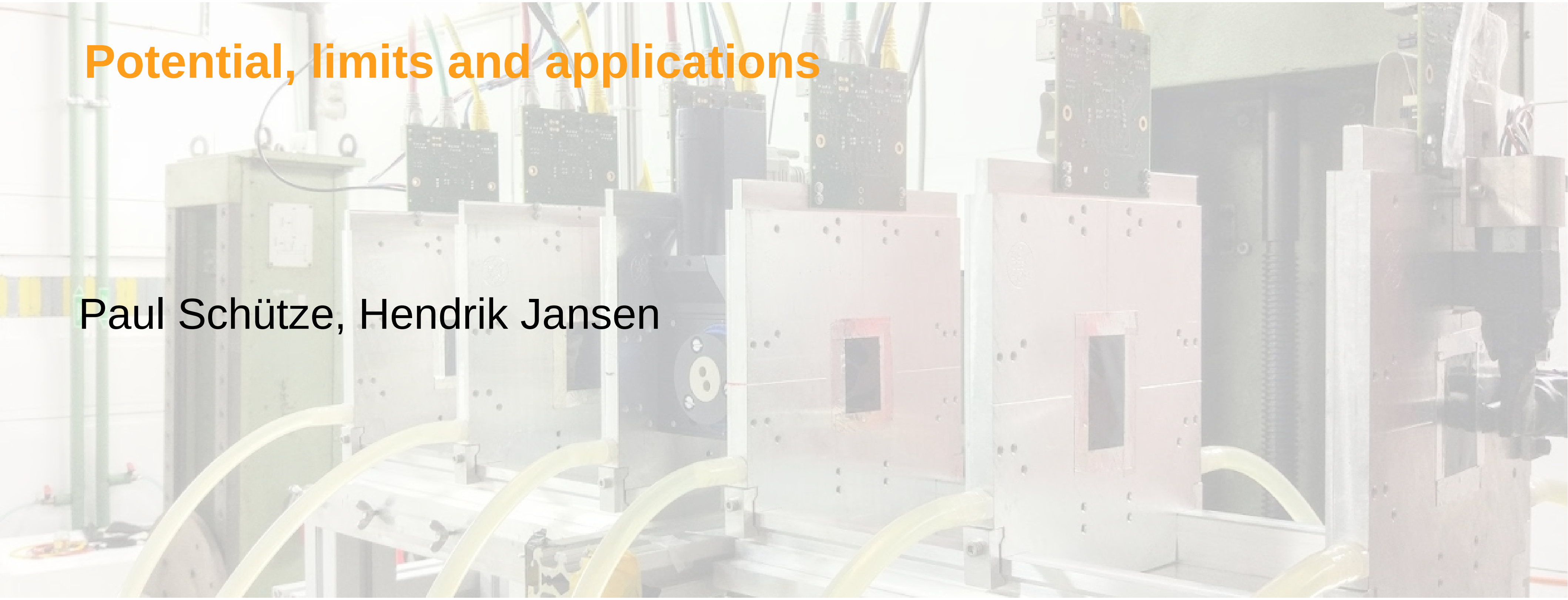
Material Budget Imaging



Potential, limits and applications

Paul Schütze, Hendrik Jansen

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

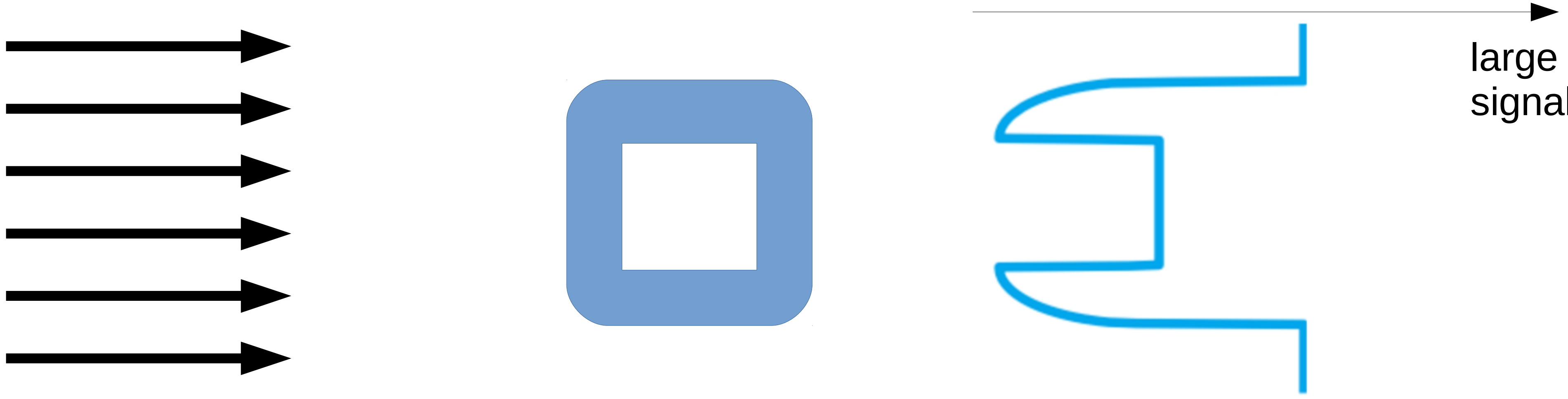
DESY.

Imaging in a 

Probe
- x-ray, neutron

Interaction with the target
- absorption

Measure physical quantity
- intensity

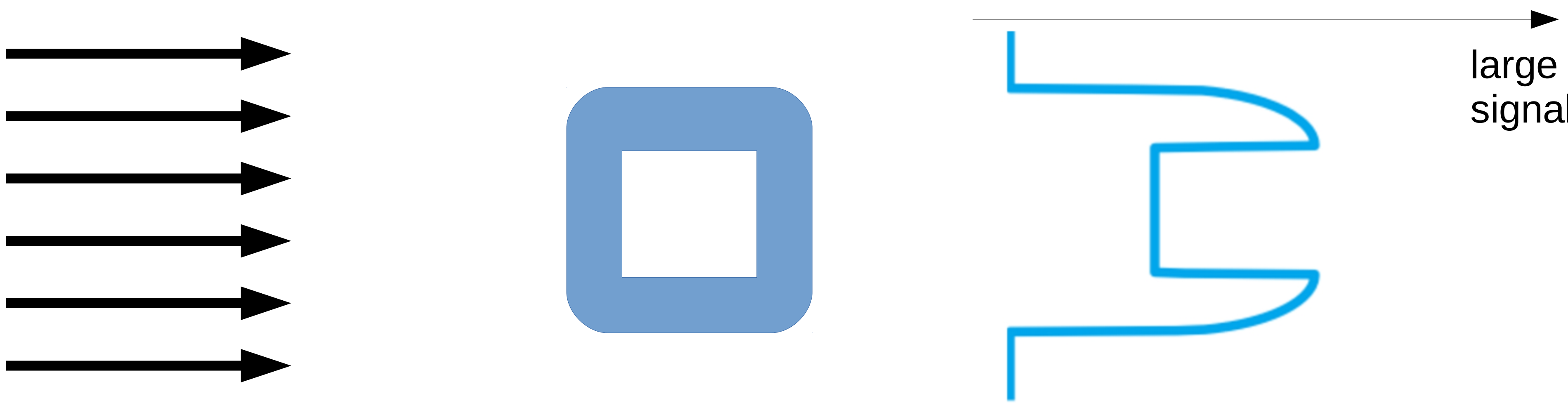


Imaging in a 

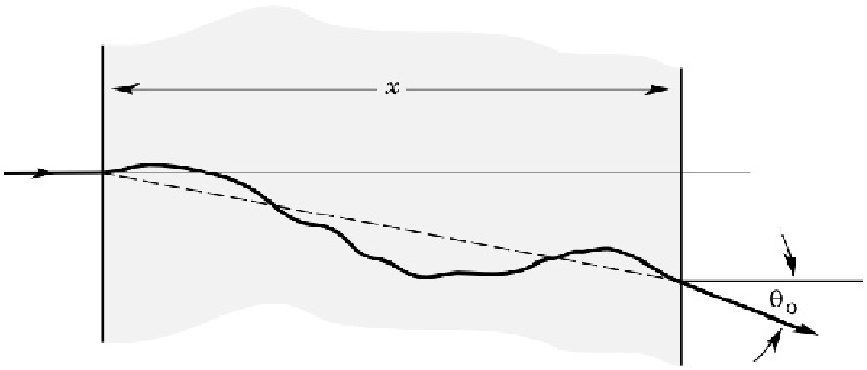
Probe
- x-ray, neutron
- charged particle

Interaction with the target
- absorption
- energy loss
- scattering

Measure physical quantity
- intensity
- energy loss (delta E)
- variance of deflection angle



Physics of Material Budget Imaging



- High-energy particle undergoes multiple Coulomb scattering when traversing material
  - ➔ Particle is deflected
- Scattering angle distribution:
  Gaussian-like centre with tails at larger angles

