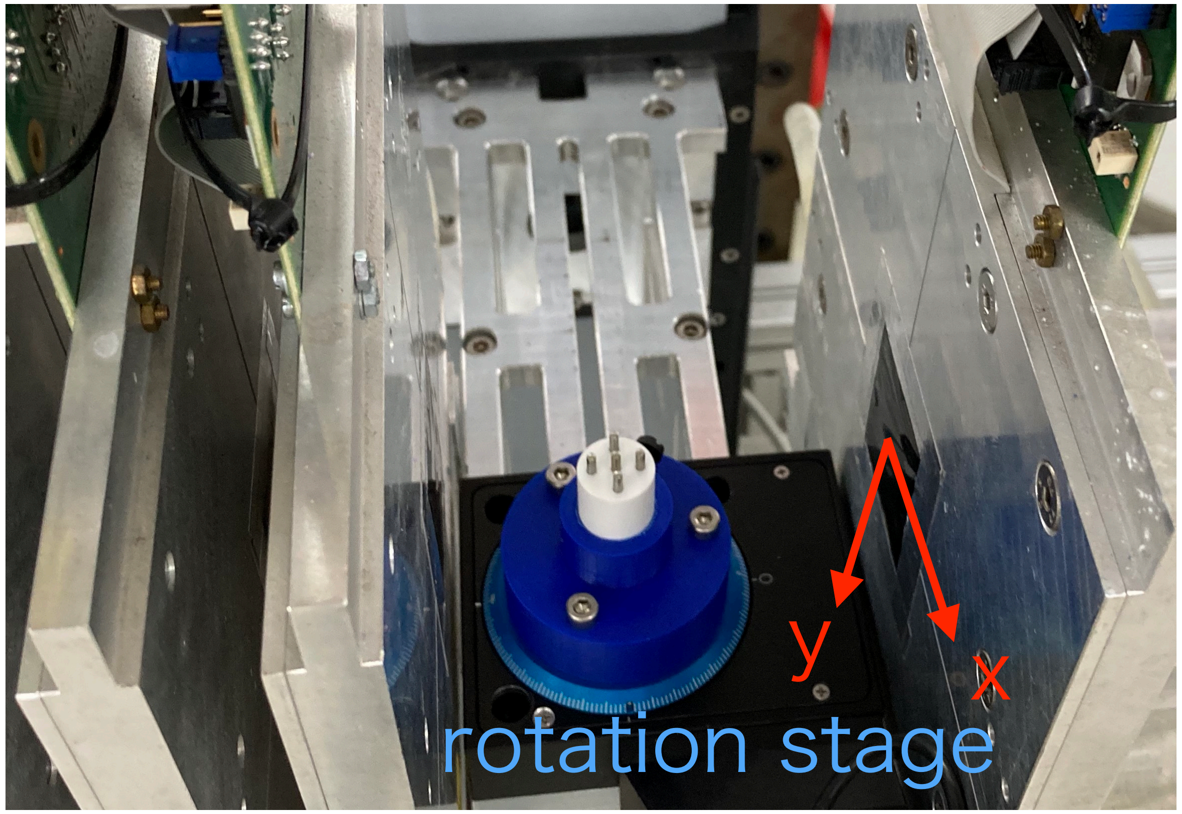
- Computing time 😥
  - Concurrent processing in forward/back projection
- Statistical noise 🤔
  - Unknown statistical noise of the width (AAD_{90}) of the scattering angle distribution
- Regularization 🙂
  - Many variety of the regularization term can be implemented in the iterative algorithm

