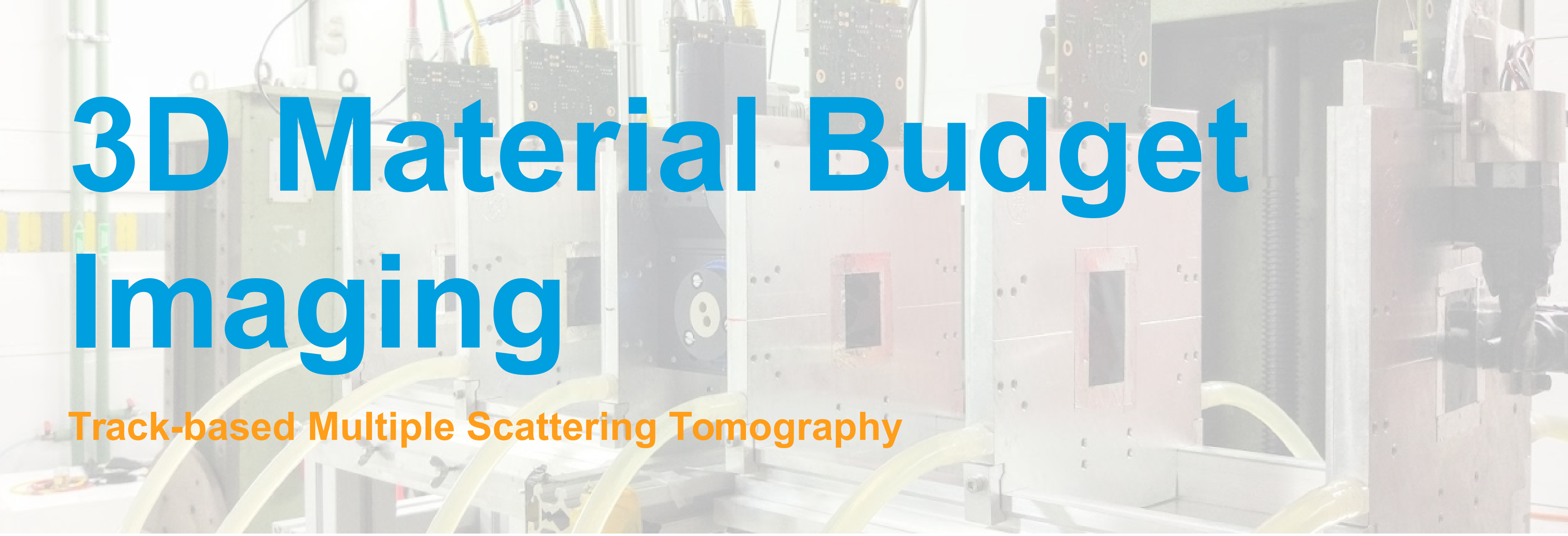


3D Material Budget Imaging

Track-based Multiple Scattering Tomography

Hendrik Jansen, Paul Schütze
BTTB6, Zürich – 17.01.2018

2D Imaging

- Setup
- Image reconstruction concept

3D Imaging

- Simulation
- Measurement
- Performance

Multiple Scattering & 2D Material Budget Imaging

Multiple Scattering & Material Budget

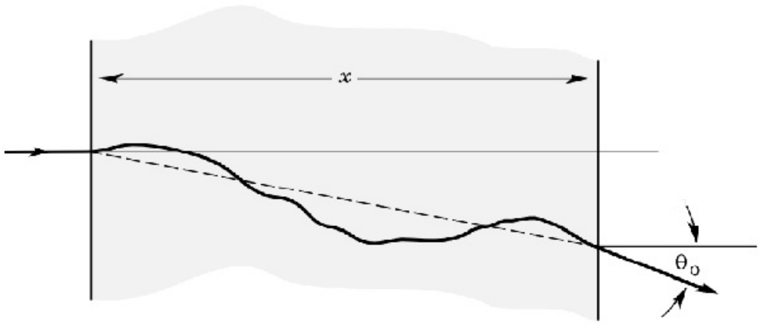
- High-energy particles undergo multiple Coulomb scattering when traversing any material
  - ➔ Particle is deflected
- Scattering angle distribution:
  Gaussian-like center with tails at larger angles
- The width of the gaussian-like center is well predicted by the Highland formula [1]:

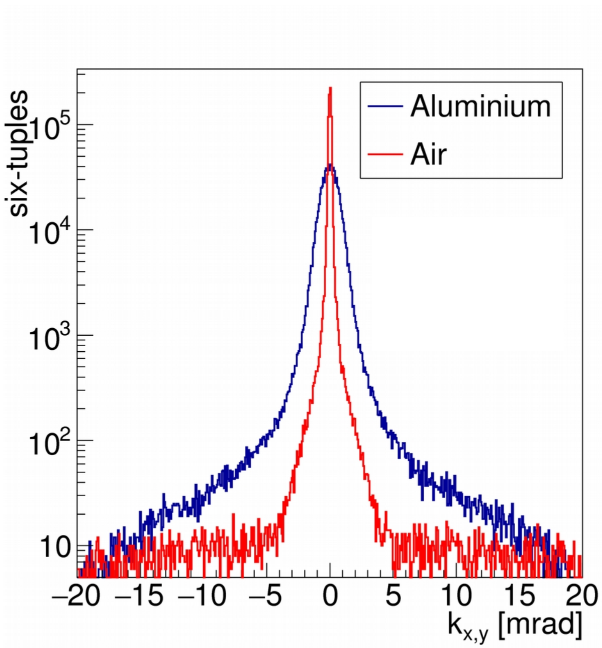
$$\theta_{x,y} = \frac{13.6\,MeV}{\beta c p}\sqrt{\frac{x}{X_0}}\left(1 + 0.038\ln\left(\frac{x}{X_0}\right)\right)$$

x: Path length in the material
X_0: Material's radiation length
$\varepsilon = x/X_0$: *Material budget*

➔ Measurement:
Scattering angle distribution

➔ Characteristic quantity:
Material budget

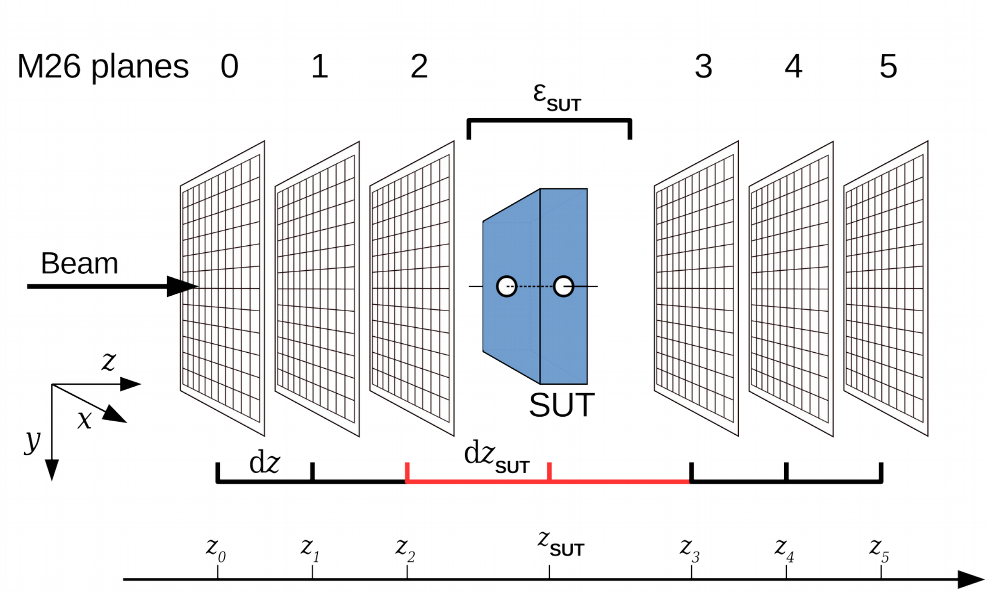




[1]: PDG, *Review of particle physics*

Material Budget Imaging – 2D

- Goal:
  - Position-resolved measurement of the material budget via the deflection angle
- Required:
  - Measurement of the scattering angle at the sample
  - Extrapolation of the track to the position of the sample
- Four steps:
  - Illuminate a sample with a charged particle **beam**
  - Measure the *hits* in the **pixel sensor** planes around it
  - Reconstruct the particles' **trajectories** through the telescope
  - Extract the **width** of the kink angle distribution

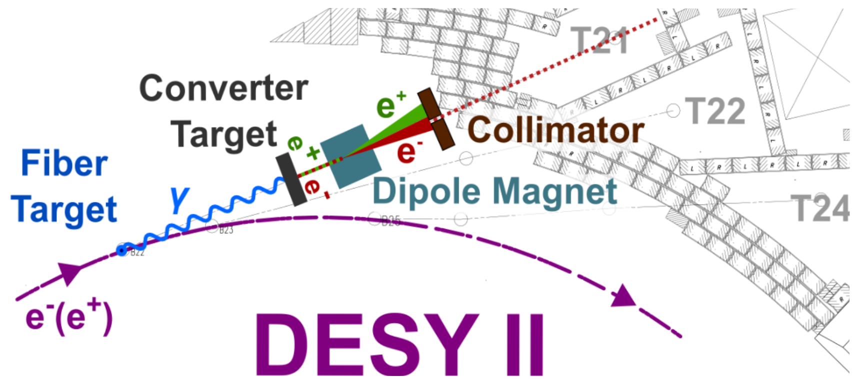


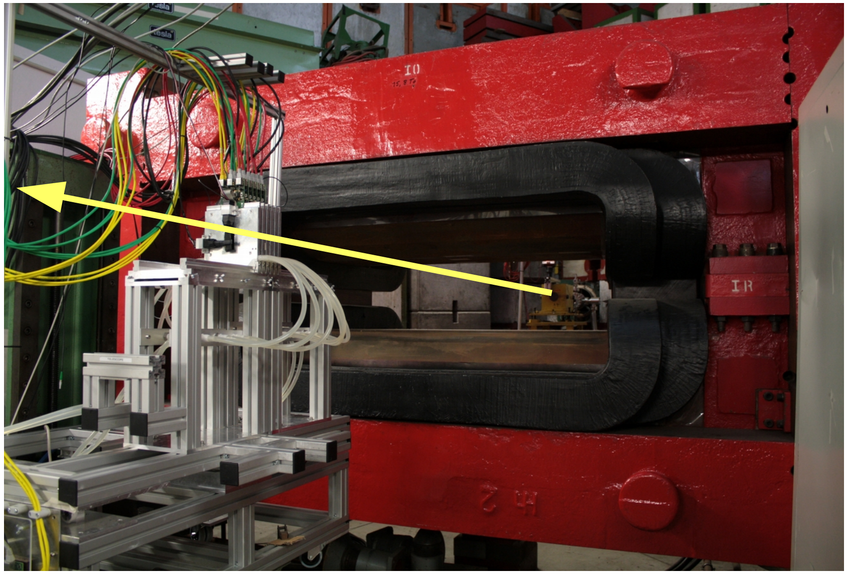
DESY II Test Beam Facility [2]

The Beam

- Free positron or electron beams created from bremsstrahlung
- Energy: 1 – 6 GeV
- Particle rate: < 50 kHz (energy dependent)
- Three beam lines available
- Two Beam Telescopes available

- This measurement (simulation):
  - TB 21 (AllPix Detector Simulation Framework)
  - 1.6 GeV positrons (5 GeV electrons)
  - DATURA Beam Telescope [3] (simulated response tuned accordingly)



