Application of material budget imaging for the design of the ATLAS ITk strip detector.

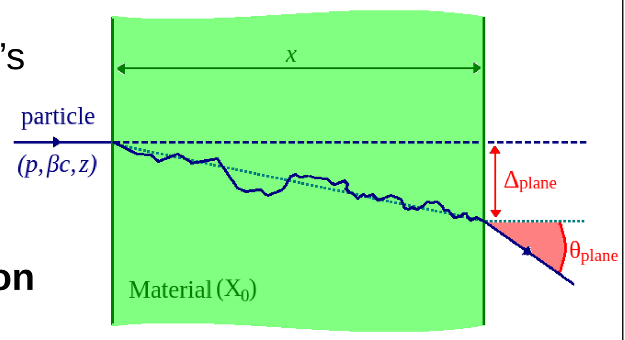
Jan-Hendrik Arling, Ingrid-Maria Gregor

Motivation.

» a charged particle in a material interacts with the nuclei's electric field and can be **deflected** via Coulomb scattering

» for a material traversal, many small-angle scatters sum up to an effective deflection of the incident particle, called **multiple Coulomb scattering**

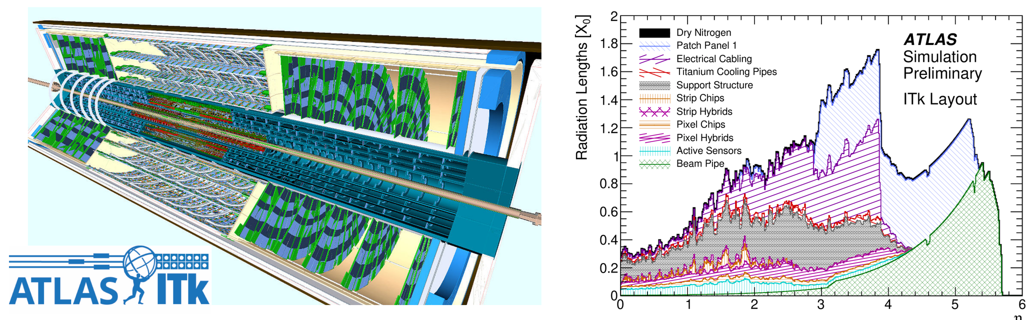
» the deflection angle depends on the material's **density and thickness**



» the **material budget** ε is defined with the **thickness x** and the material specific **radiation length X_0** as

$$\epsilon := \frac{x}{X_0}$$

» minimizing the material budget is important factor in the **design of tracking detectors** → e.g. in the design of the new phase-2 ATLAS Inner Tracker (ITk) [1]



» **radiation length values not known** for each material/ component (e.g. composites, glues) → only approximate values used for detector simulations

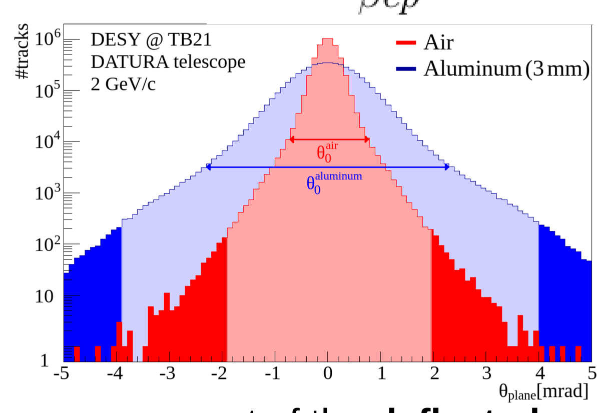
» idea: **direct measurement** of material budget of samples

Method.

» the scattering distribution can be described in the core by a **Gaussian function** (central-limit theorem) superposed with **non-Gaussian tails** due to less frequent hard scatters

» the theoretical description of multiple Coulomb scattering by Molière with **Highland formula** as good approximation:

