Material Budget Imaging in two and three dimensions

Potential, limits and applications

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Imaging in a Probe
- x-, y-photon
- charged particle

Interaction with the target
- absorption
- scattering
- ...

Measure physical quantity
- intensity

large signal
Imaging in a

**Probe**
- x-, y-photon
- charged particle

**Interaction with the target**
- absorption
- scattering
- ...

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

large signal
Imaging in a

Integral effect over depth

→ no/little information along the depth
Imaging in a

Integral effect over depth

→ no/little information along the depth
Imaging in a

Integral effect over depth

→ no/little information along the depth

Sinogram

Projection position (pixels)

0 50 100 150

Projection angle (deg)

Reconstruction

Pixel
Imaging in a

Probe source

Target

(Set of) Sensor(s)

or

GEANT4

or ...
Material Budget Imaging

→ Repeat measurement for various rotation angles
Physics of MBI

• 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 the Highland
  \[
  \Theta_0 = \left( \frac{13.6 \text{ MeV}}{\beta c p} \cdot z \right) \cdot \sqrt{\varepsilon} \cdot (1 + 0.038 \ln \varepsilon)
  \]

\( \varepsilon = x/X_0 \): Material Budget
\( x \): Path length in the material
\( X_0 \): Material’s radiation length

➔ Measurement:
  Scattering angle distribution
➔ Characteristic quantity:
  Material budget
EUDET Beam Telescopes / *AllPix*

- 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 (this application): σ = 2 – 10 μm
- *AllPix* Detector Simulation Framework (based on *Geant4* libraries)
  - Simulation of the particle propagation and detector response
Track reco and MB estimation

• GBL for track fitting
  - Find the most probable trajectory based on the measured hits
  - Includes multiple scattering
  - Kink angle at the sample: Local, unbiased parameter

• Method for MB 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

• Challenges:
  - Non-Gaussian tails of the distribution
  - Low statistics
Why MBI?

Considerable interest and potential in MBI

- Various upgrade activities in particle physics
  → Estimate of MB distribution for realistic detector description

- Non-destructive testing of prototypes
  → e.g. batteries, high-Z material

- Medical imaging
  → possible dose advantage
  → less artefacts
MBI at Belle II / ATLAS

Belle II PXD module

ATLAS Tracker endcap petal

U. Stolzenberg et al.

M. Queitsch-Maitland et al.
Examples of 3D MBI

- 2D Material Budget map
- Vert. slice
- Sinogram
- Reconstruction
Examples of 3D MBI

2D Material Budget map

Vert. slice

Sinogram

Reconstruction
Examples of 3D MBI

2D Material Budget map
Vert. slice
Sinogram

Reconstruction

2D Material Budget map
Vert. slice
Sinogram

Reconstruction
Comparison to CT

grip ripples

inner conductor

insulator
Example of 3D MBI

50 µm voxel

16 mm diameter
3D printed nickel
Example of 3D MBI

100 μm voxel

16 mm diameter
3D printed nickel
Comparison to CT

Cross-sections

CT scan at 170 kVp (inverted)

MBI

Helmholtz-Zentrum Geesthacht
Zentrum für Material- und Küstenforschung
Interested?
Conclusion & Outlook

MBI works up to at least $\varepsilon = 100\%$
  - In simulation up to 200\%

Pixel/voxel size limit 5 to 10 $\mu$m, practical 50 $\mu$m

Improve image reconstruction
Calibration curves for various materials
Understand market potential
Try biological samples
Contrast vs Resolution