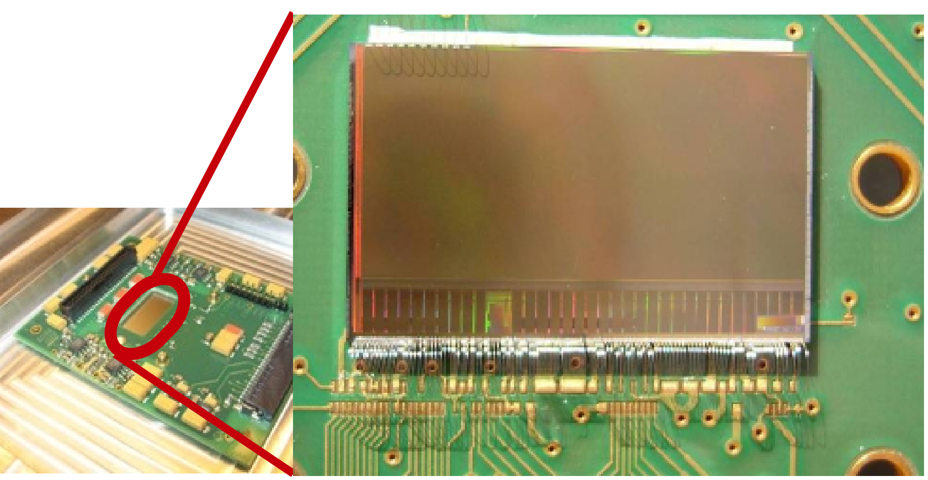


[2]: http://testbeam.desy.de
[3]: http://telescopes.desy.de

EUDET-type Beam Telescopes

The Detector

- 6 sensors: Mimosa 26
- 4 PMTs as coincidence trigger
- TDAQ system & infrastructure available
- Good track resolution (σ > 1.86 µm) due to …
  - good intrinsic sensor resolution
  - low material budget
    - ➔ Reduce multiple scattering at the sensor planes

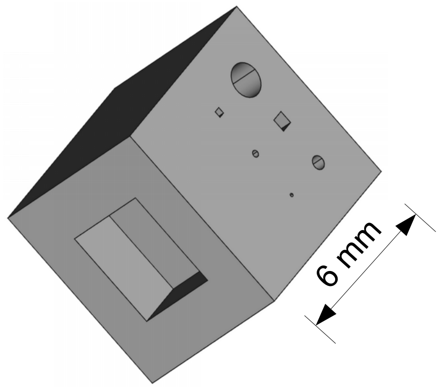


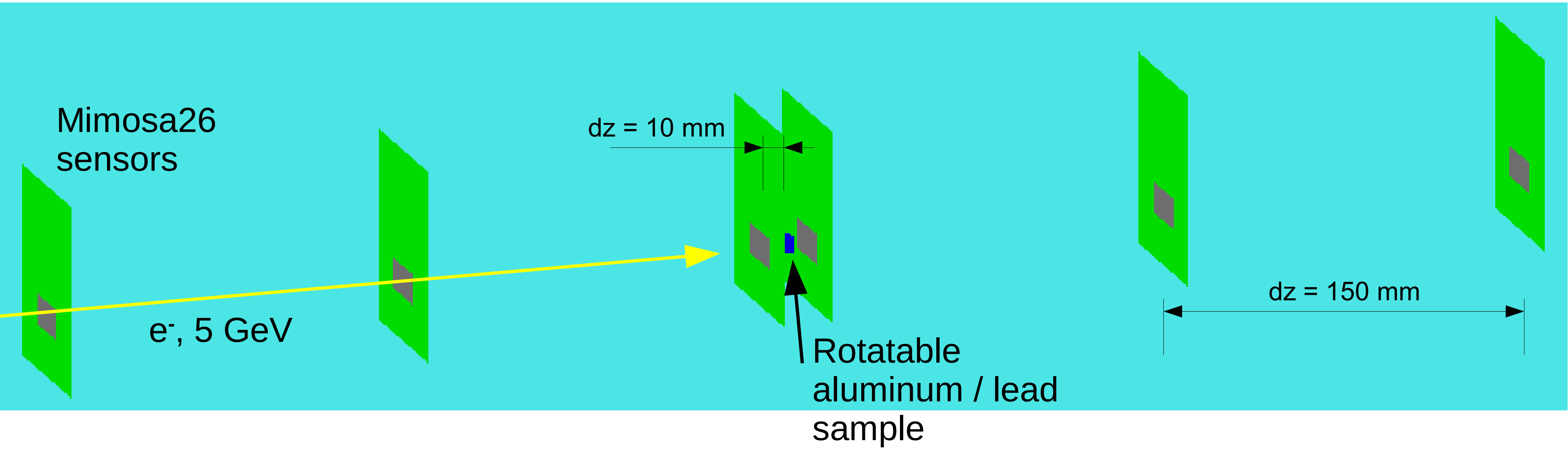
- Mimosa 26:
  - Pixel Pitch: 18.4 µm x 18.4 µm
  - Active area: 10.6 mm x 21.2 mm
  - Intrinsic sensor resolution: > 3.24 µm
  - Thickness:
    50 µm sensor + 50 µm capton foil

AllPix Detector Simulation Framework [4]

Beam / Detector for Simulation

- Particle propagation and energy deposition from *Geant4* [5]
- Includes multiple scattering in sensors and sample
- Simulates the detector response
- Setup adapted to the conditions at the DESY Test Beam Facility
- 180 data samples for rotation angles from 0° – 179°



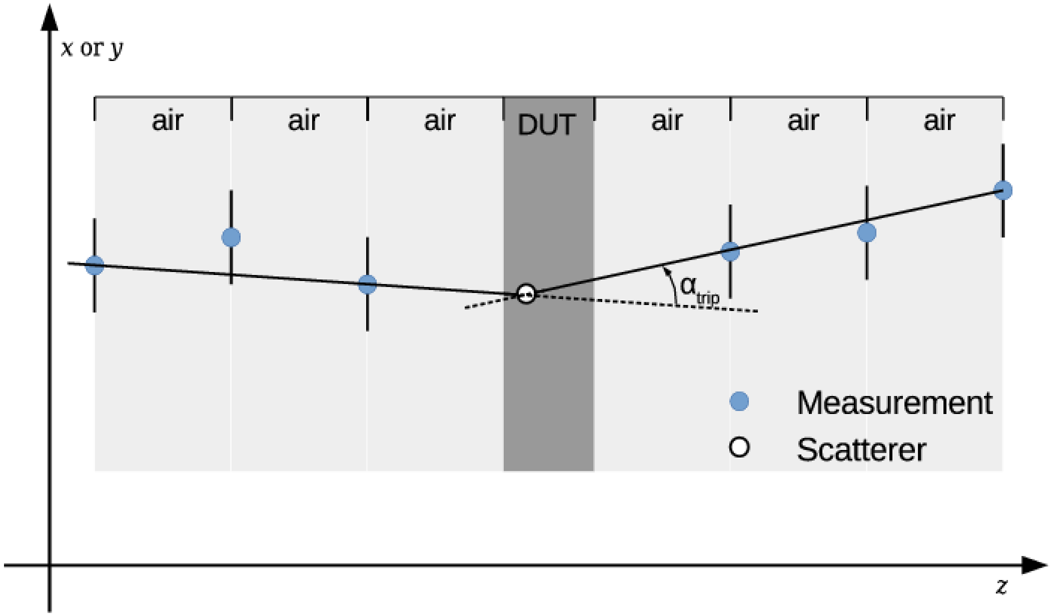


[4]: https://github.com/ALLPix/allpix
[5]: http://geant4.cern.ch/

Track Reconstruction

The Track

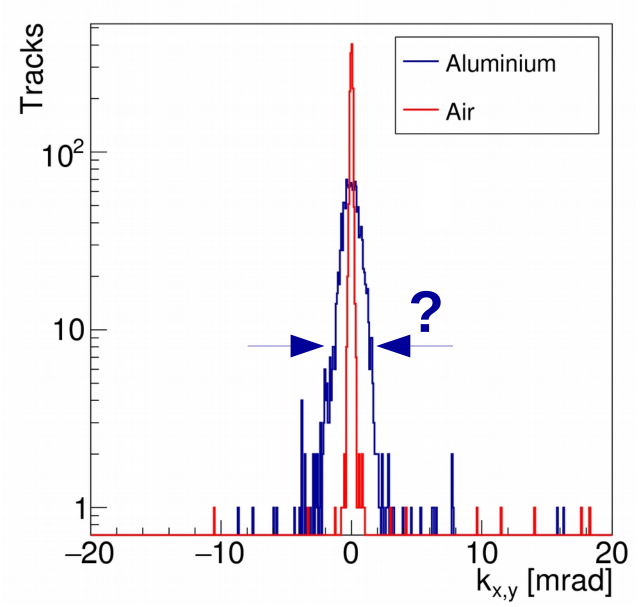
- Triplet Method:
  - Matching hits in upstream (*downstream*) planes form **triplets**
  - Matching upstream and downstream triplets form **track** candidates
  - Kink angle at the sample: Difference of upstream and downstream slopes



Material Budget Estimators

The Width

- Needed:
  - The width of the kink angle distribution for each image cell
    - ➔ Calculate the MB via Highland formula
- Challenges:
  - Non-gaussian tails of the distribution
  - Low statistics
- Possible methods:
  - Calculate RMS
  - Calculate Median Absolute Deviation (MAD)
  - Calculate Average Absolute Deviation (AAD)
  - Fit Gaussian distribution
  - Fit Student's t-distribution (modeling of tails)
  - Many more …

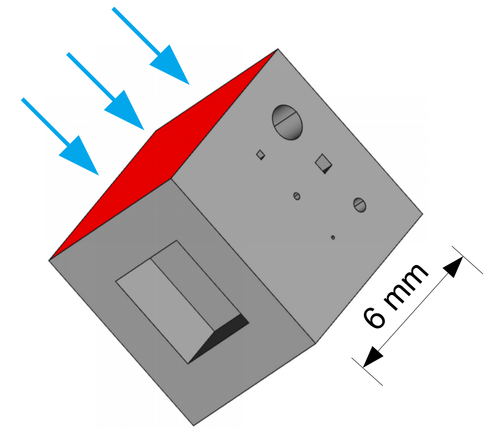


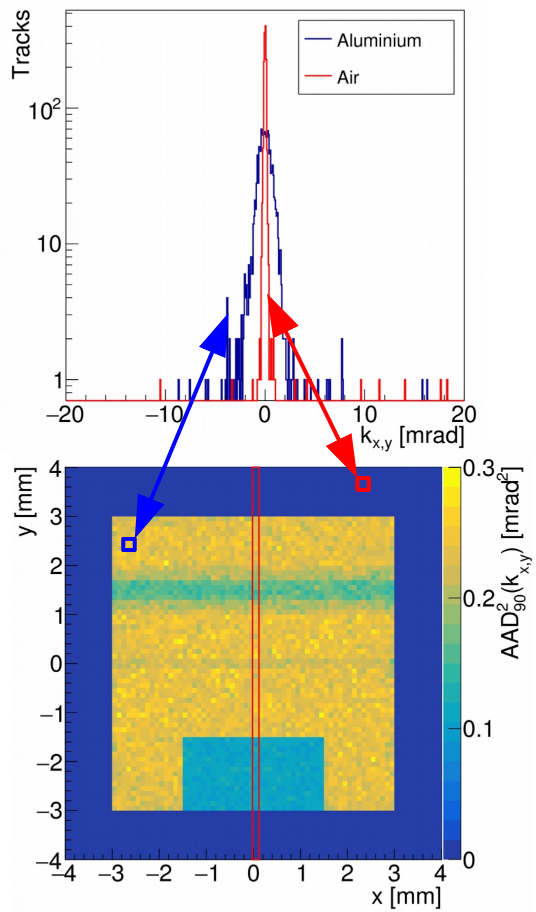
… for the full dataset or inner XX% quantiles