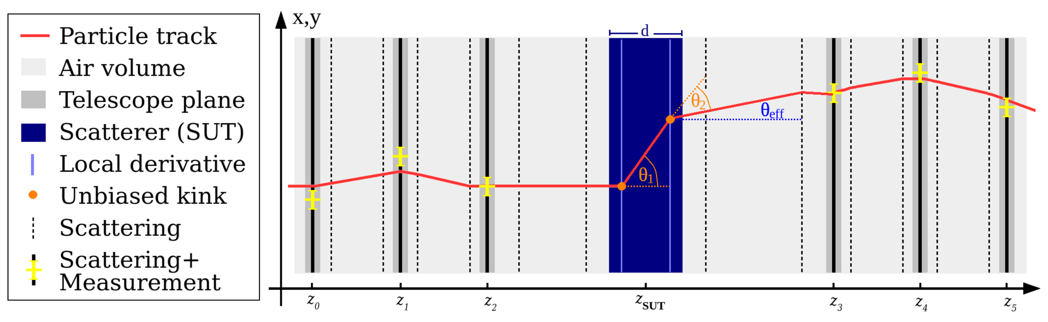
$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p} z\sqrt{\epsilon}\left(1 + 0.038\ln\left(\epsilon\right)\right)$$



» exploit dependence between the scattering width and the material budget in a **test beam experiment** → use of the **DESY II test beam facility** [2] with electrons (1-6 GeV/c)

» measurement of the **deflected particle tracks** after material traversal with highly sensitive beam telescopes → use of the high resolution **EUDET-type beam telescopes** [3]

» **track reconstruction** and unbiased measurement of the individual **scattering angles** → use of the **EUTelescope** framework [4] with the **General Broken Lines** track model

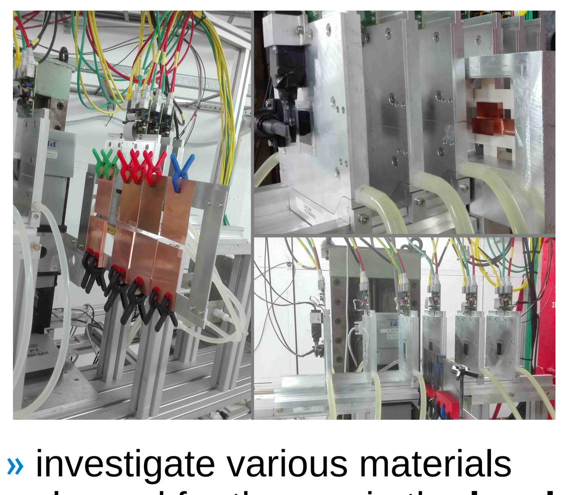


Experiment.

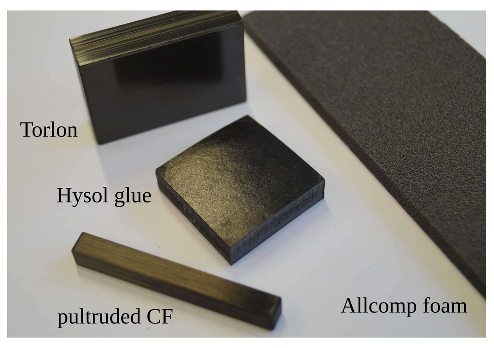
» several **test beam campaigns** on material budget studies were performed at DESY between 2017 and 2020

» systematic testing of **beam and telescope parameters** → **momentum scan** between 1 to 6 GeV/c and variation of **telescope geometry** to optimize angular & spatial resolution

» measurement routine:
→ choose **parameters**
→ measure **air scattering**
→ insert **scatterer (SUT)**



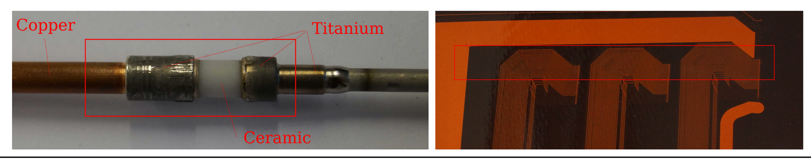
» investigate **homogeneous** samples with **known X_0**
→ Al, Cu, C, Fe, Ni, Sn, Ti, W
→ d = 0.05 to 10.0 mm
→ ε = 3.5·10⁻⁴ to 1.42



» investigate various materials planned for the use in the **local supports** of the ATLAS ITk detector with **unknown X_0**