- The Gaussian width predicted by **Highland**

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

Material Budget: $\varepsilon = x/X_0$

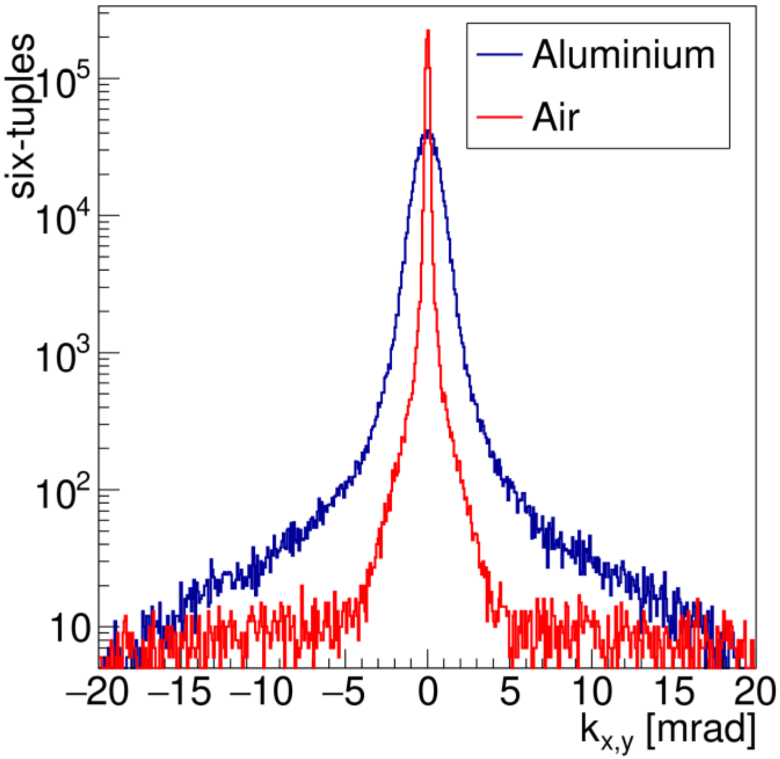
x: Path length in the material

X_0: Material's radiation length

(e- loses all but 1/*e*-th of its energy)

➔ Measurement:
Scattering angle distribution

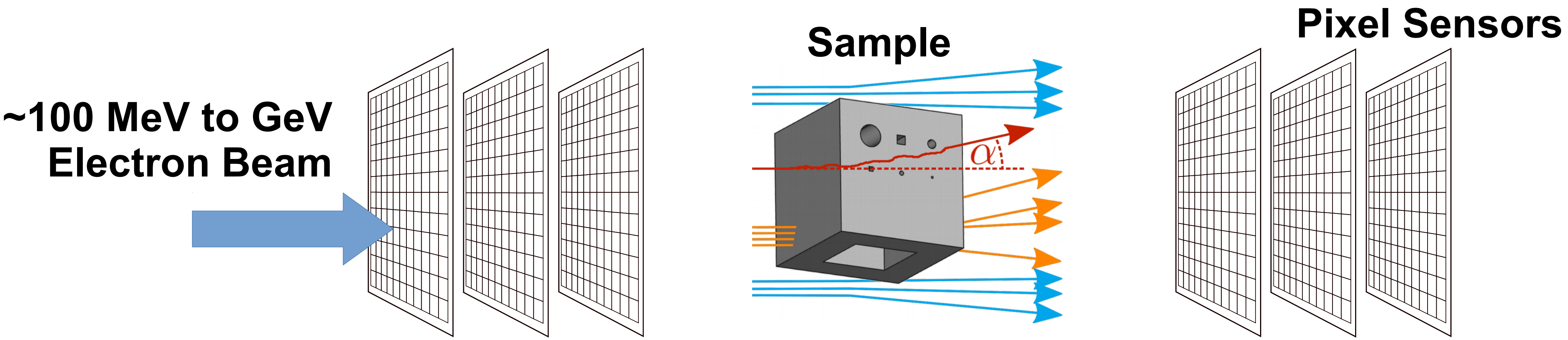
➔ Characteristic quantity:
Material budget



Material Budget Imaging

Imaging method based on multiple scattering

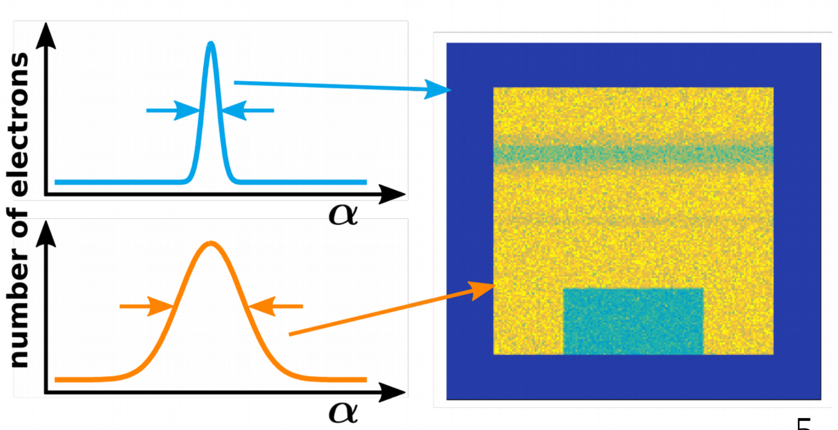
→ Measure each trajectory (in front and behind sample!)



→ Group electrons into pixels at virtual plane through sample

→ Calculate width of angular distribution per pixel

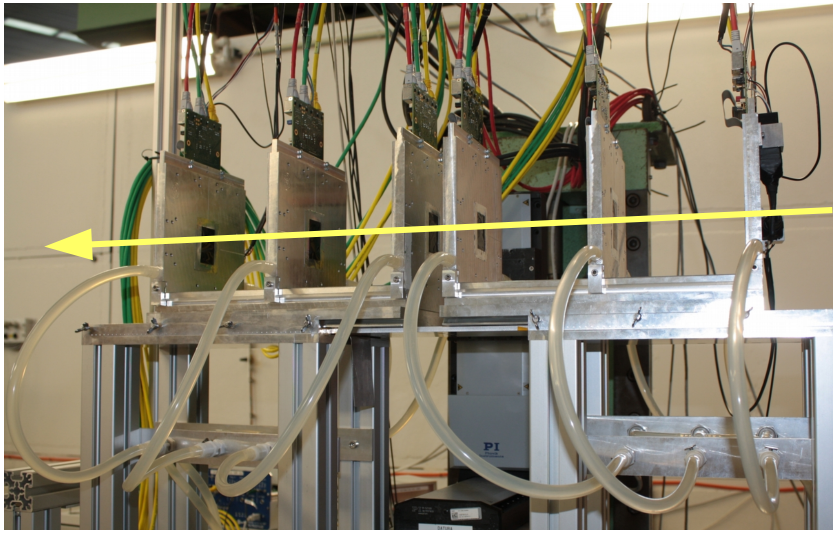
→ Repeat for all projections and perform backprojection



EUDET Beam Telescopes

- 6 sensors: 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
- 4 PMTs as coincidence trigger
- Track resolution at sample: $\sigma = 2 - 10$ μm



- *AllPix* Detector Simulation Framework (based on *Geant4* libraries)

  - Simulation of the particle propagation
  - Simulation of detector response
  - Data processing via exact same chain as with data

Reconstruction chain

From data taking to tomographic images

EUDAQ → **EUTelescope** → **AAD calc** → **Tomographic reco**

Data acquisition framework:

Saves data from six planes for triggered events

Track reconstruction framework:

‘tracking’ delivers x_i, y_i, kx_i, ky_i

Width estimator python script:

AAD90

Simple backprojection python script:

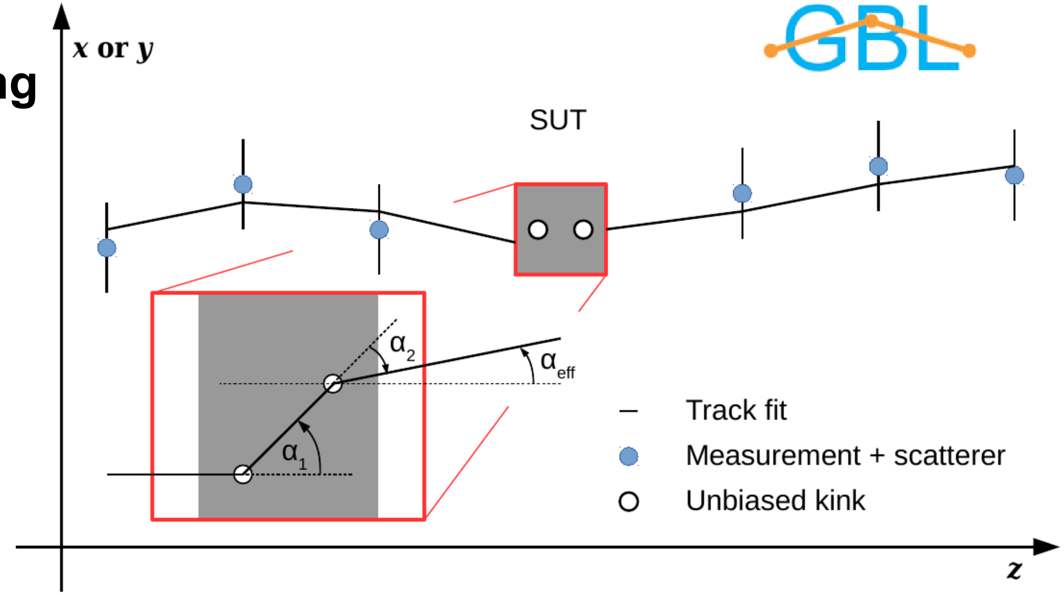
Based on scikit
Optional calibration to MB