Material Budget Estimators

The Width

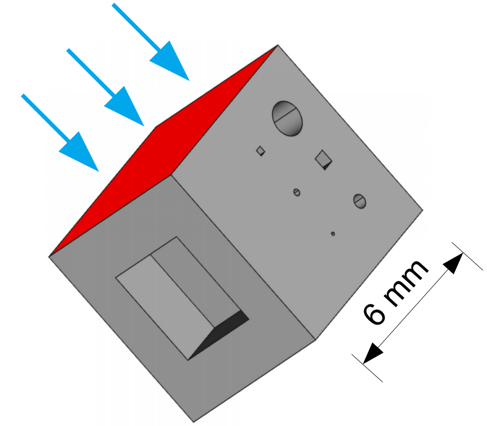
- Tested several methods on a 2D image of a simulated sample
- In regions of air, 3mm and 6mm of aluminum, compare the mean and the standard deviation of the different estimators
  - ➔ Gives a measure on the robustness of the estimator and therefore the image contrast





Material Budget Estimators

The Width



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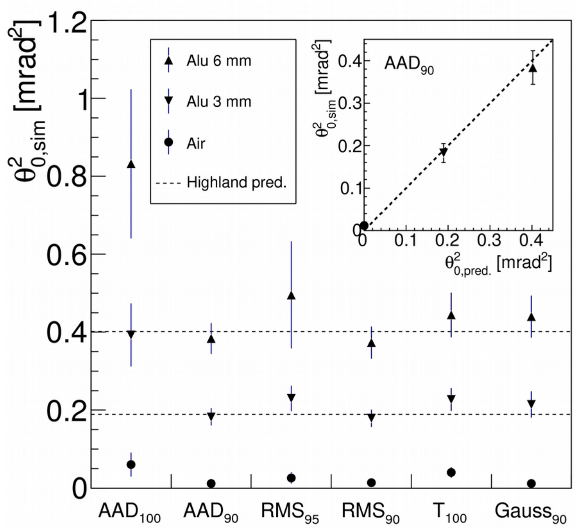
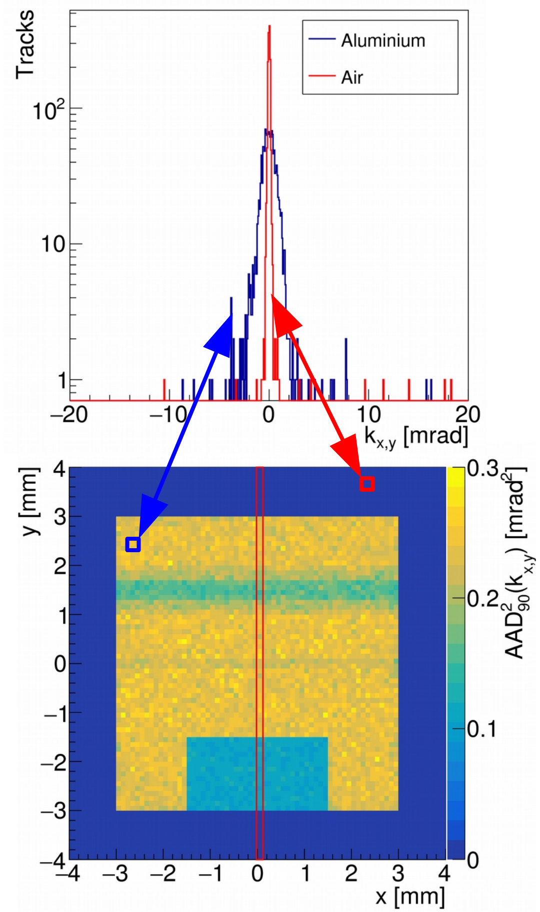




➔ Using quantiles is more robust due to the neglected tails

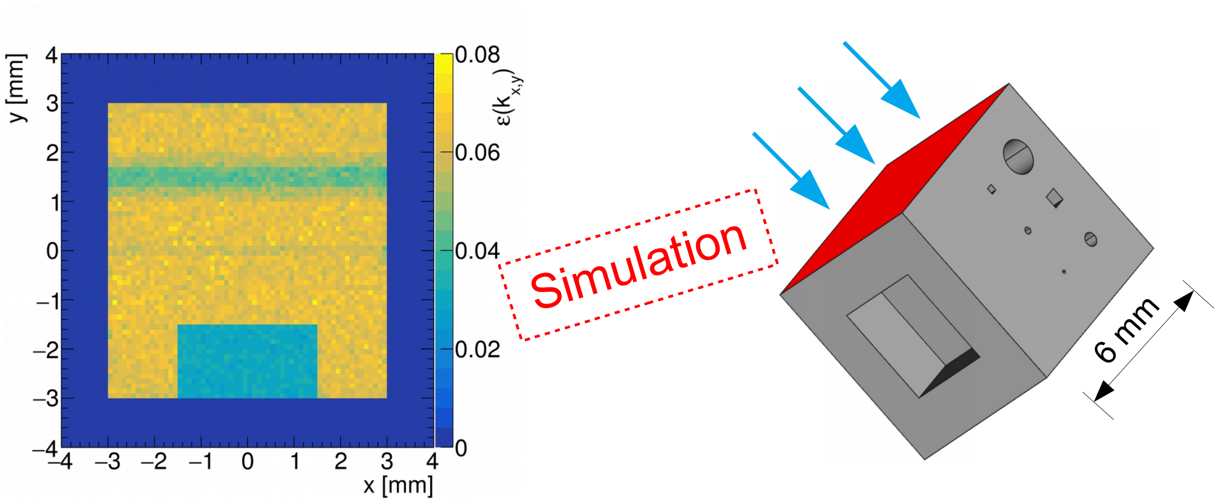
➔ Fitting is not always better

➔ AAD90 yields the highest contrast + matches prediction

Material Budget Imaging – 2D

Image Reconstruction

- Map the distributions’ widths of each image cell to yield a projection of the material budget



Material Budget Imaging – 2D

Image Reconstruction

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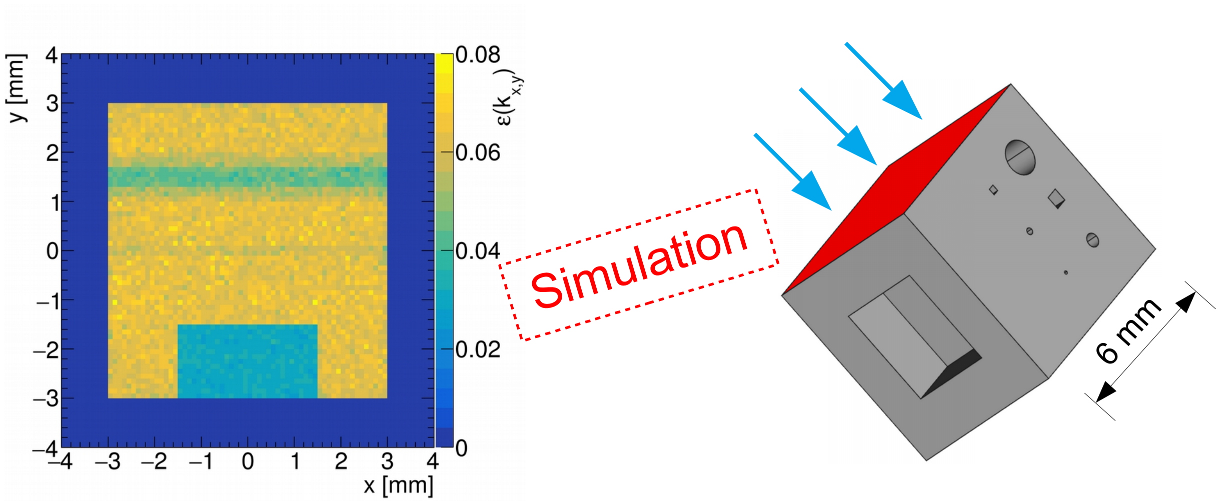

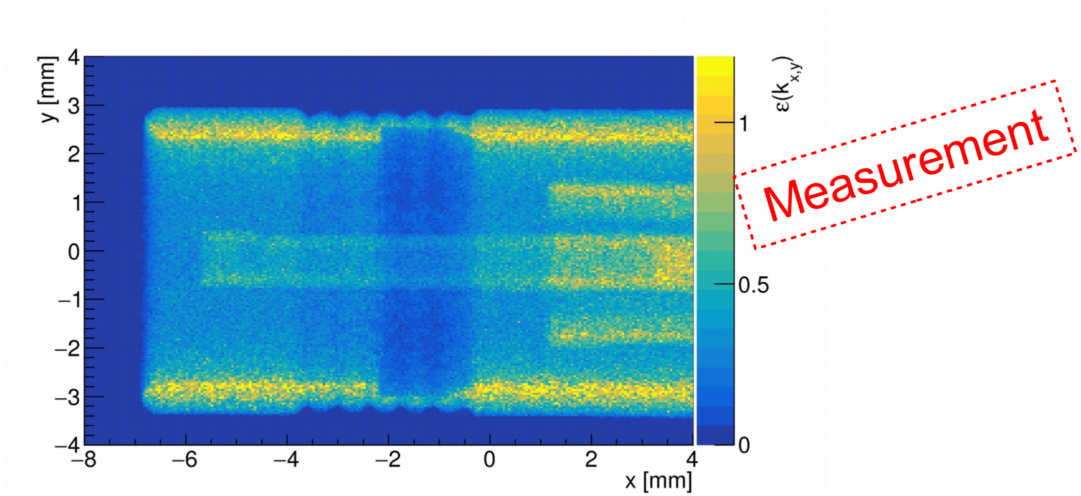

Material Budget Imaging – 2D

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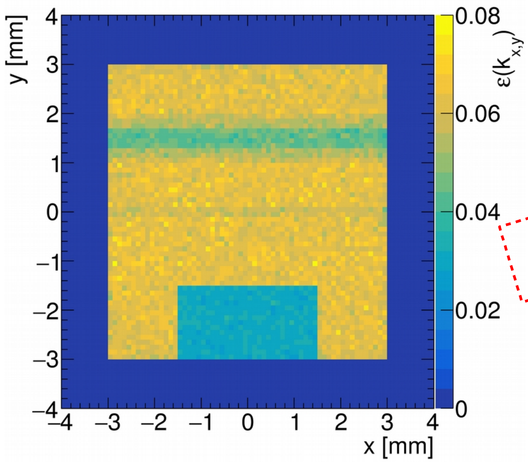
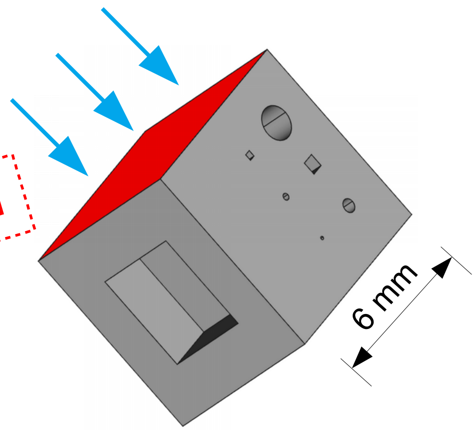
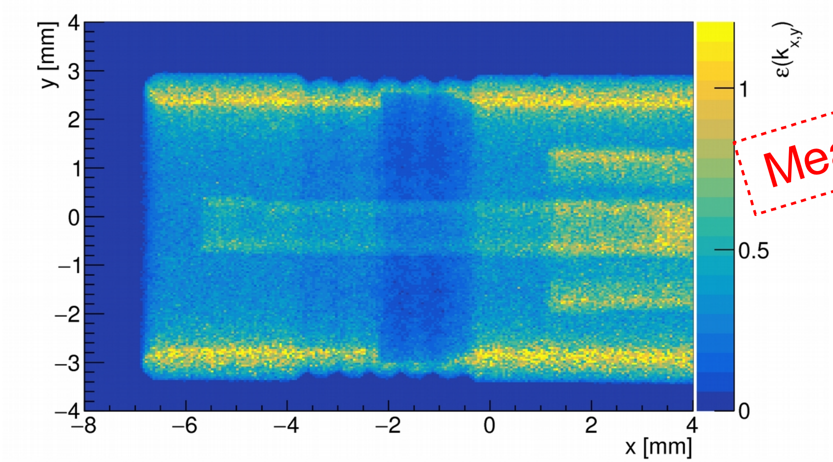
- Map the distributions' widths of each image cell to yield a projection of the material budget