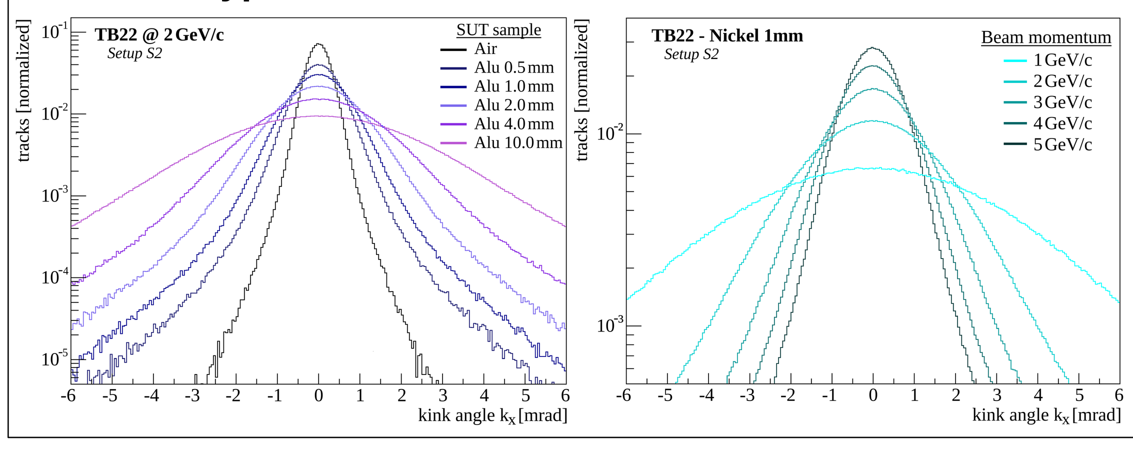
» **position-resolved** analysis allows **2D imaging** of structures and assemblies

→ **petal core:** CFK sandwich with embedded Ti pipe
→ **electrical break:** welded Ti-Cu-ceramic assembly
→ **cocured bus tape:** CFK + Kapton with Cu traces

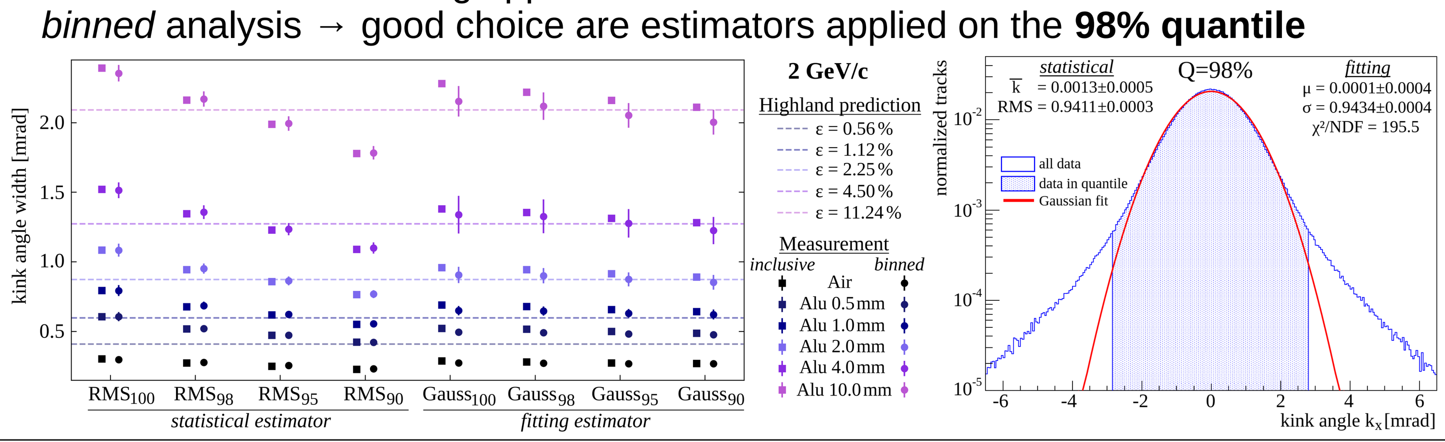


Analysis.

» the distribution of scattering angles depends on the traversed **material type** and **thickness** as well as the **beam momentum**



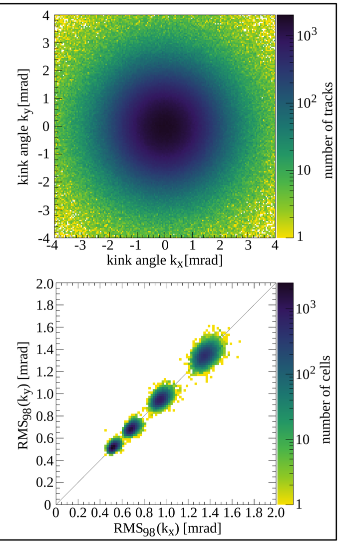
» evaluate a suitable **width estimator** for the kink angle using a statistical approach with the **RMS** and a fitting approach with the **Gaussian fit** for the *inclusive* and *binned* analysis → good choice are estimators applied on the **98% quantile**