scikit-image
image processing in python

Track reco and width estimation

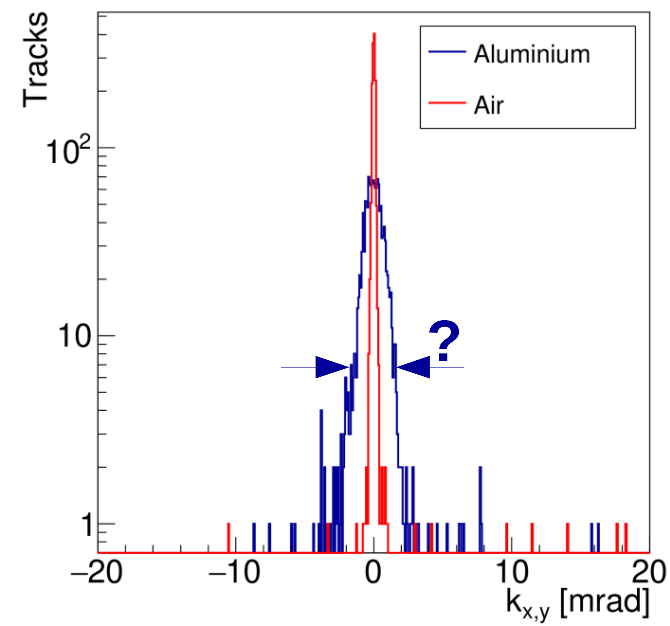
General Broken Lines (GBL) for track fitting

- 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

Calibration

Calculation of the Material Budget from scattering width

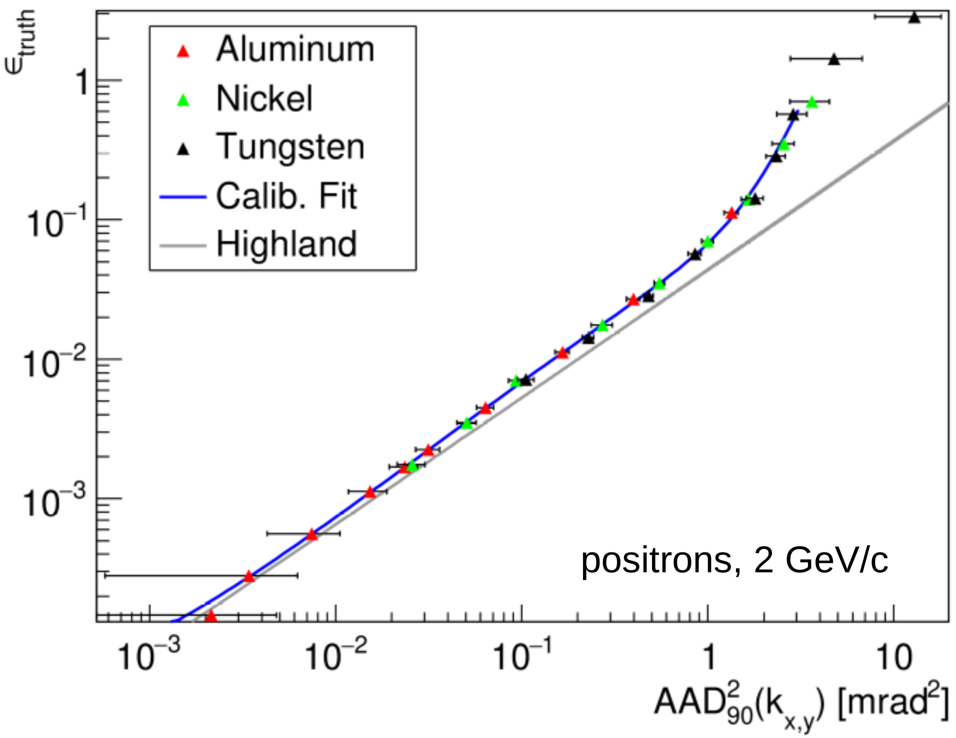
- Inverting the Highland formula for a determination of the material budget leads to discrepancies to expected values

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

Acquiring calibration curves

- Measure the angle distribution for known scatterers
- Metal foils from 13 um of aluminum to 2 cm of tungsten
  → AAD90(ε; E)

- Invert fit to data for the calibration of unknown samples
  → ε(AAD90; E)



Why MBI?

Considerable interest and potential in MBI

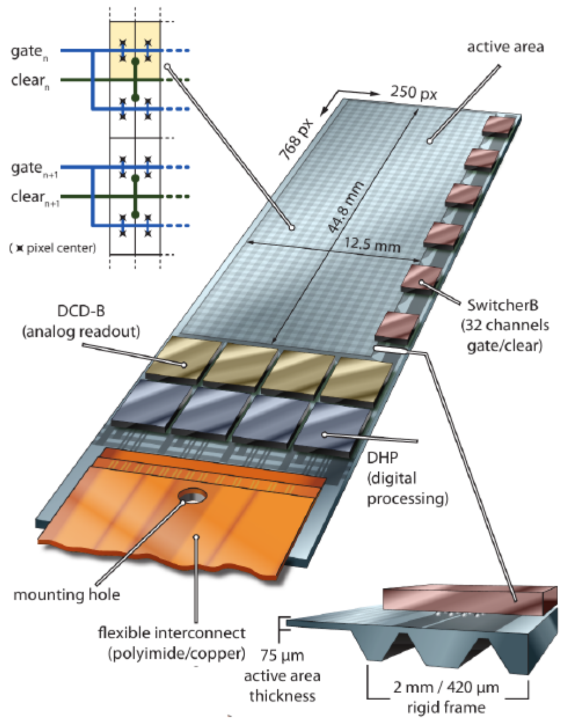
- Various **LHC upgrade activities** in particle physics
  → Estimate of 2D MB distribution for realistic detector description
- **Non-destructive testing** of prototypes
  → e.g. batteries, high-Z material
- **Medical imaging/treatment planning**
  → possible dose advantage
  → possibly less artefacts

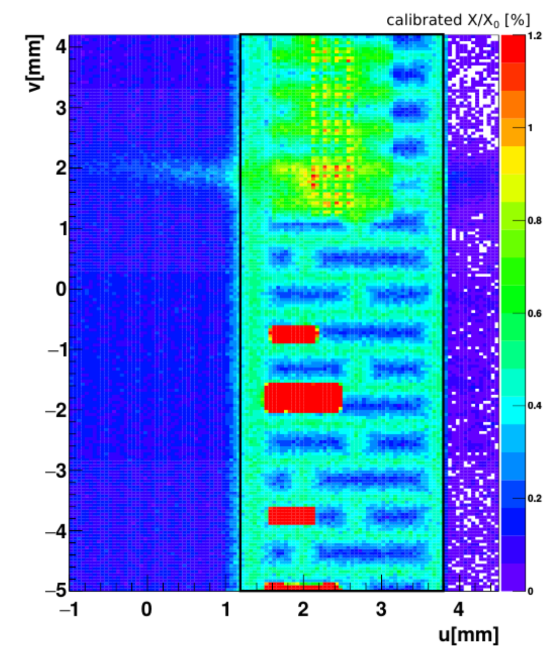
Measure 200 to 2000 projections
→ Need **high rates**

Seamless image/no stitching
→ Need **large area** beam + detector

MBI at Belle II / ATLAS

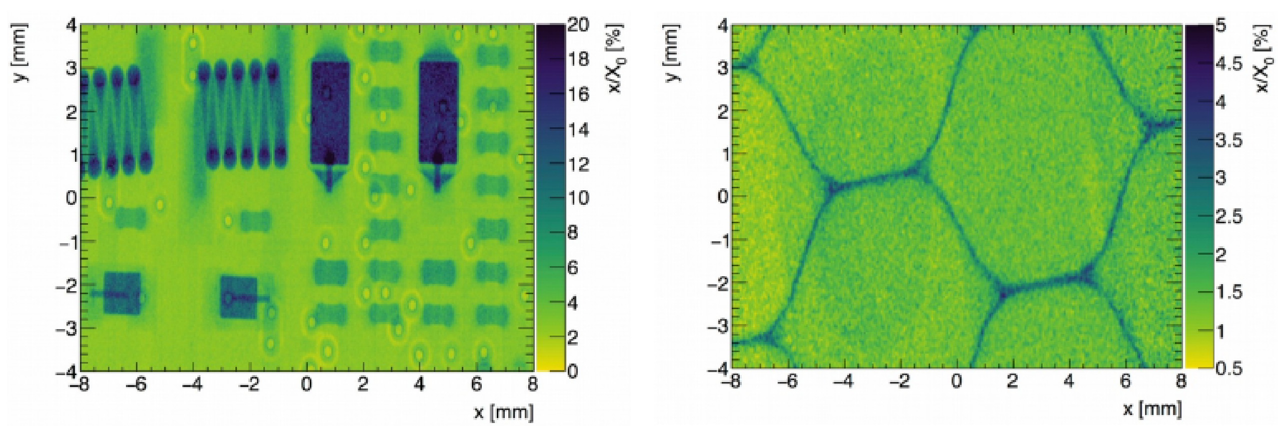
Belle II PXD
module





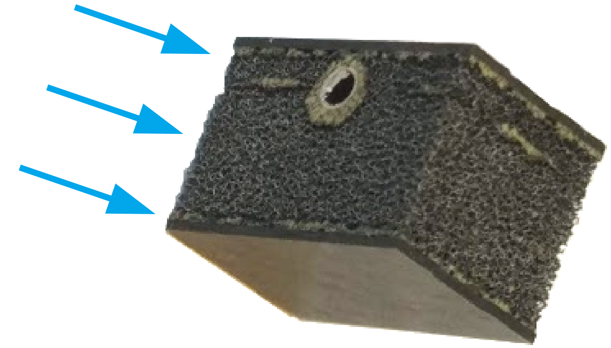
U. Stolzenberg et al.