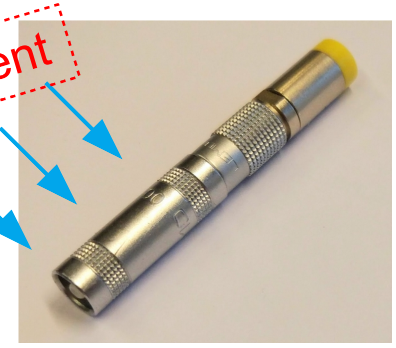


Simulation





Measurement



Material Budget Imaging – 3D

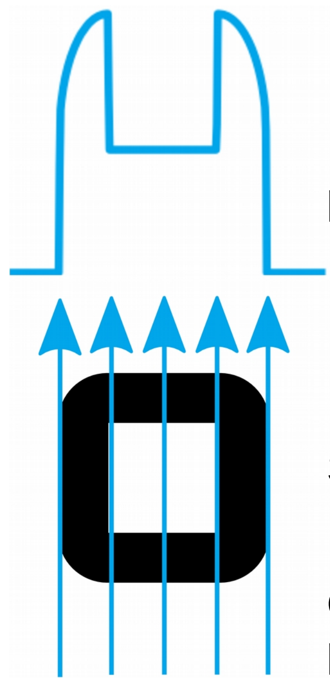
Track-based Multiple Scattering Tomography

Simulation

Material Budget Imaging – 3D

Concept

- Goal:
  - Reveal the inner structure of a sample from only measuring its projections



Measured projection

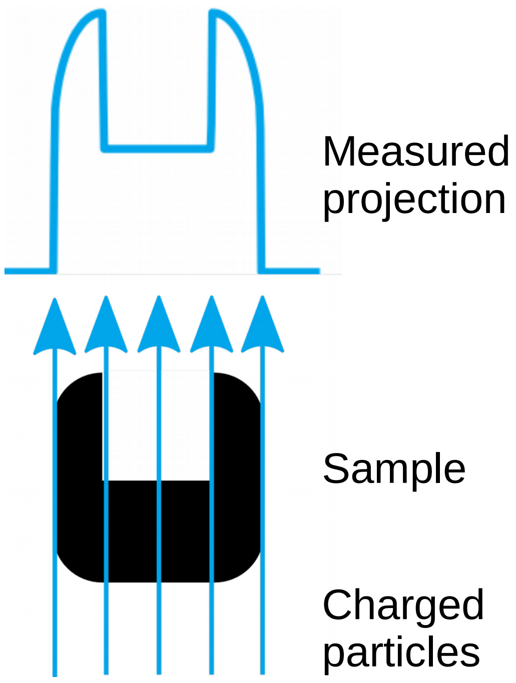
Sample

Charged particles

Material Budget Imaging – 3D

Concept

- Goal:
  - Reveal the inner structure of a sample from only measuring its projections



Material Budget Imaging – 3D

Concept

- Goal:
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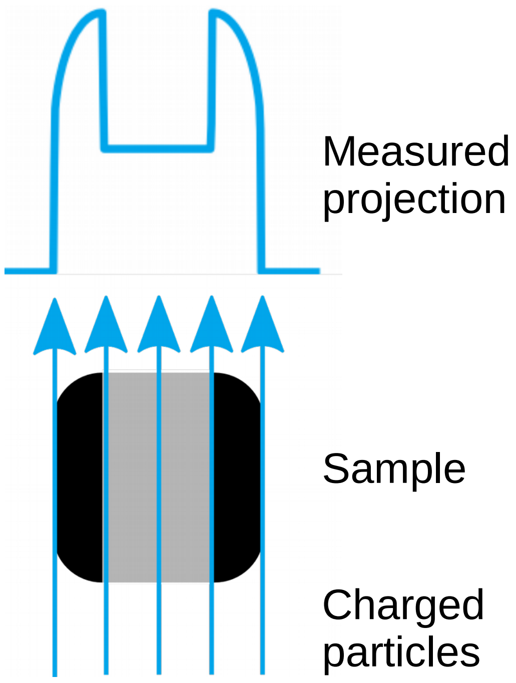
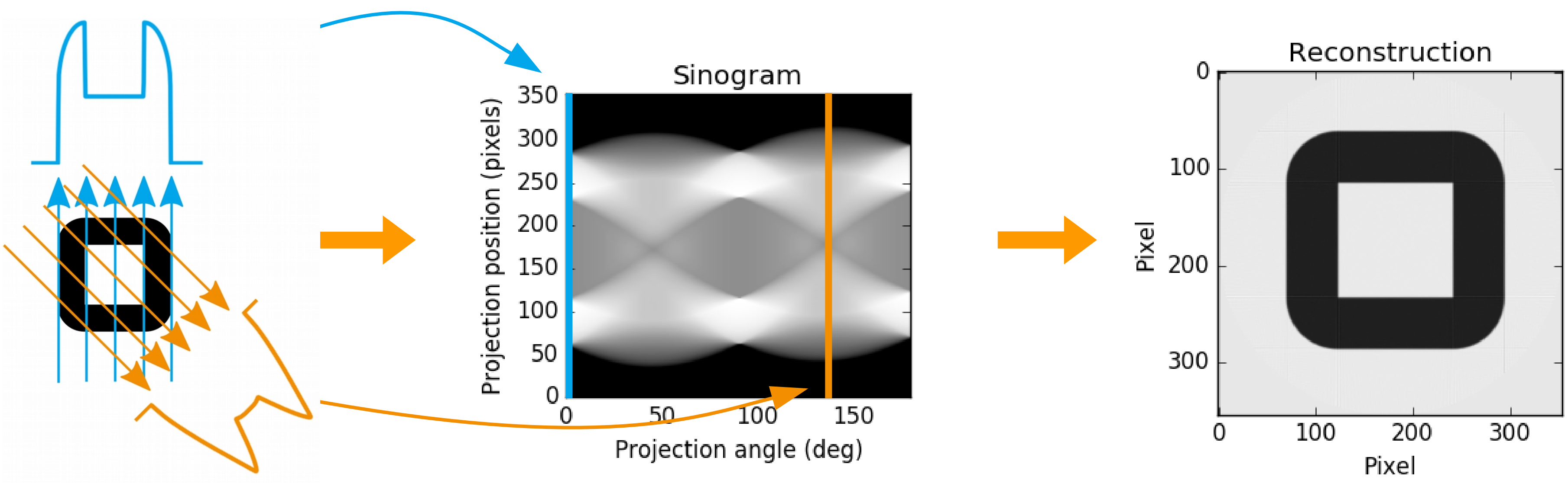


Material Budget Imaging – 3D

Concept

- Goal:
  - Reveal the inner structure of a sample from only measuring its projections
- Method:
  - Repeat the projection measurement for different rotation angles
  - Perform an inverse radon transform [7] to reconstruct the internal material budget distribution

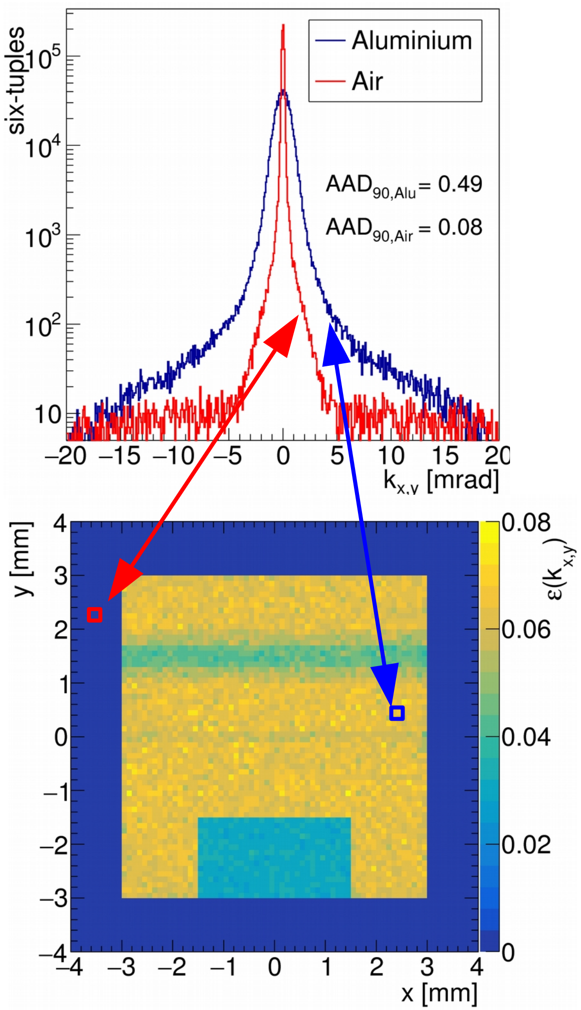


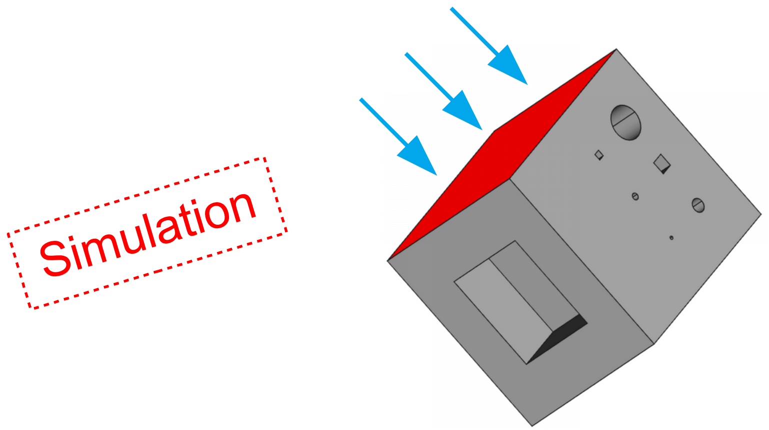
[7]: S.R. Deans, *The Radon Transform and some of its applications*

Material Budget Imaging – 3D

Image Reconstruction

- Mapping of the material budget for one rotation angle



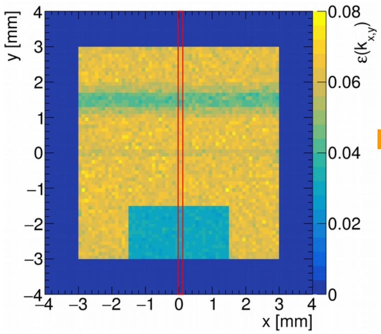


Material Budget Imaging – 3D

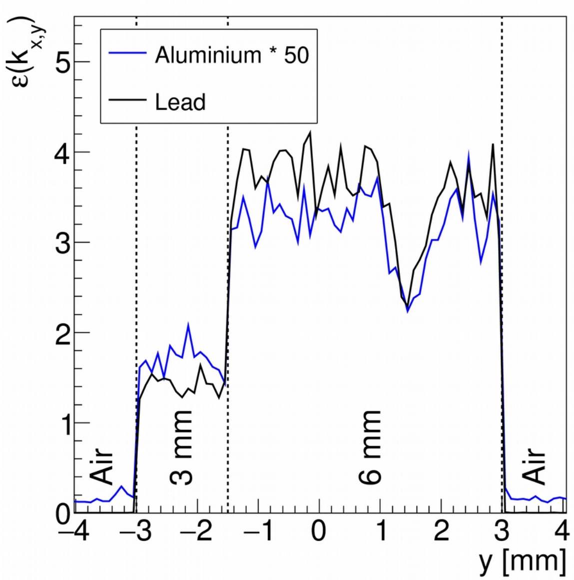
Image Reconstruction

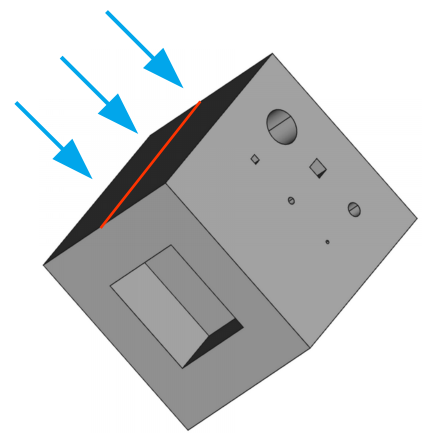
- Mapping of the material budget for one rotation angle
- Extract a slice perpendicular to the rotational axis