» two independent measurements of deflection angle in **horizontal** and **vertical** plane

→ kink angles are fully **uncorrelated** but width estimators are **correlated**

→ **combination** k_{x+y} increase statistics



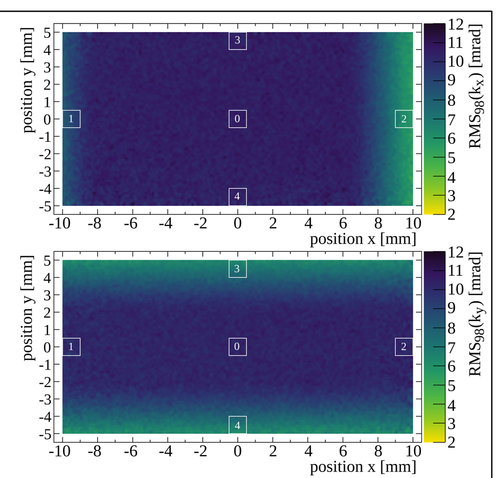
Dependencies.

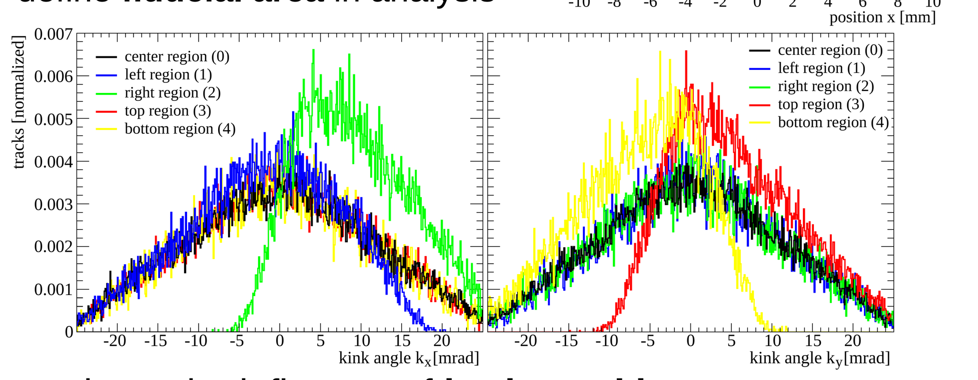
» investigate **acceptance effect** for edge regions in spatially-resolved kink angle maps due to limited active sensor area