ATLAS Tracker
endcap petal



M. Queitsch-Maitland et al.

Results of 2D MBI

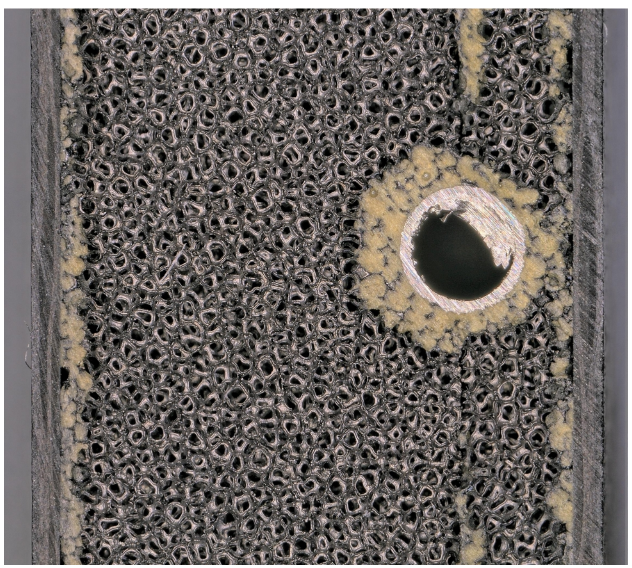


CMS Tracker Support Structure Prototype

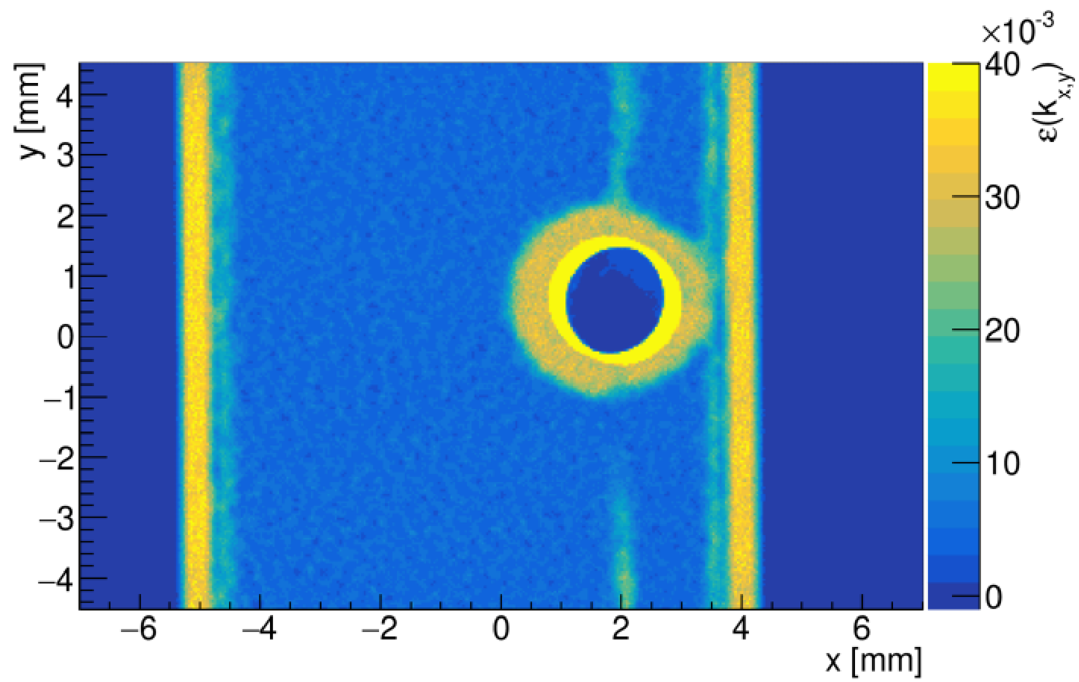
- Carbon Foam / CFRP plates / Cooling pipe / Glue

➔ Qualitative analysis

➔ Quantitative analysis

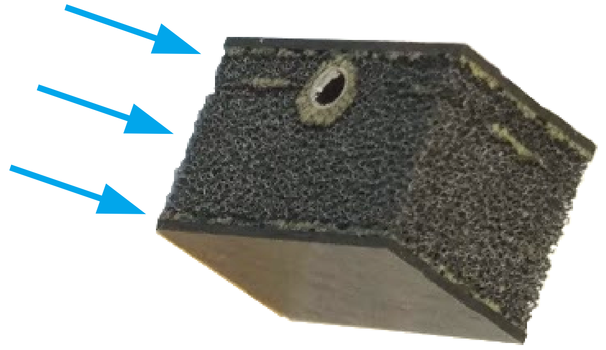


Microscope Image



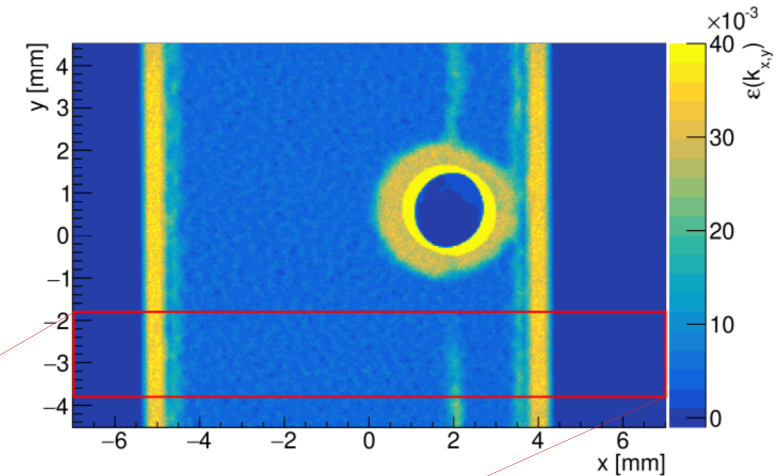
Material Budget Image

Results of 2D MBI



Qualitative Analysis

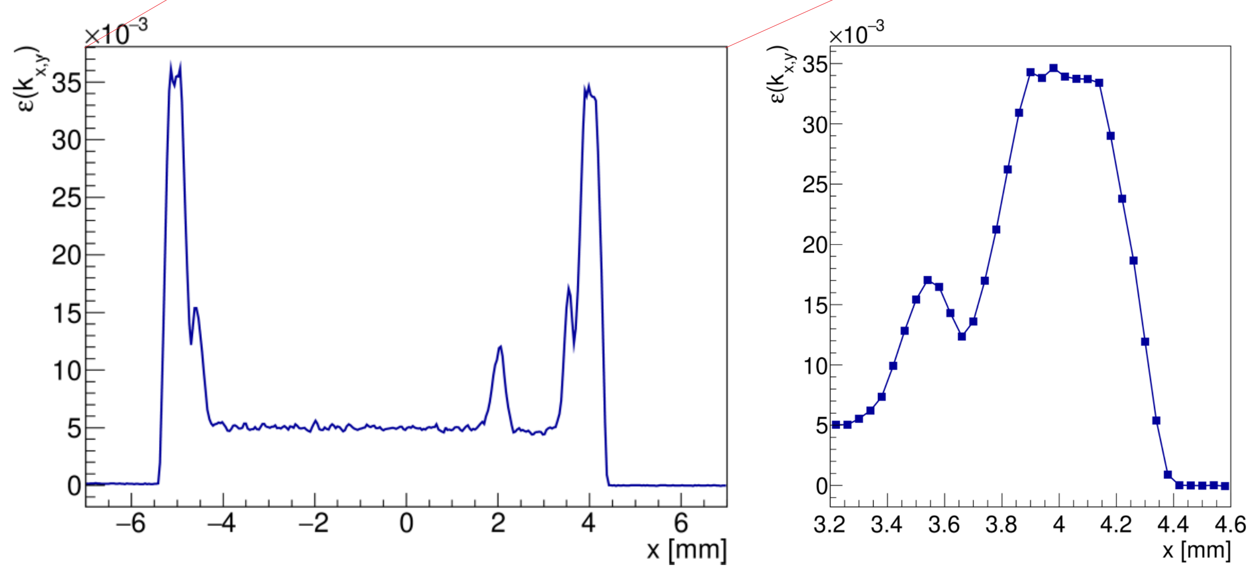
- E.g. investigate glue distribution



Quantitative Analysis

- Measure the actual material budget or radiation length of the sample

X_0 [mm]	Prediction	MBI
Carbon foam	2247 ± 10%	**1930 ± 360 (std)**
CFRP	264 ± 10%	**274 ± 17 (std)**
Water	360.8	**soon!**