Material map



Vertical slice



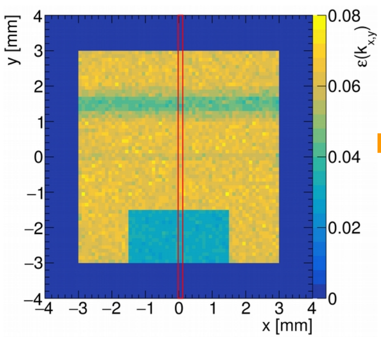


Material Budget Imaging – 3D

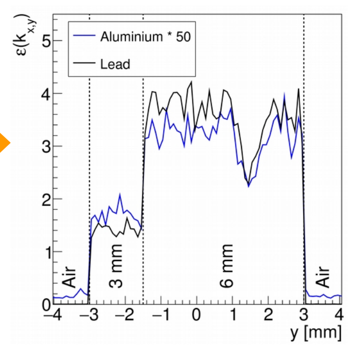
Image Reconstruction

- Mapping of the material budget for one rotation angle
- Extract a slice perpendicular to the rotational axis
- Slices from multiple rotational angles form the *sinogram*

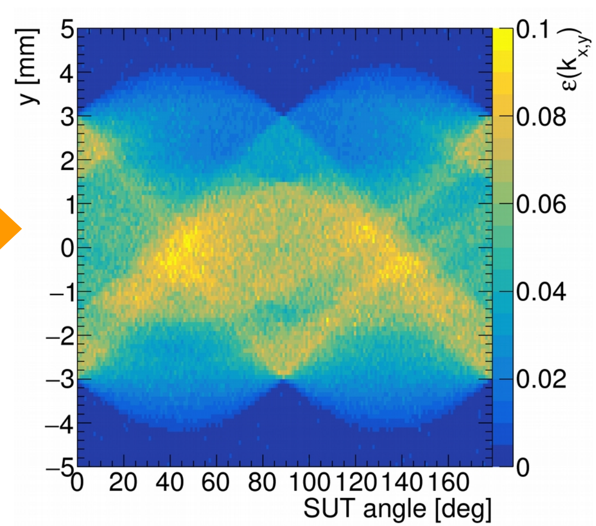
Material map



Vert. slice



Sinogram

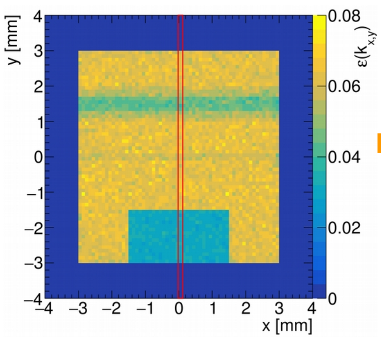


Material Budget Imaging – 3D

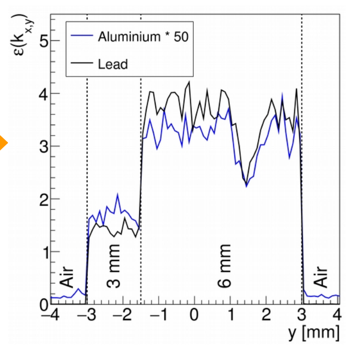
Image Reconstruction

- Mapping of the material budget for one rotation angle
- Extract a slice perpendicular to the rotational axis
- Slices from multiple rotational angles form the *sinogram*
- Filtered back projection (inverse radon transform) yields the reconstructed density distribution

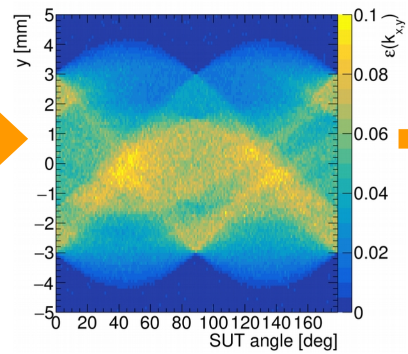
Material map



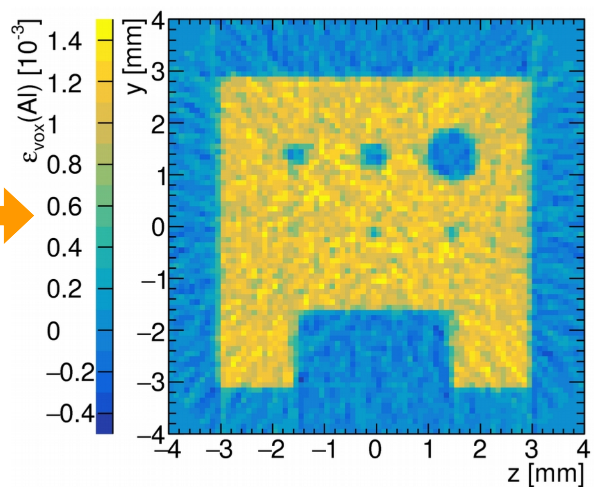
Vert. slice



Sinogram

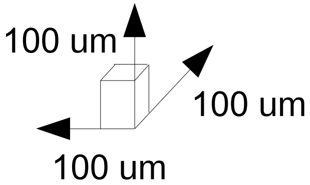


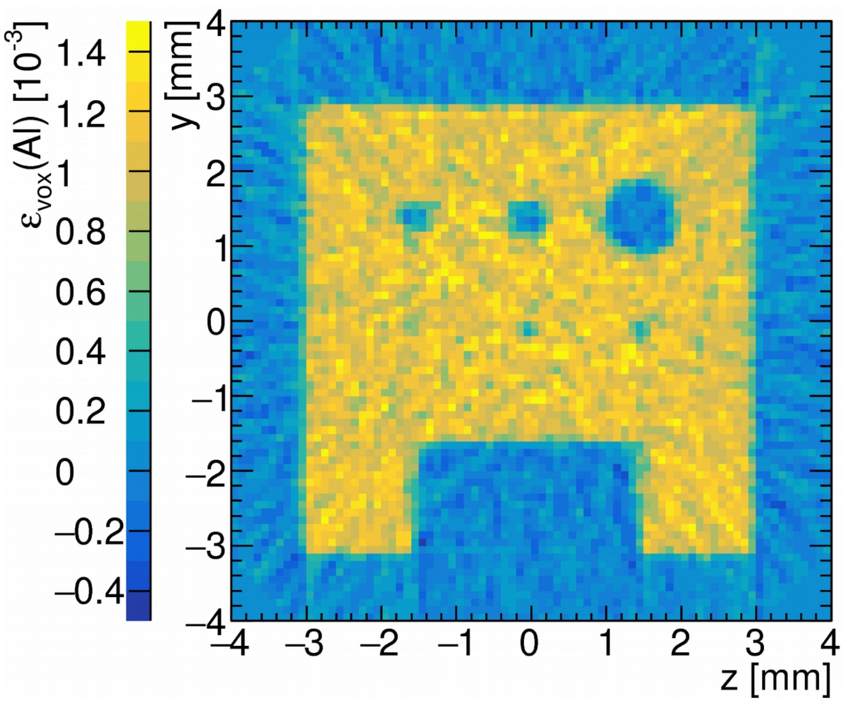
Reconstruction

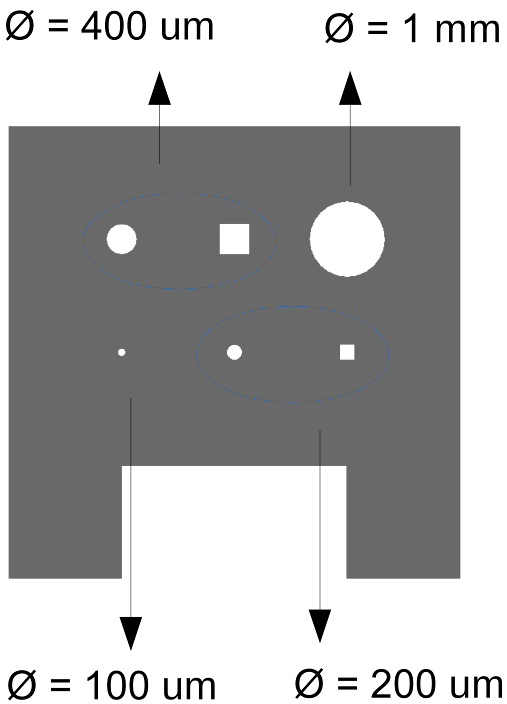


Simulation Results

- 3D bin: “voxel”







Simulation Results

Resolution & Contrast

- Contrast-to-noise ratio:

$$C = \frac{|\mu_{alu} - \mu_{air}|}{\sqrt{\sigma_{alu}^2 + \sigma_{air}^2}}$$

  – Mean μ and variance σ_i^2 of the signal in regions of air and aluminum (blue/red boxes)

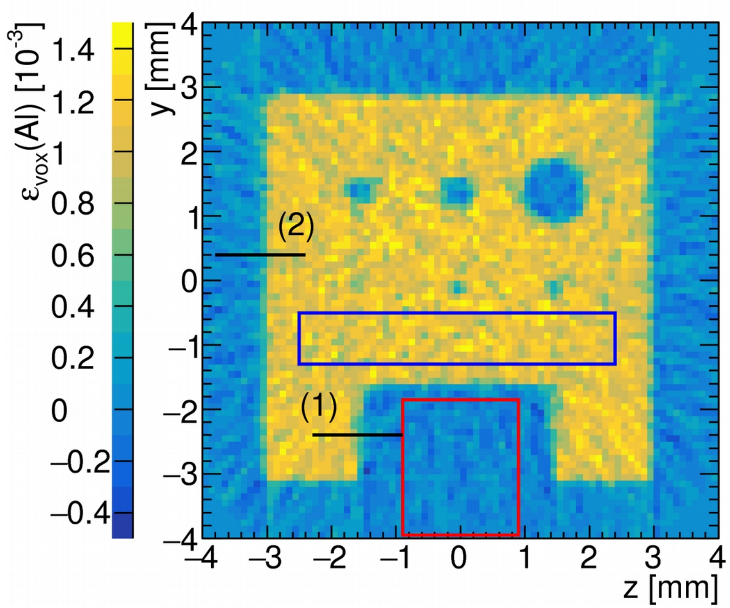
- Resolution:

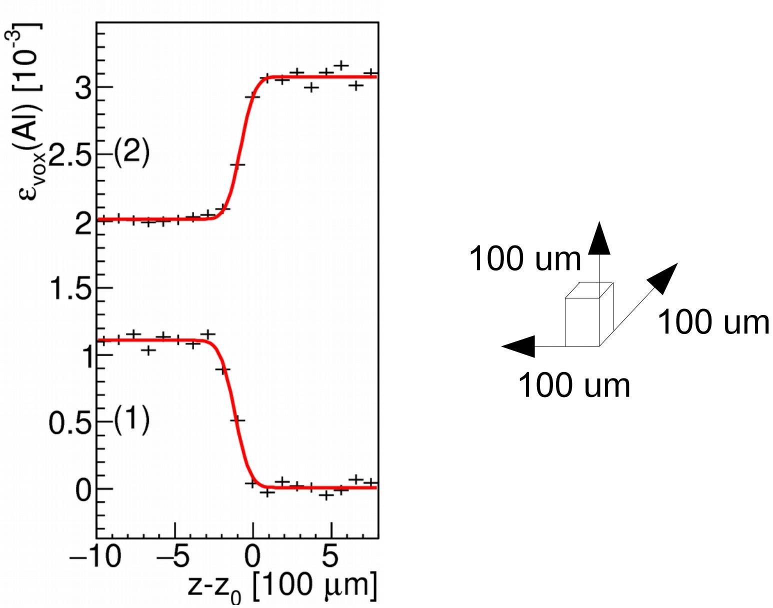
  – Fit modified error function with the Gaussian width σ to the sharp edges

$$f(x) = A \int_0^x e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

C = 5.6 ± 0.2

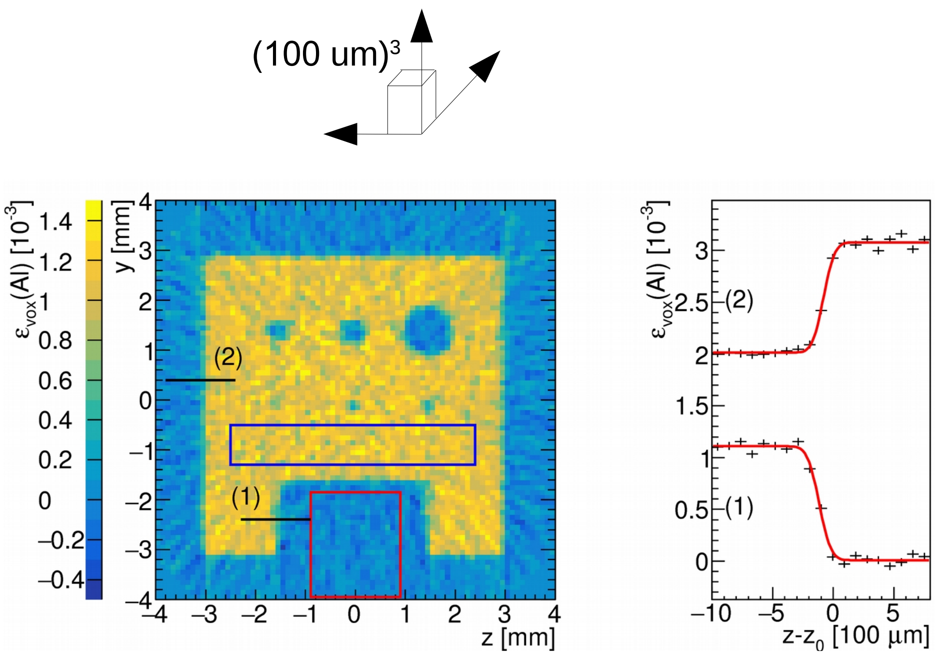
σ = 75 ± 6 μm

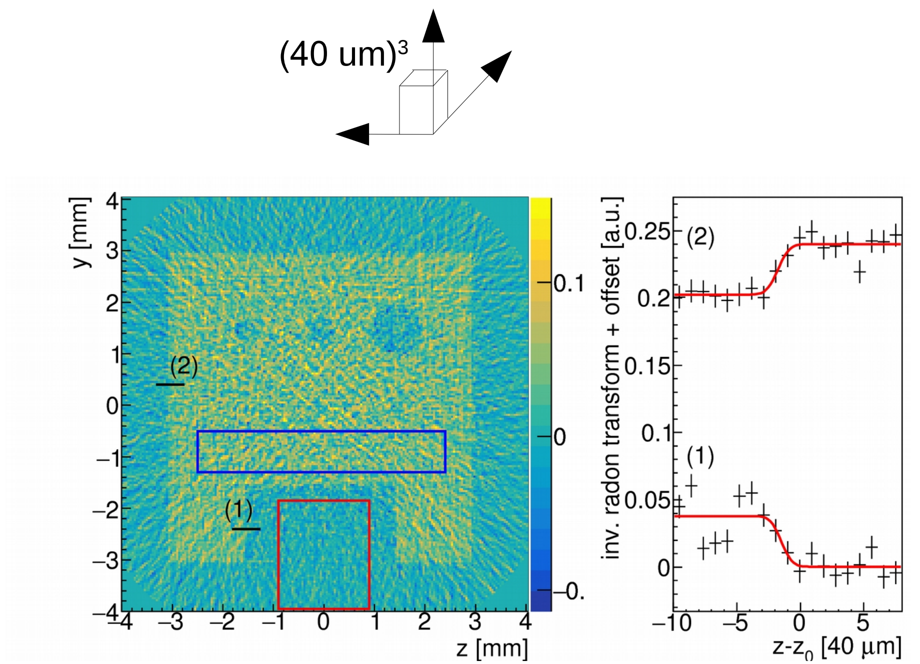




Simulation Results

Resolution & Contrast





C = 5.6 ± 0.2

σ = 75 ± 6 µm

C = 0.89 ± 0.02

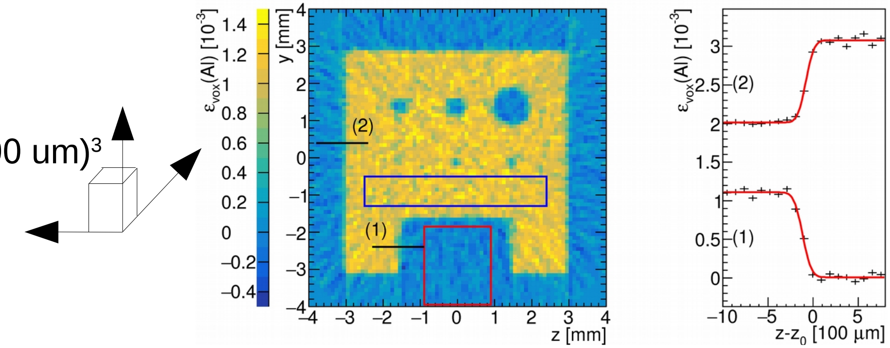
σ = 28 ± 11 µm

Simulation Results

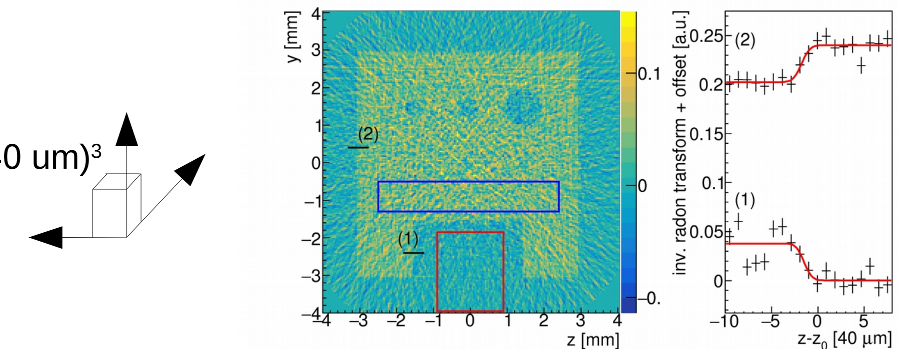
Resolution & Contrast

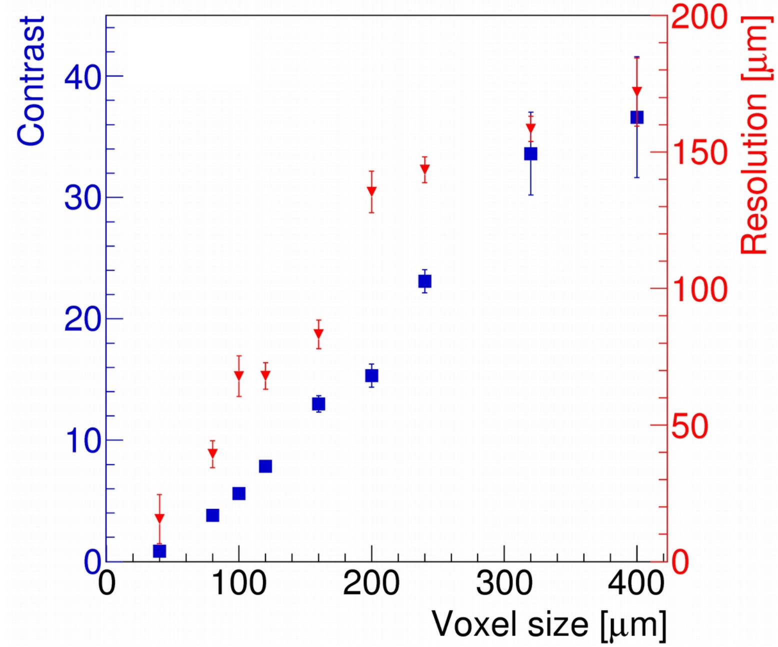
- There's a trade-off between resolution and contrast
  - Lowering the voxel size by a factor x reduces the number of tracks in each 2D cell by x^2
  - Choice of voxel size depends on the application and the recorded number of tracks