→ particles can be strongly deflected to the outside of the **detection area**

→ **biasing** of the measured kink angle distribution and its width

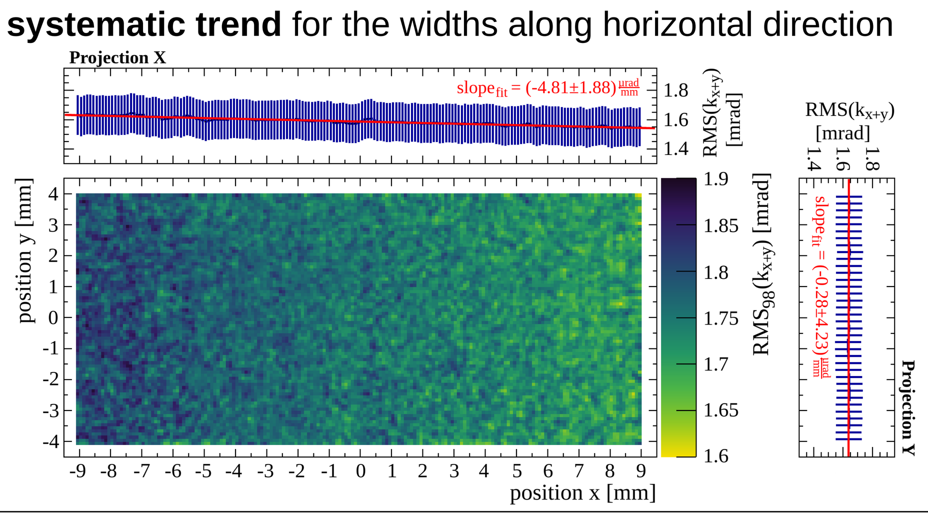
→ define **fiducial area** in analysis





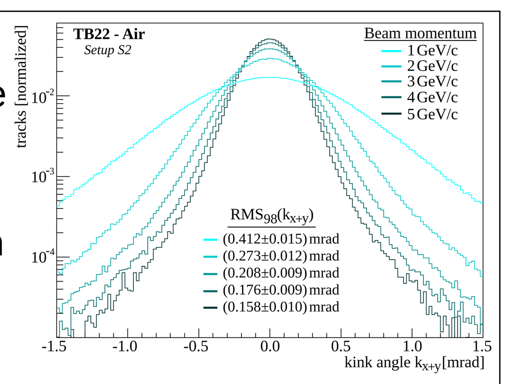
» investigate the influence of **horizontal beam momentum variation** on the estimated kink angle widths due to the momentum spread of the DESY II test beam

→ **systematic trend** for the widths along horizontal direction



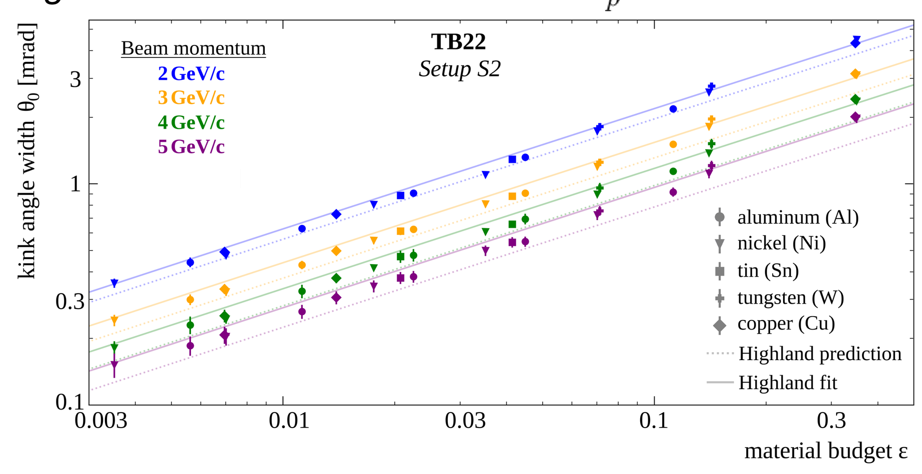
Calibration.

» subtract effect of **scattering** caused by traversed **air** volume

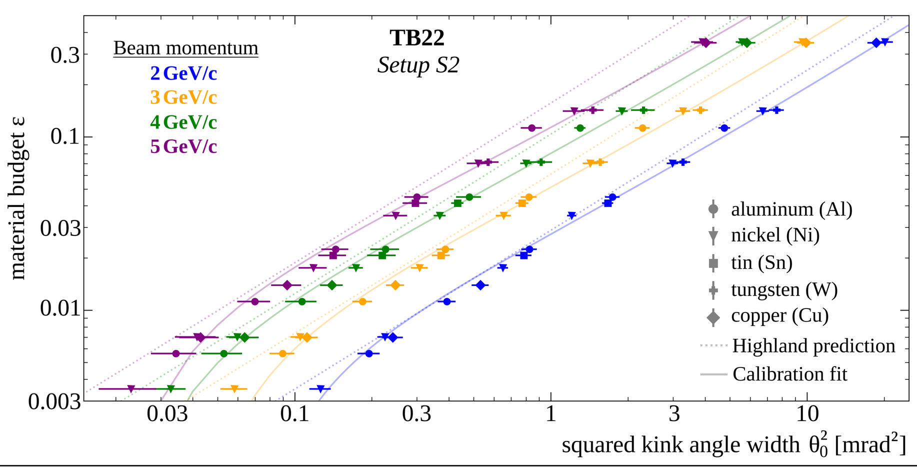


» **calibrate** the reconstructed scattering angle width using measured samples with **known material budgets**

→ *model-dependent Highland calibration* $\theta_0 = f\left(\epsilon\right) = a \cdot \frac{13.6\,\mathrm{MeV}}{p}\sqrt{\epsilon}\left(1 + 0.038\ln\left(\epsilon\right)\right)$



→ *model-independent empirical calibration* $\epsilon = f\left(\theta_0^2\right) = \left[p_0 + p_1 \cdot \theta_0^2\right] \cdot \left[1 + \left(\theta_0^2\right)^c\right]$