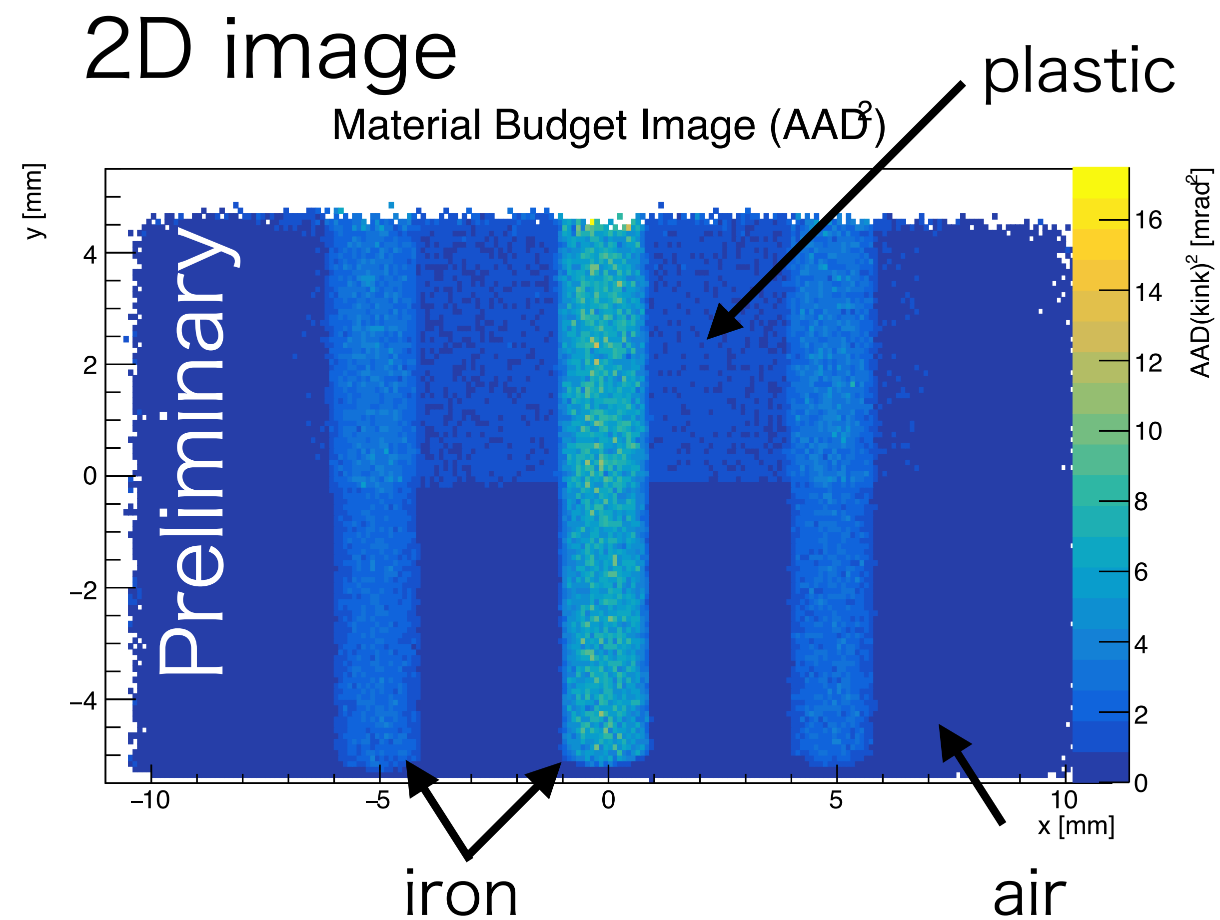
U(x): energy function

$$\overrightarrow{x}^{(k+1)} = \overrightarrow{x}^{(k)} + \alpha \left[A^T(\overrightarrow{y} - A\overrightarrow{x}^{(k)}) + \beta \frac{\partial U(\overrightarrow{x})}{\partial \overrightarrow{x}} \right]$$