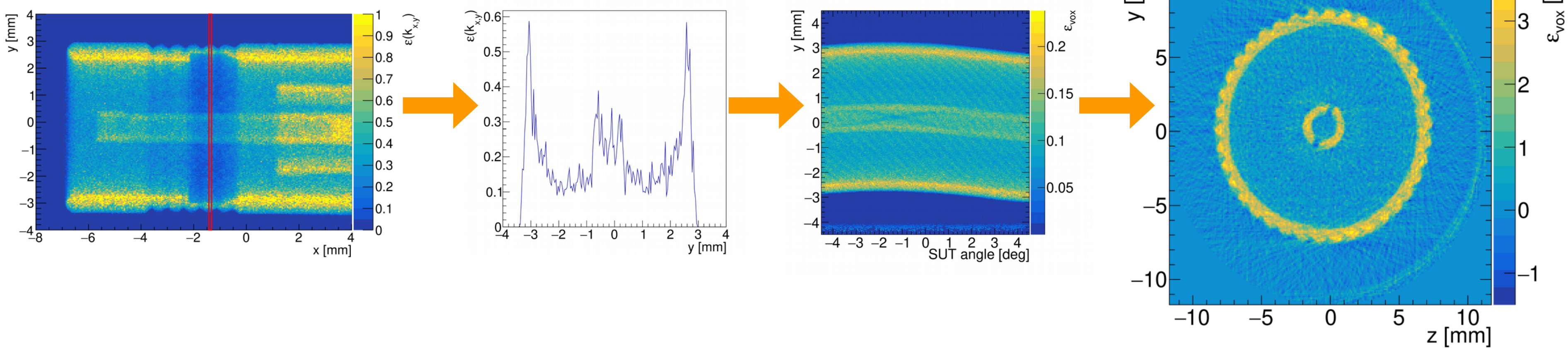
Examples of 3D MBI

2D Material Budget map

Vert. slice

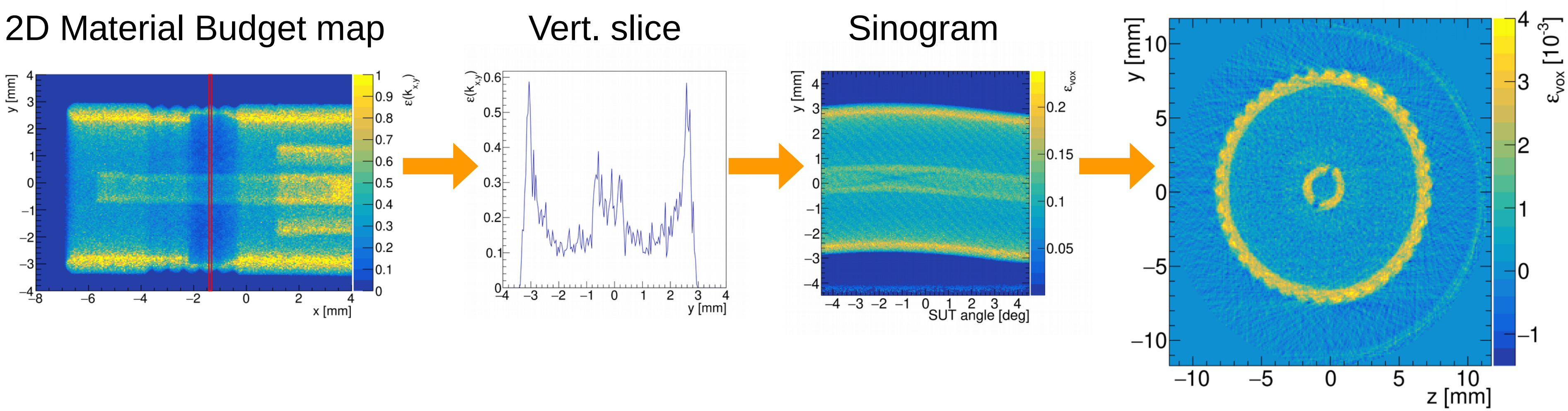
Sinogram

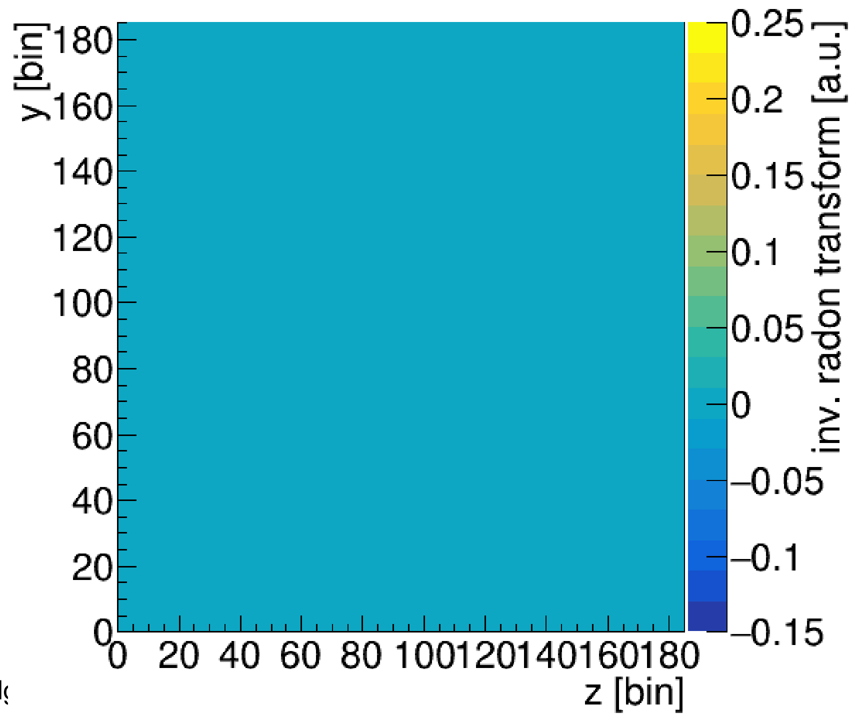
Reconstruction



Examples of 3D MBI

Reconstruction

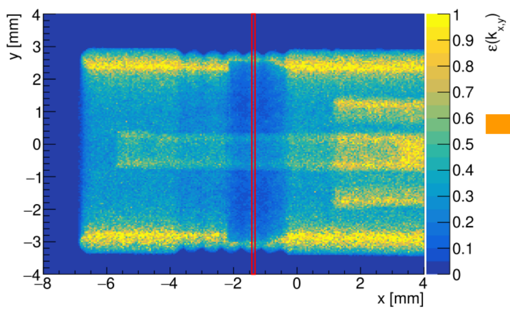




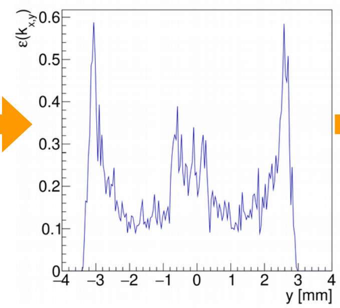
Examples of 3D MBI

Reconstruction

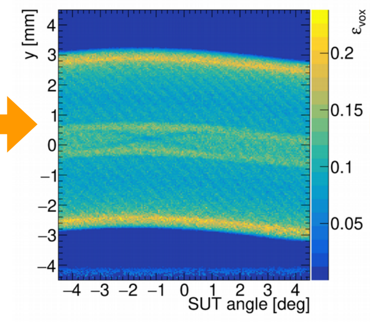