(100 um)^3



(40 um)^3





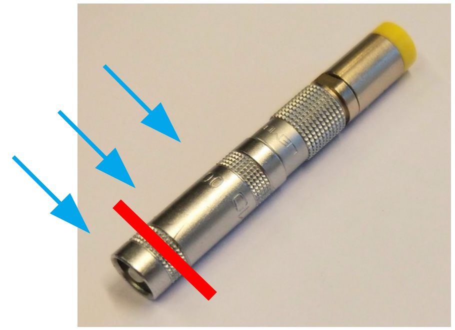
Material Budget Imaging – 3D

Track-based Multiple Scattering Tomography

Measurement

Material Budget Imaging – 3D

Image Reconstruction



- Mapping of the material budget for one rotation angle
- Extract a slice perpendicular to the rotational axis
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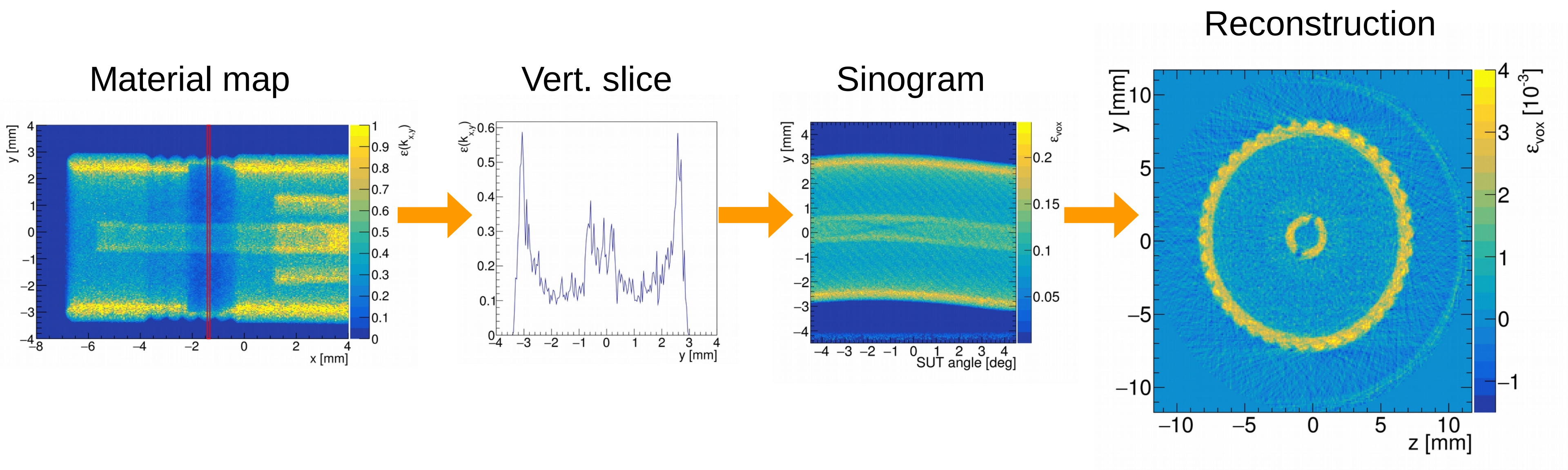
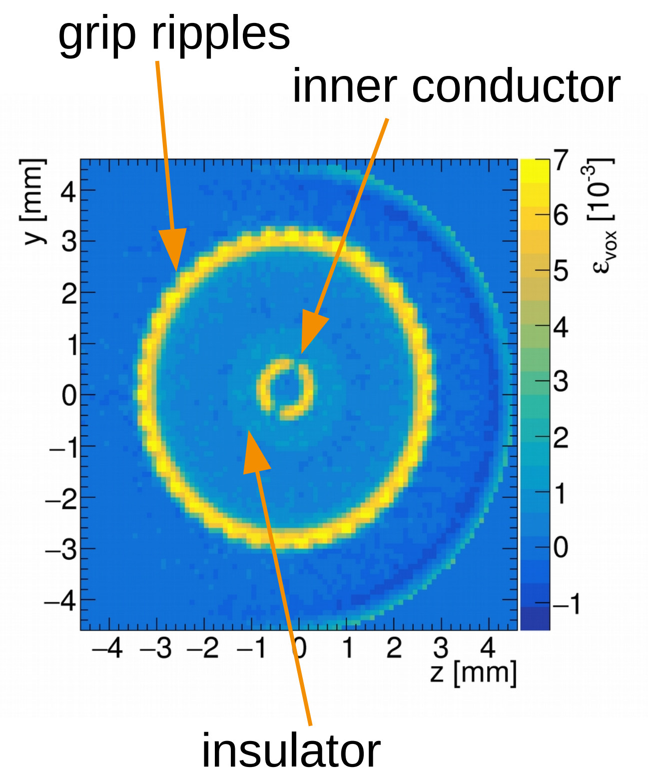
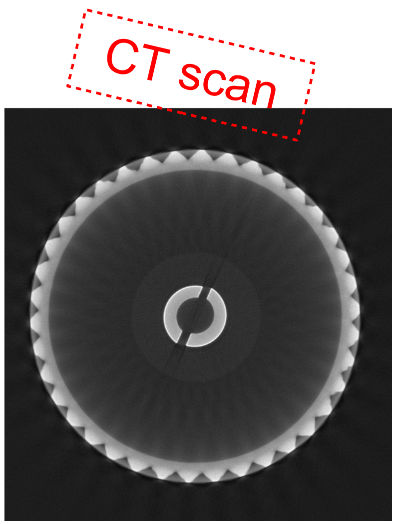


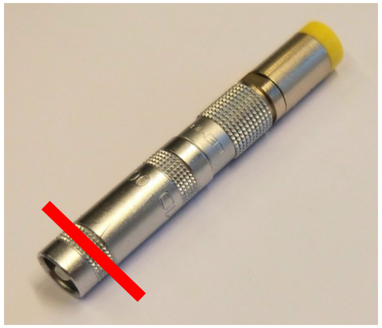
Material Budget Imaging – 3D

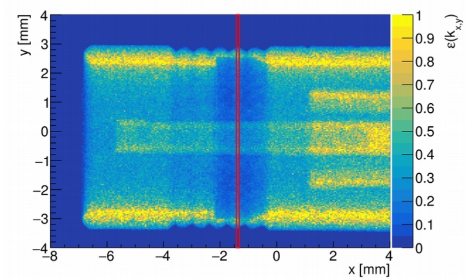
Results

- Reconstruction reveals several details of the sample









Material Budget Imaging – 3D

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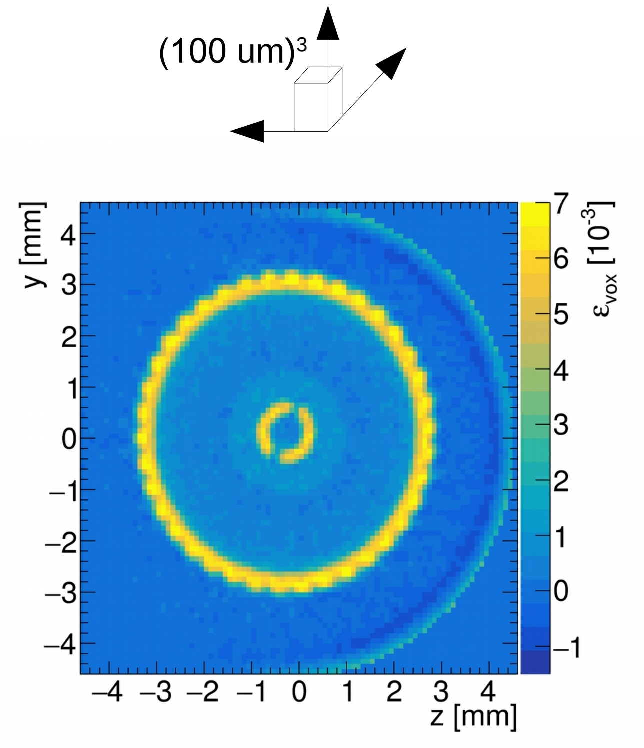
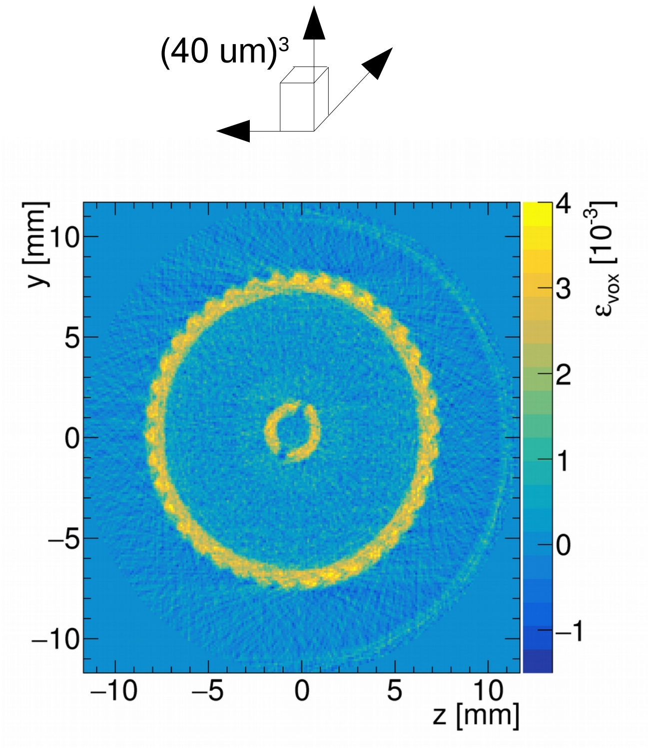
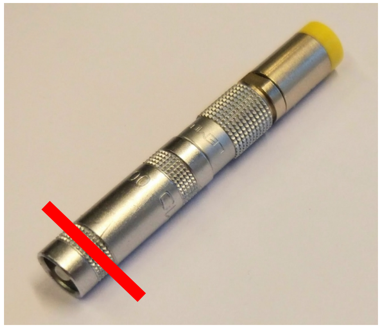
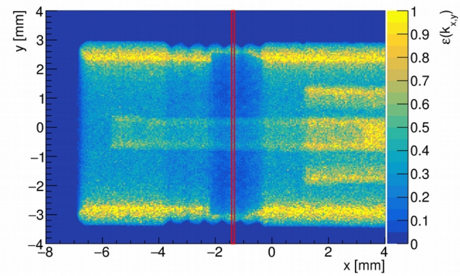
- Reconstruction reveals several details of the sample





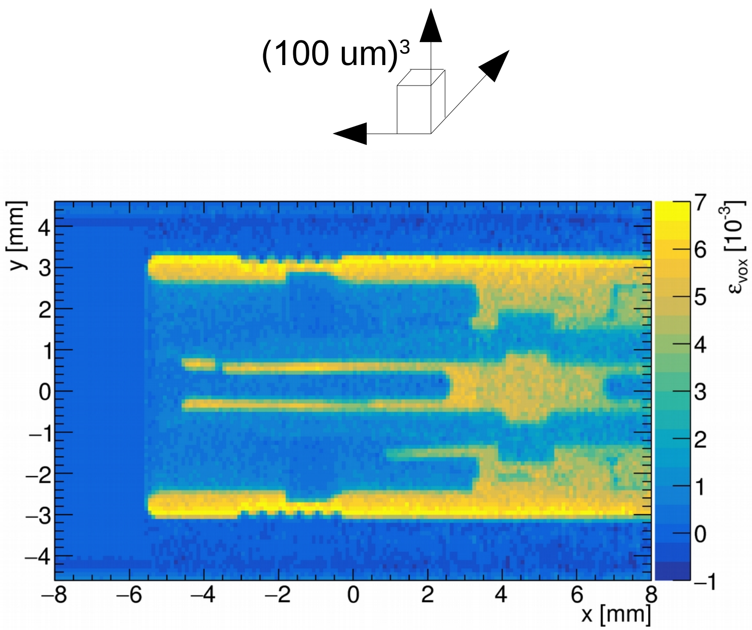


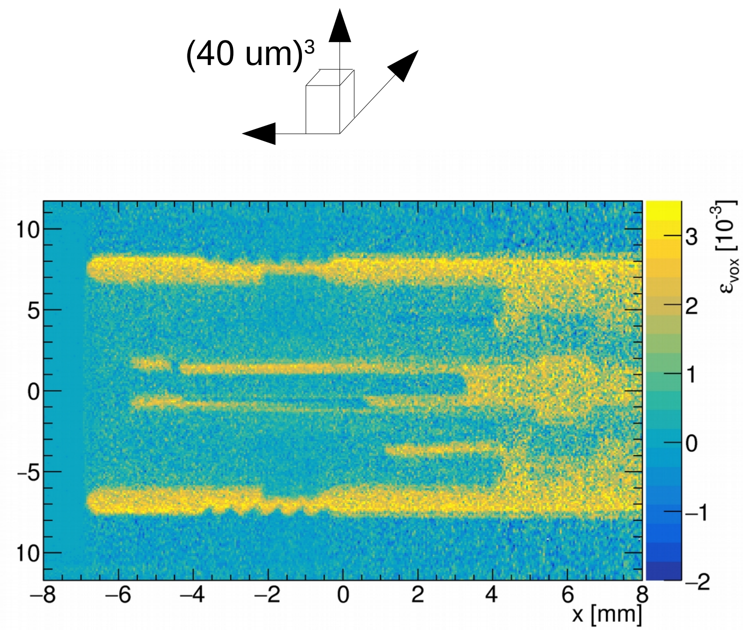


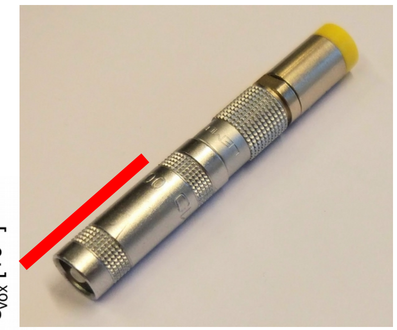
Material Budget Imaging – 3D

Results

- Reconstruction reveals several details of the sample
- Combine the reconstructions of all slices to yield the full 3D material budget distribution







- Reducing the voxel size is not always a good idea
    - Without contrast, the better resolution does not improve the reconstructed image

What about CT?