Function: quadratic, gaussian, total variation, ⋯

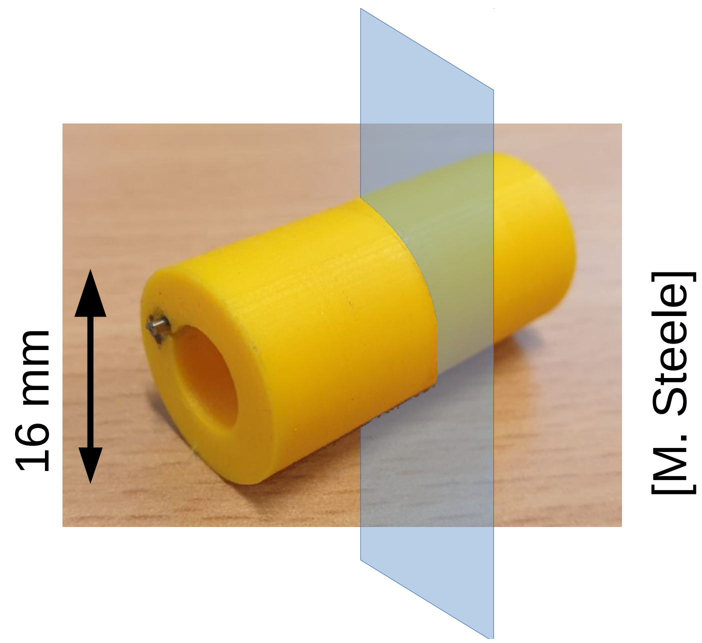
Alignment Phantom

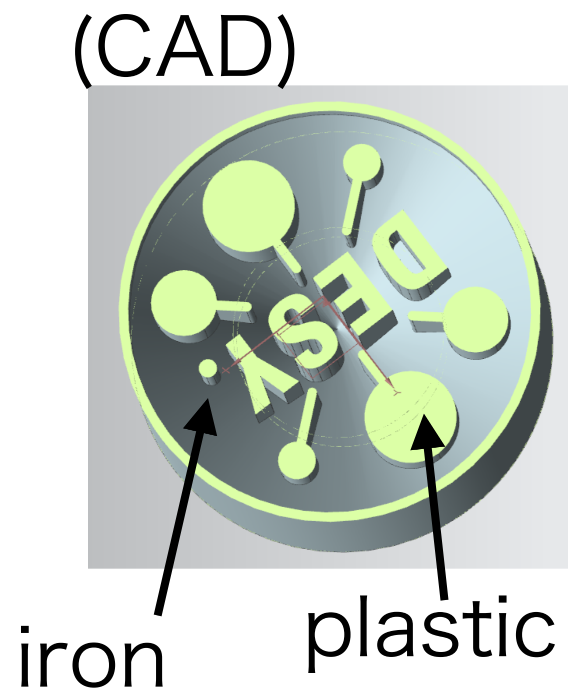




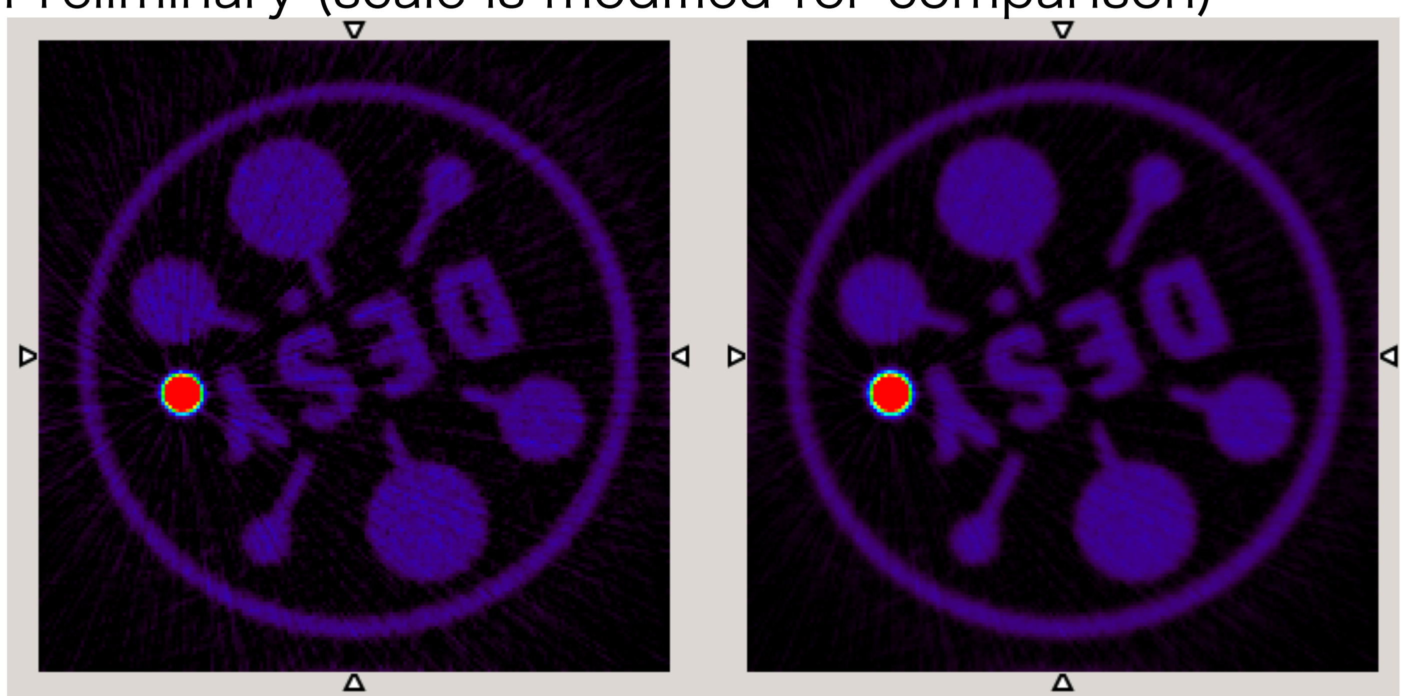
- 5 iron rods in a half-length plastic cylinder
- Online monitoring was performed to fix the position of the rotation stage
- 360° scan with 0.9° step scan for 3D image reconstruction (= 400 projections)