2D Material Budget map

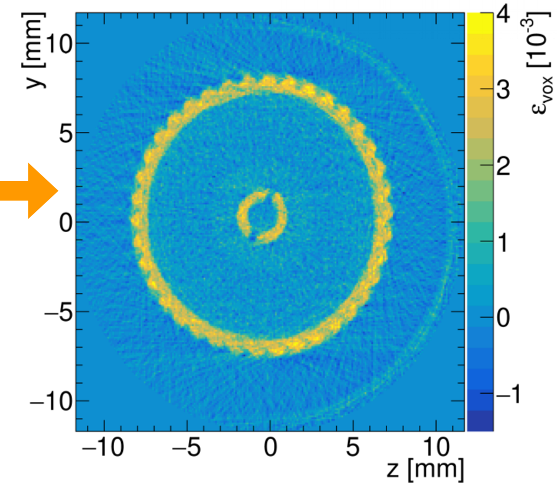


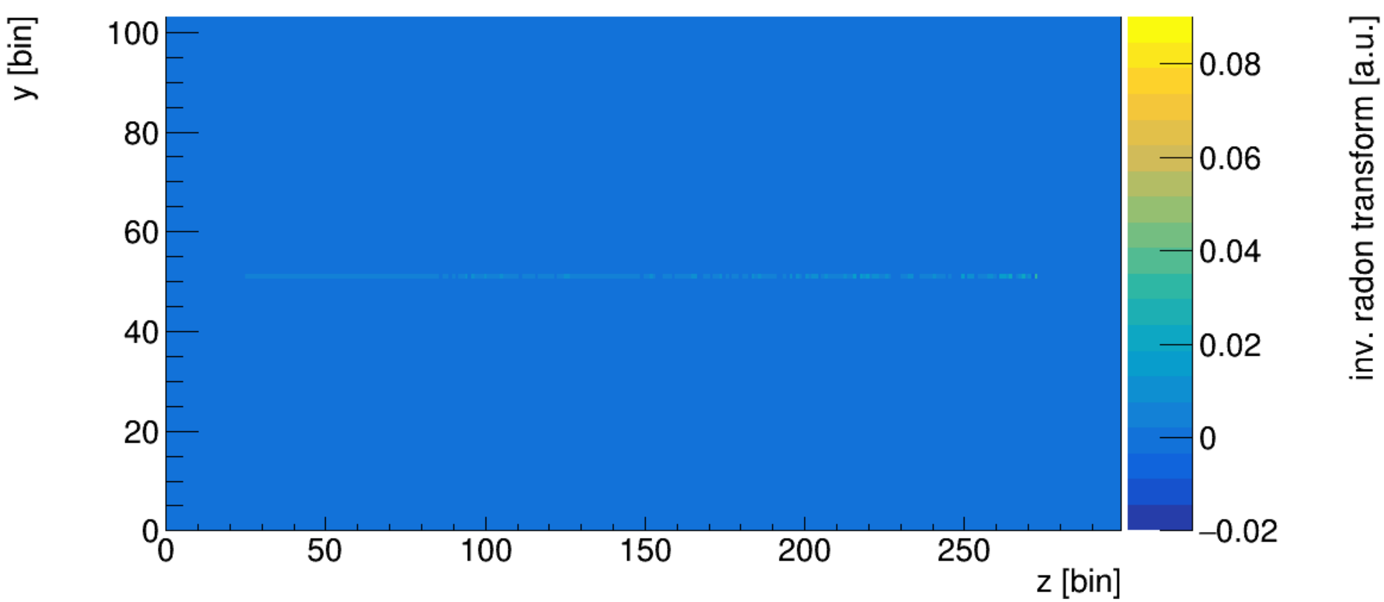
Vert. slice



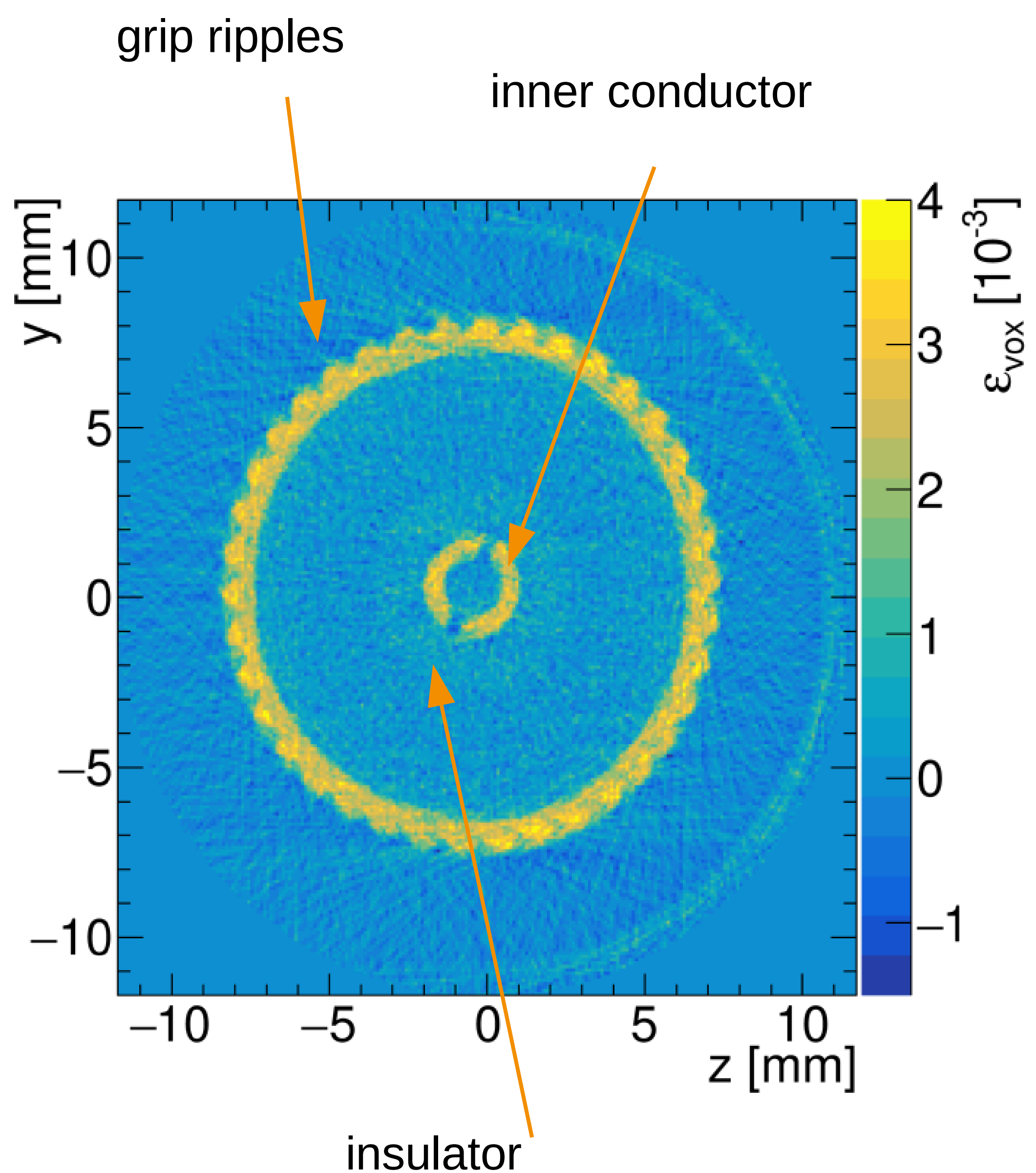
Sinogram

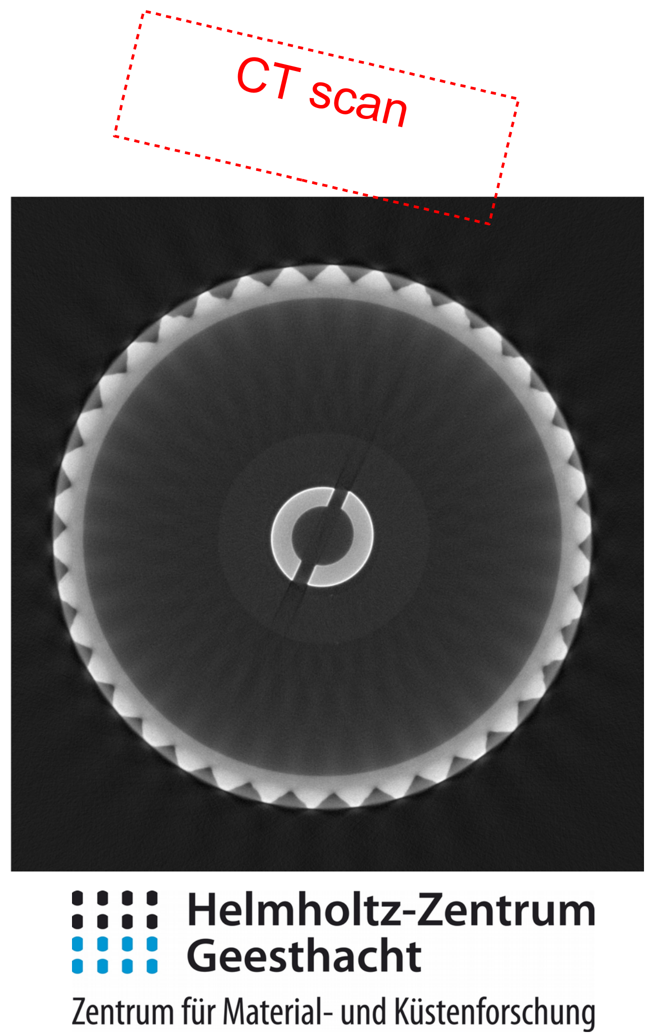






Comparison to CT

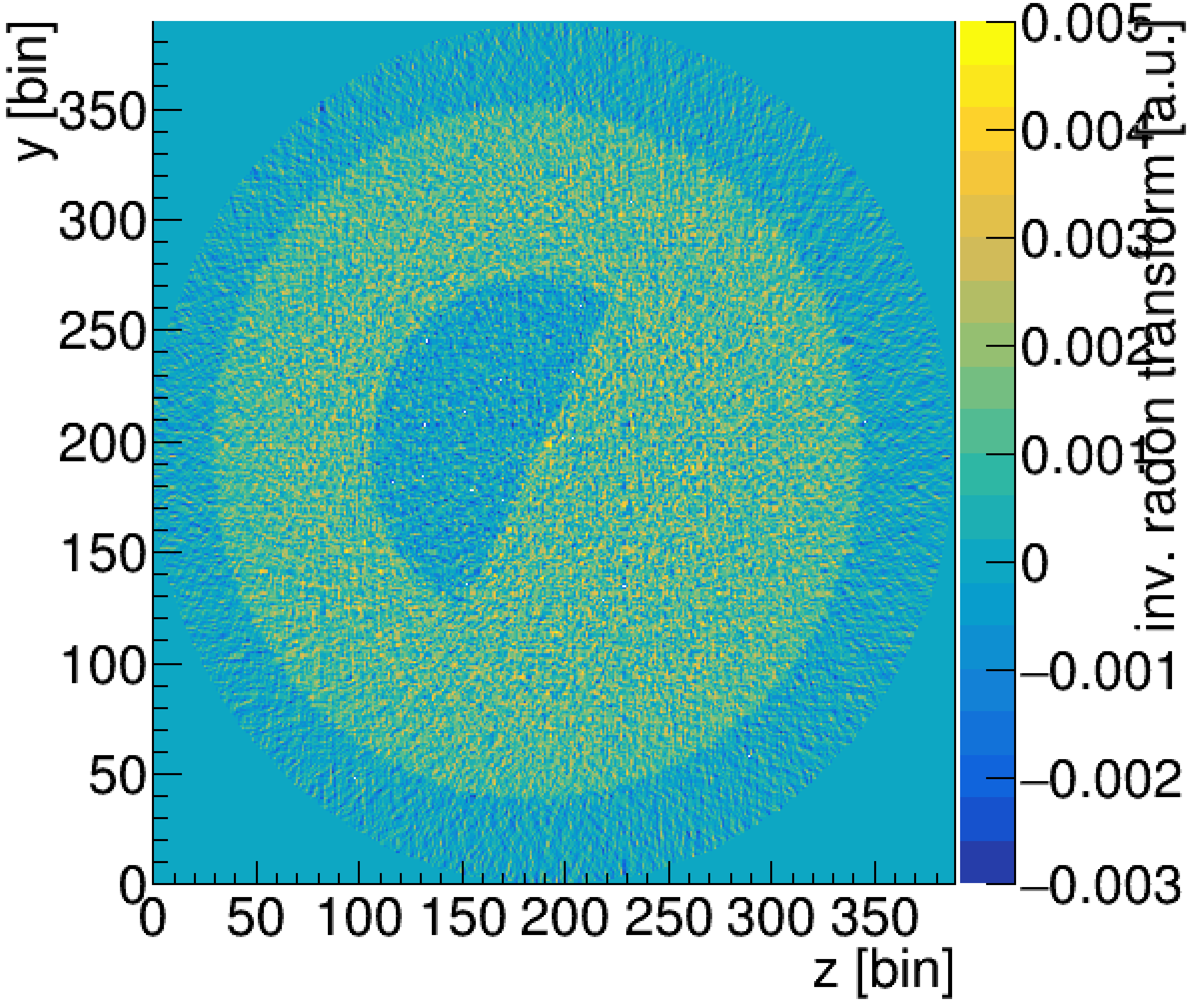




Example of 3D MBI

16 mm diameter
3D printed nickel

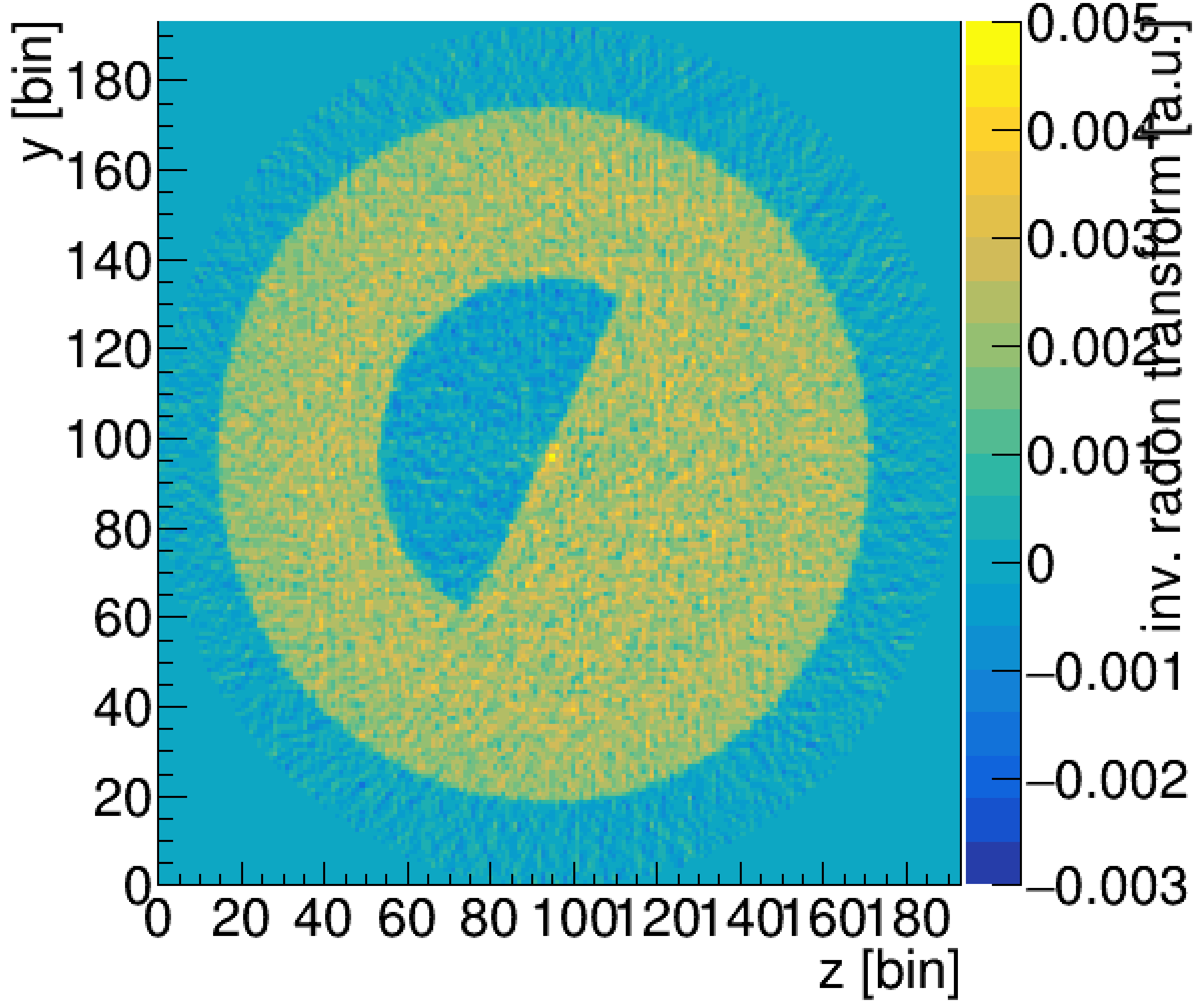