X-Rays vs. Electrons

- CT (Computed Tomography) is a well established method for 3D imaging, but ...
- for X-rays, the attenuation length is shorter than the radiation length of high-energy particles
  - E.g. Lead:
    - Attenuation length (photons): ~0.1 mm (50 keV) / ~0.7 mm (200 keV)
    - Radiation length (highly relativistic charged particles): 5.6 mm

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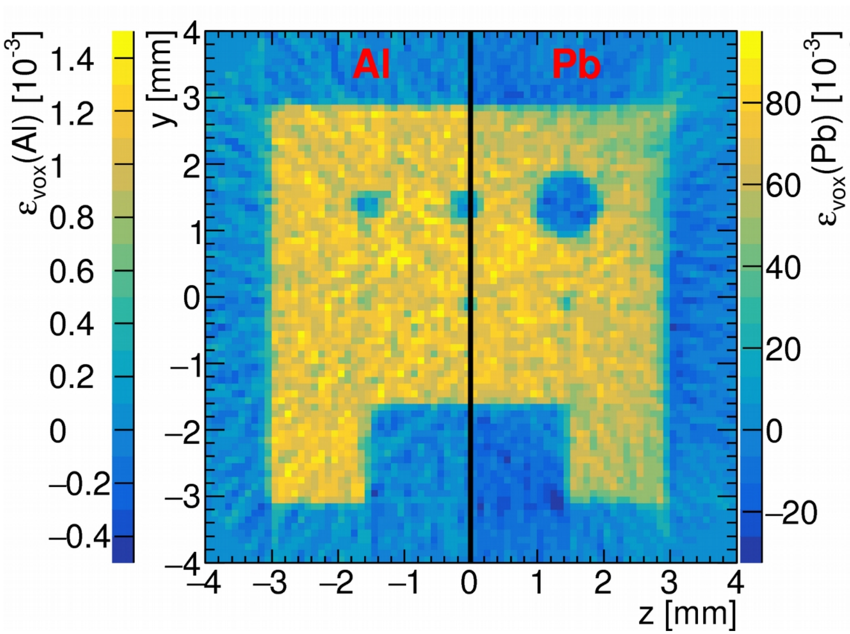
➔ GeV-electrons can probe thicker materials than X-rays!

➔ Simulation: **Lead** cube with the same geometry as shown before



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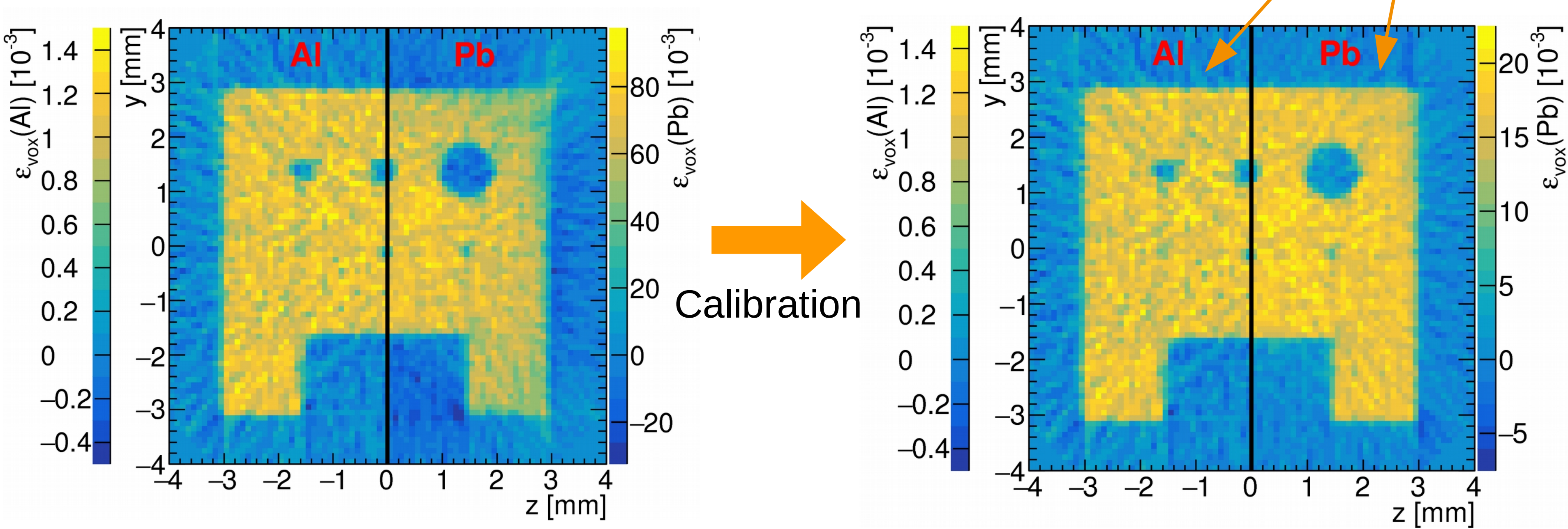
  - ➔ GeV-electrons can probe thicker materials than X-rays!
  - ➔ Simulation: **Lead** cube with the same geometry as shown before

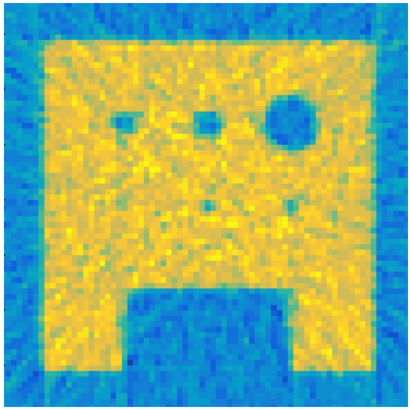
Higher contrast for **lead** sample!



Summary

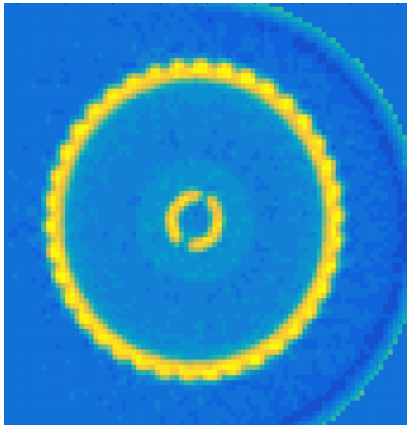
Current status

- Reconstruction of 3D material budget using multiple scattering distributions has been achieved from simulated and measured data
- Performance studies on simulated data:
  - Resolution: >28 µm
  - Theoretical limit @ DESY TB, Alu sample: ~5 µm



- Acceptance area: Limited to telescope sensor planes, 1 cm x 2 cm
- Measurement time: ~ 3 days

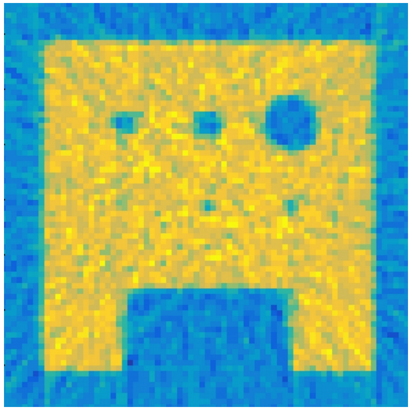
- Data for performance measurements is recorded – evaluation pending

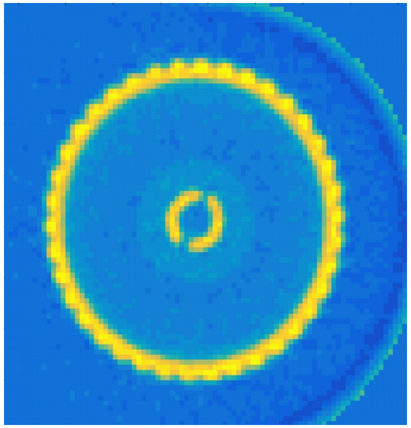


Outlook

Improvements

- The method can be improved by …
  - higher particle rates / faster tracking devices
    → reduce measurement time
    - Upgrade of the DESY Test Beam is considered
    - Other facilities
  - improved reconstruction algorithms
    → increase resolution and contrast
    - In contact with experts on CT
      and experts on reconstructions with low statistics data
  - larger sensor planes
    → measure larger objects
  - Calibration with targets of known material budget
    → reduce artefacts and yield absolute numbers
  - Using a more sophisticated tracking algorithm (GBL)





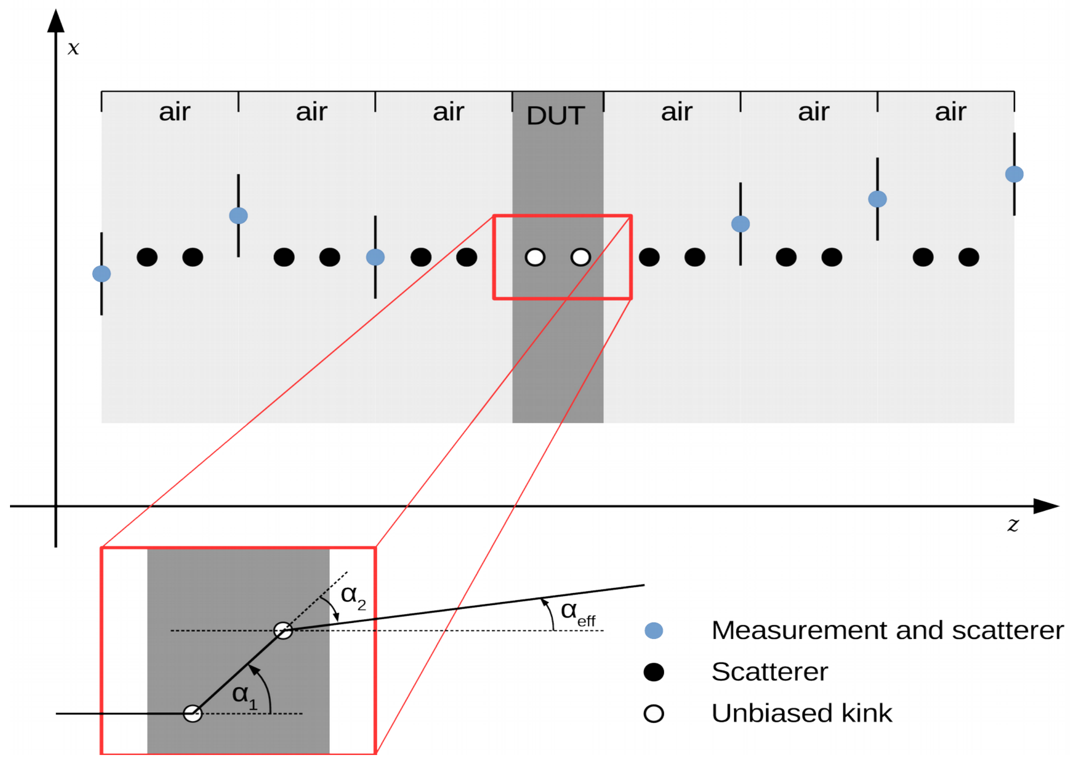
Backup

Restricted Area

Track Reconstruction

The Track

- Triplet Method:
  - Matching hits in upstream (*downstream*) planes form **triplets**
  - Matching upstream and downstream triplets form **track** candidates
  - Kink angle at the sample: Difference of upstream and downstream slopes



- Advanced: GBL for track fitting [6]
  - Optimizing the trajectory
  - Allows for scattering
  - Kink angle at the sample: Local, unbiased parameter in the track model

[6]: C. Kleinwort, *General broken lines as advanced track fitting method*