DESY Logo Phantom





Preliminary (scale is modified for comparison)



w/o regularization w/ regularization

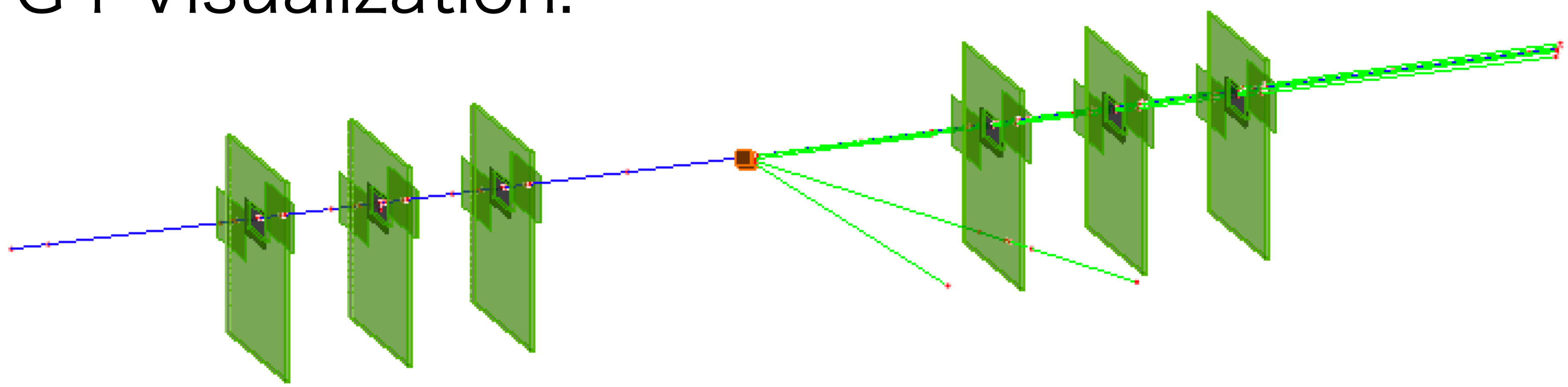
- 40 iterations
- Regularization reduces the noise
  - Energy function: quadratic (smooth the image)

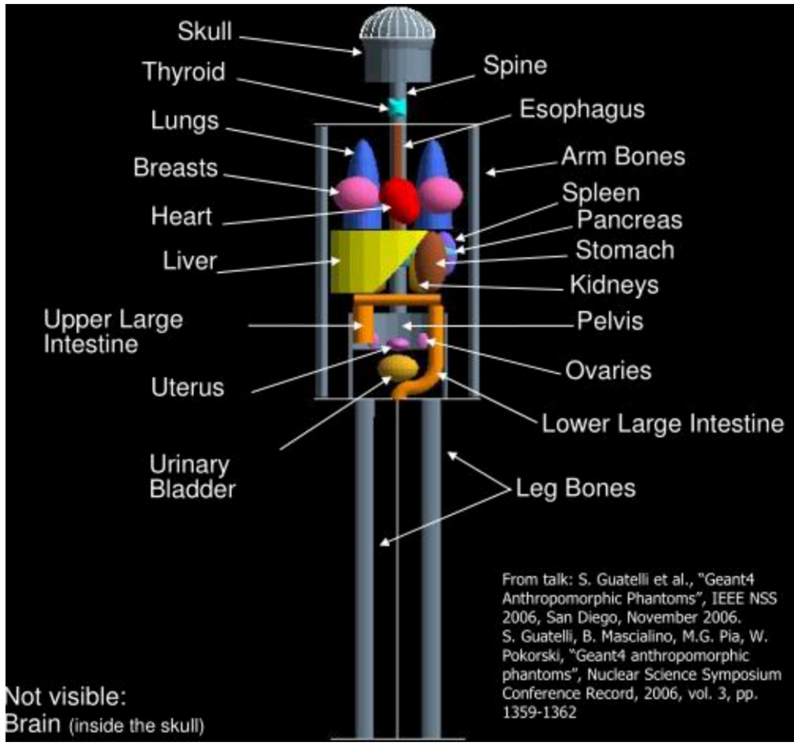
Quantitative study is on-going!