50 um voxel



Example of 3D MBI

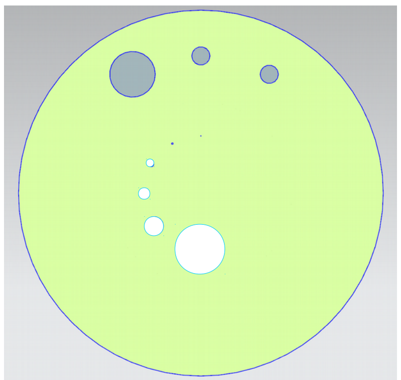
16 mm diameter
3D printed nickel

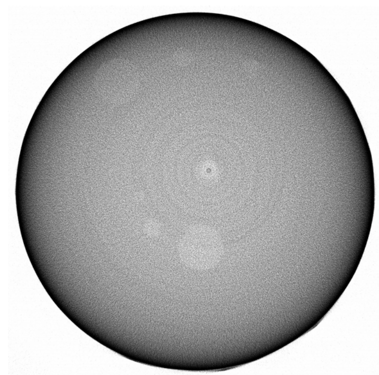
100 um voxel

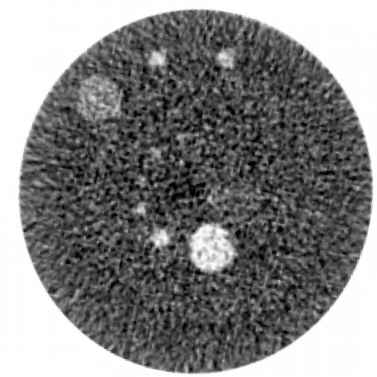


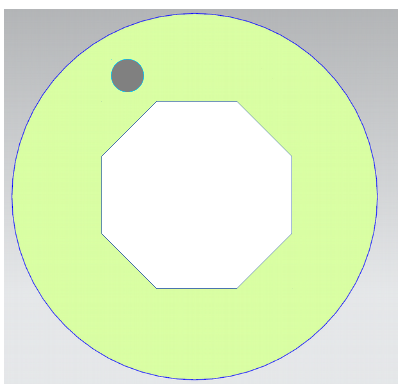
Comparison to CT

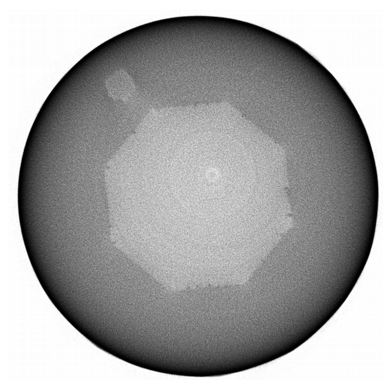
Cross-sections | **CT scan at 170 kVp (inverted grey scale)** | **MBI**