Toward the Electron CT for Medical Imaging

https://www.slideserve.com/taylor/gean4-human-phantom-advanced-example-a-geant4-anthropomorphic-model

G4 Visualization:





- All-pix^2 simulation framework
  - https://project-allpix-squared.web.cern.ch/project-allpix-squared/
  - Based on Geant4 toolkit
- Study of systematical effect
  - Mechanical misalignment, metal artifacts, most likely path estimation, …
- Feasibility study of medical imaging with O(100) MeV electron
  - Target: Anthropomorphic model with GDML
  - CNR, resolution, dose, …

Conclusions

- Material Budget Imaging/Electron CT has potentials for non-destructive imaging and clinical imaging
- Test beam experiment was performed at DESY in June
- Iterative image reconstruction algorithm was developed for 3D reconstruction
  - Regularization contributes to the noise reduction
- MC simulation has been developed for systematic study and clinical imaging

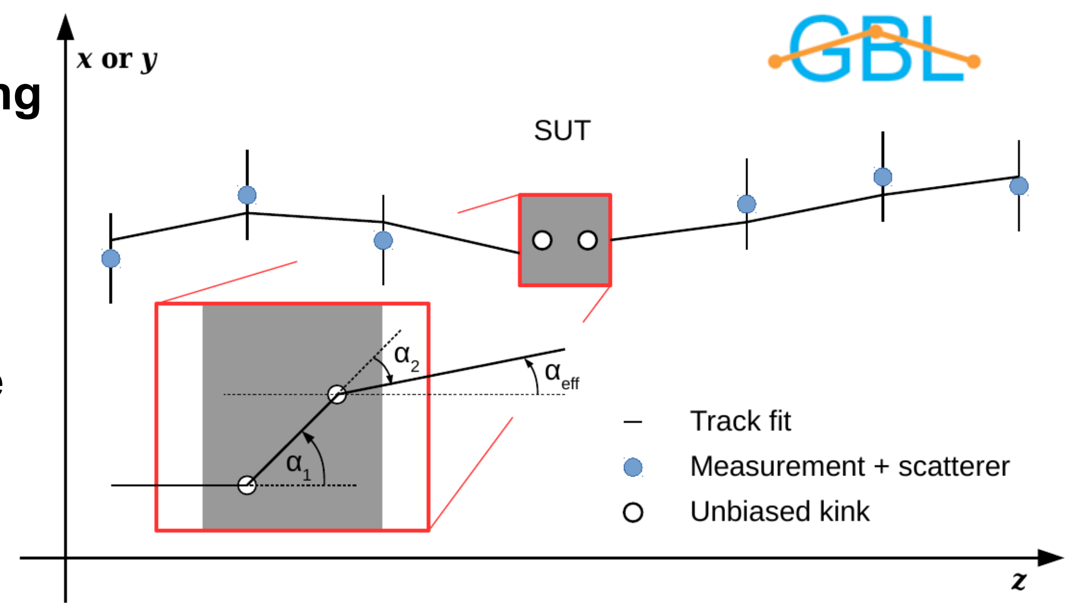
Any ideas/comments are welcome!