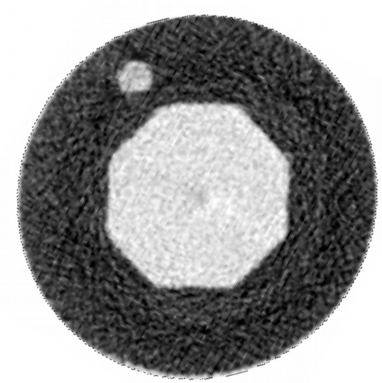






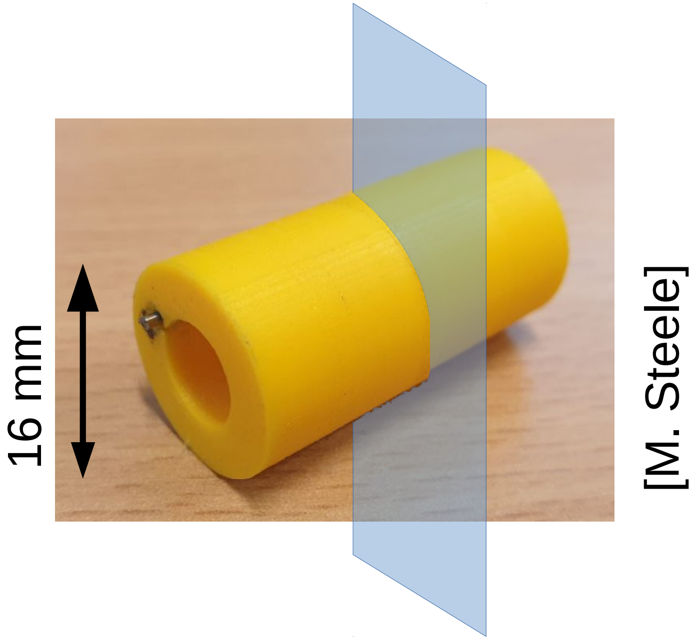


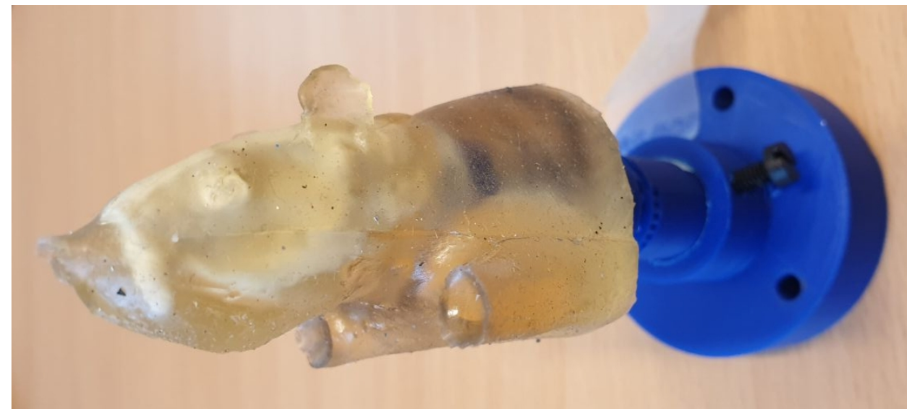


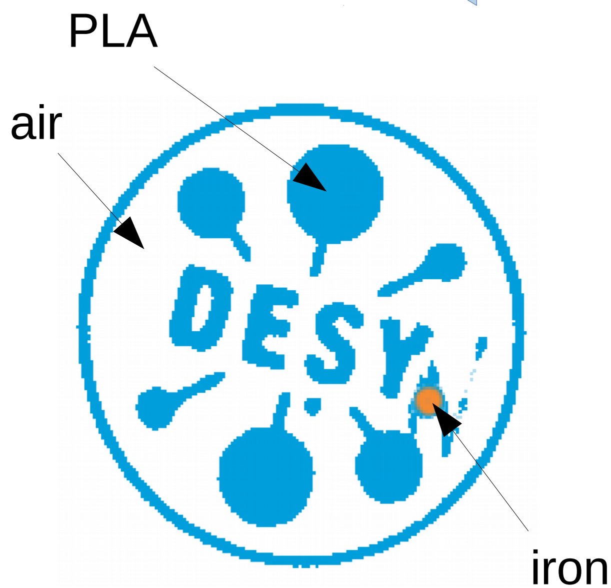


Helmholtz-Zentrum Geesthacht
Zentrum für Material- und Küstenforschung

Tissue-like samples, 500 MeV







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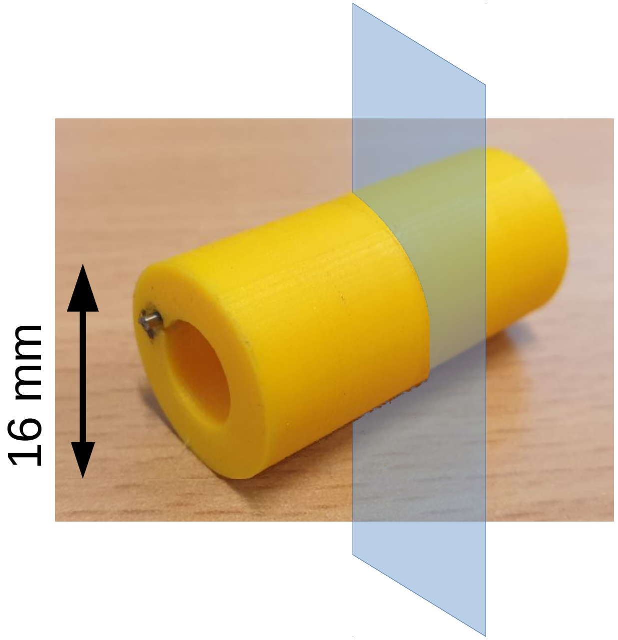
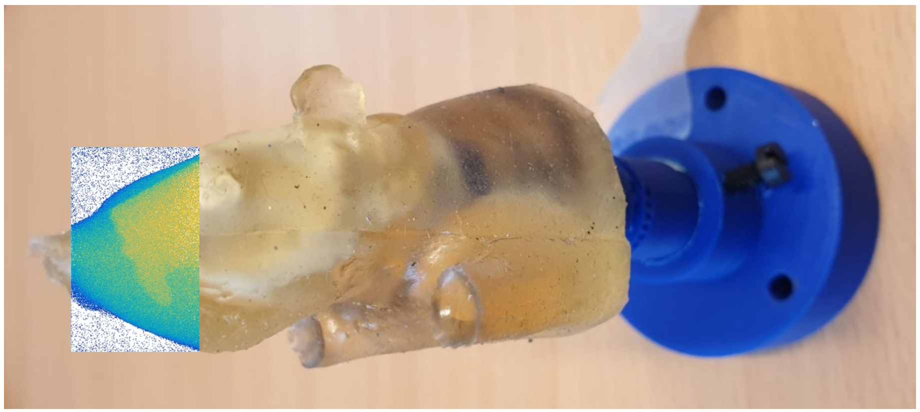
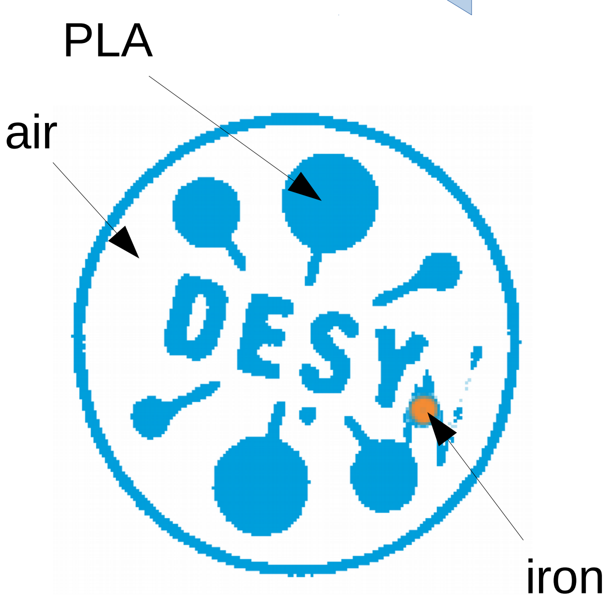
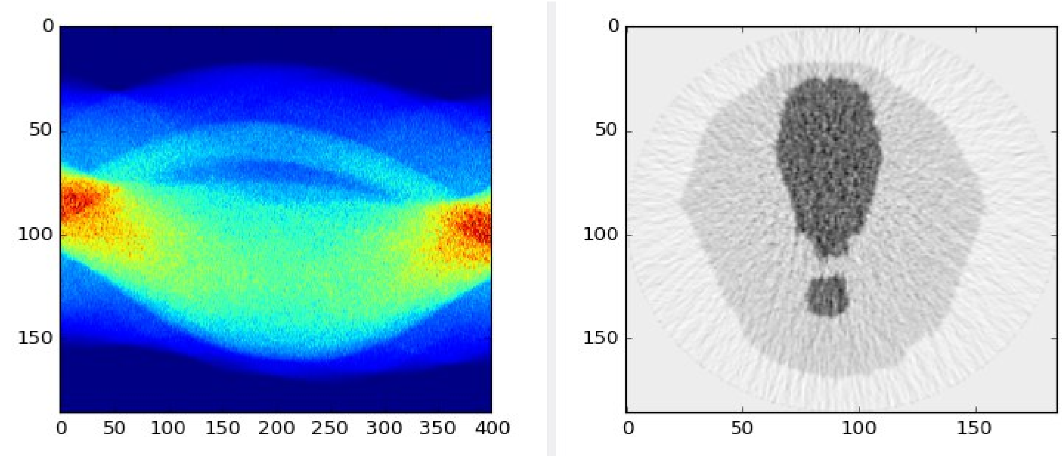


[M. Steele]



[True Phantom]





Conclusion

- MBI works up to at least ε = 100% (human's head ~80%)
- Voxel size limited to ~10 µm
  practical limit is rate dependent → 50 µm @ DESY
- Started at 2 GeV, reached 500 MeV easily (method-wise)
- Multitude of samples tested

Outlook

- Calibration curves for tissue-equivalent materials
  (Summer student)
- Improve image reconstruction (PD position open)
- Estimate CNR a.f.o. dose (particles per pixel per projection)
- Understand clinical needs (CNR, resolution) and dose limits
- Investigate market potential

Contrast vs Resolution