Backups

Track reco and width estimation

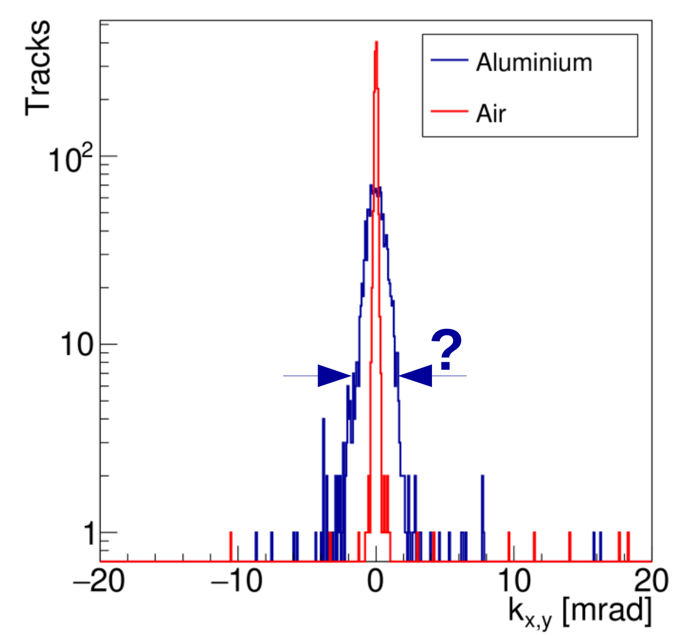
General Broken Lines (GBL) for track fitting

- Find the most probable trajectory based on the measured hits
- Includes known MB at planes
- Introduces unbiased kink at the sample



Method for width estimation

- Calculate *Average Absolute Deviation* of the inner 90% quantile
- Best performance out of 11 tested fitting and statistical methods
- Conversion to MB via Highland formula or via calibration

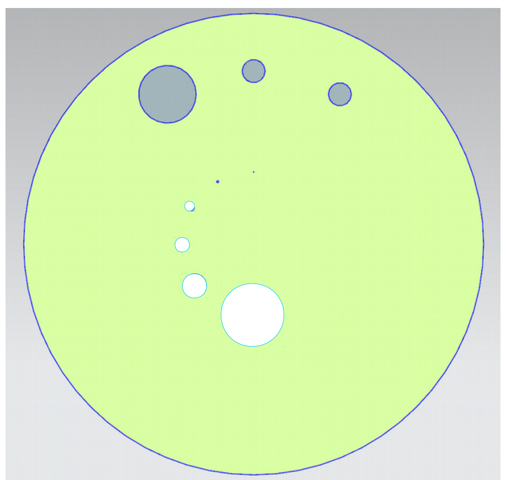


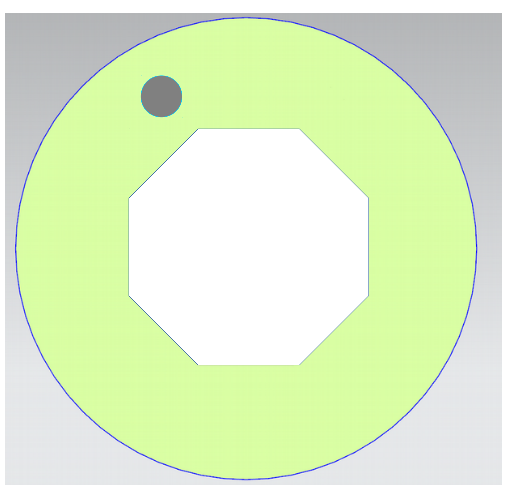
Challenges

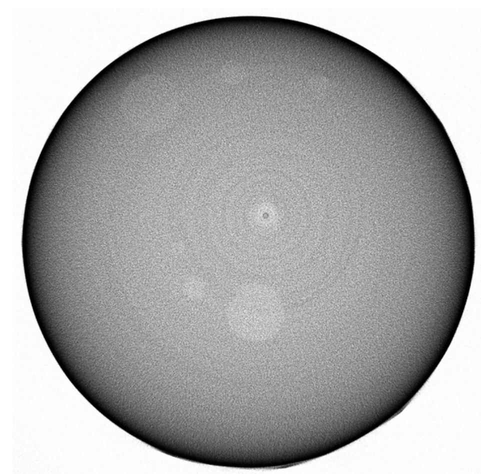
- Non-Gaussian tails of the distribution
- Low statistics

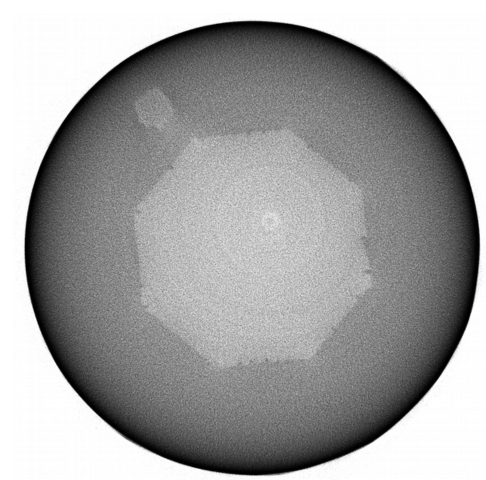
Comparison to CT

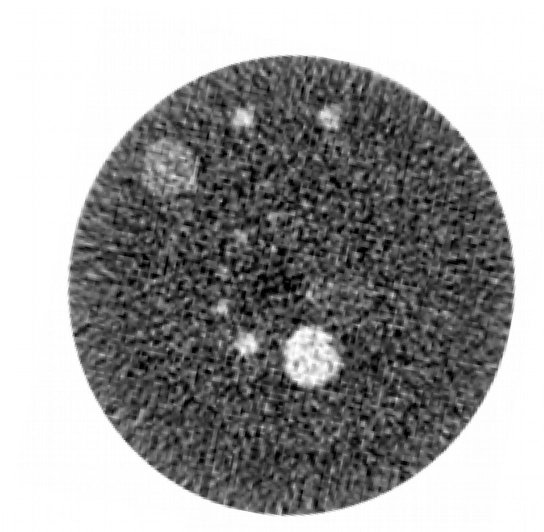
Cross-sections | **CT scan at 170 kVp (inverted grey scale)** | **MBI**

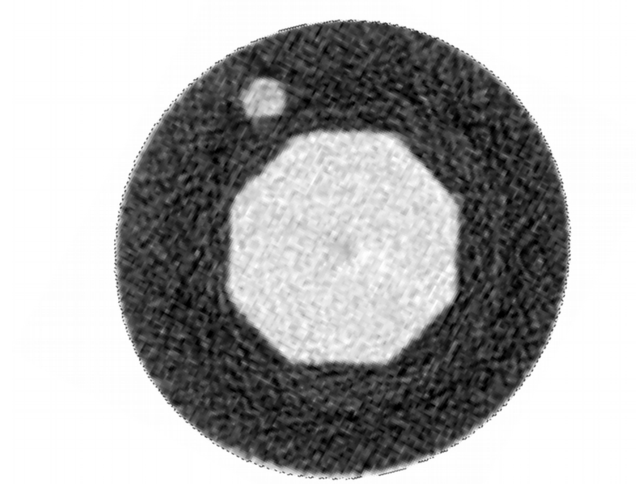






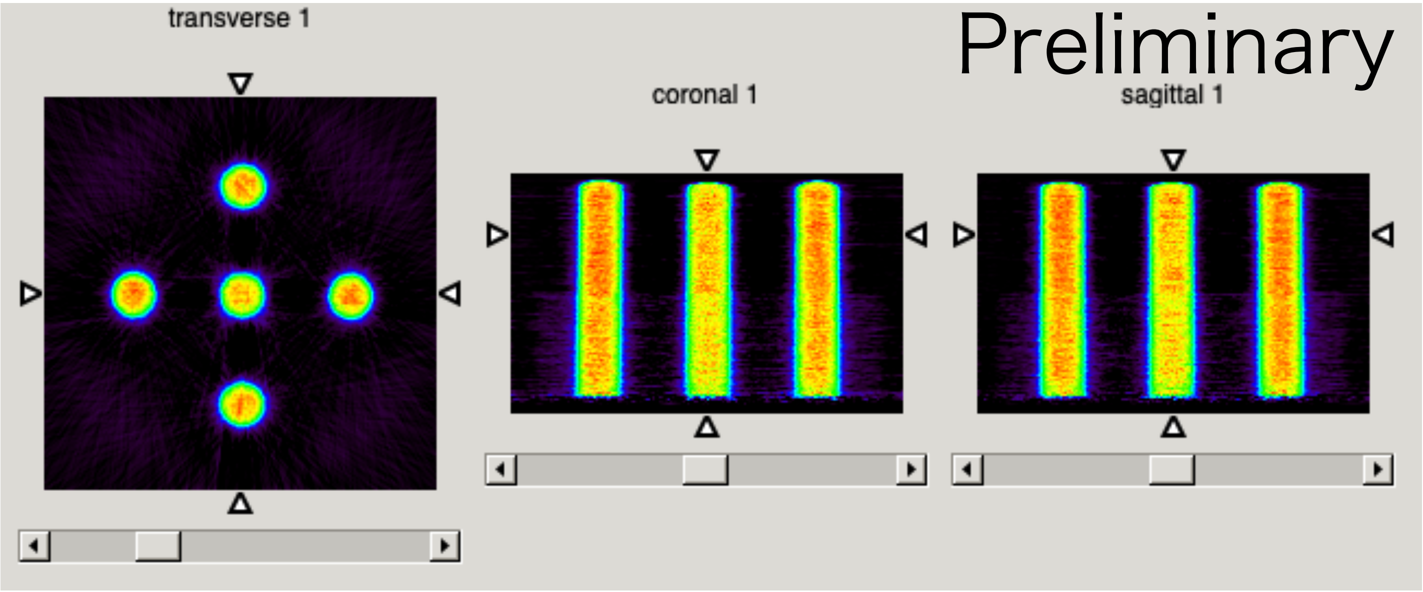




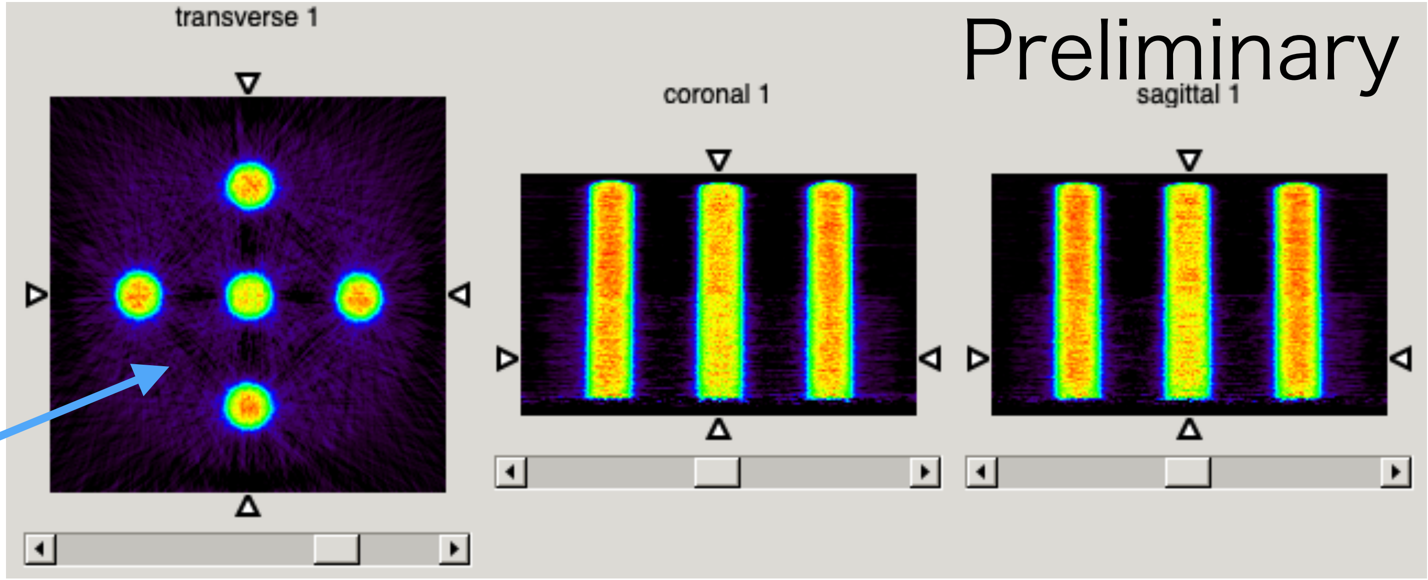


Helmholtz-Zentrum Geesthacht
Zentrum für Material- und Küstenforschung

3D reconstruction for alignment phantom



artifacts



- 10 iterations, no regularization
- Artifacts due to the absence of calibration (under study)