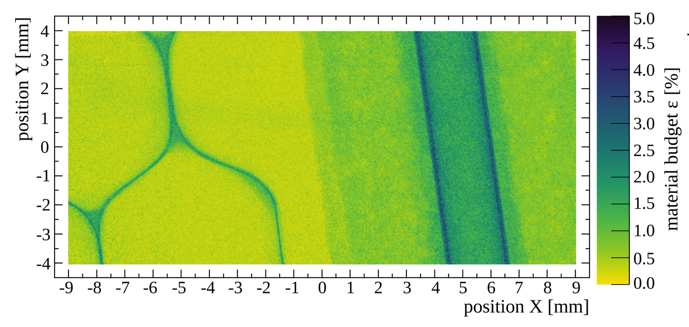


Results.

» experimentally **measured radiation length** values for ITk materials align well with the values used in **simulation**

Material type	X_0^{meas} [mm]	X_0^{sim} [mm]
Carbon-based foam (Allcomp K9)	1620^{+584}_{-549}	1860
Pultruded carbon fiber (T300 CF+adhesive)	271^{+35}_{-34} (epoxy-based) 245^{+12}_{-12} (vinyl-based)	292
Thermoplastic (Torlon 4301)	276^{+41}_{-40}	320
Hysol EA 9396	341^{+38}_{-37} (pure) 350^{+56}_{-54} (carbon-loaded)	300

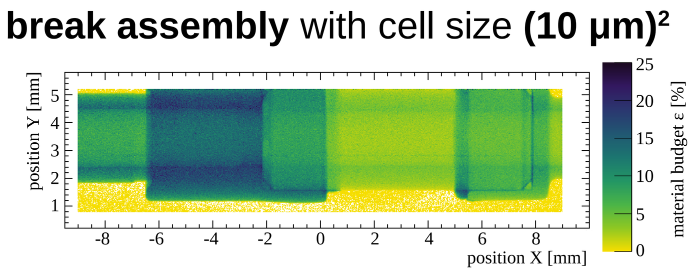
» material budget image of **petal core** with cell size **(10 μm)²**



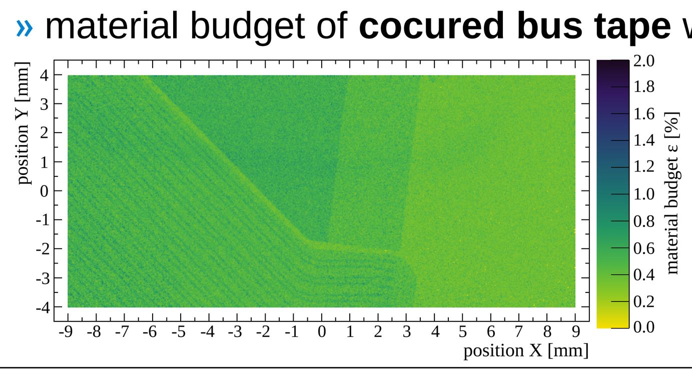
→ internal structure with *carbon fibre honeycomb* and *Titanium pipe* surrounded by *carbon-based foam* is clearly visible

» image of **electrical break assembly** with cell size **(10 μm)²**

→ high contrast in resolving regions with different ε (*metal ↔ ceramic*)



» material budget of **cocured bus tape** with cell size **(20 μm)²**



→ small differences in the material budget are resolvable (e.g. *copper traces*)

→ but limited contrast for the low ε case

Conclusion.

» The **material budget imaging** technique allows to investigate experimentally in a test beam experiment the **position-resolved material distribution** of an object under test.

» A fully functional **work flow** (test beam experiment → offline track reconstruction → analysis of scattering angle distributions) was established and analyzed in detail.

» Several **effects on the scattering distribution** (e.g. correlation, acceptance and beam momentum variation) were studied and taken into account in the analysis.

» A **calibration procedure** using the input of known material samples was implemented and is used for the extraction of the material budget as well as the radiation length values.

Outlook.

» A full overview over the **material budget imaging analysis** can be found in [5].
→ e.g. investigation of **energy loss** effects and first attempt of a **corrected** Highland model

» Possibility to enhance material budget imaging method into **3D tomography** [6].

» Exploring the **future potential** of this new imaging technique in various applications.
→ creation of a radiation length database of materials for (tracking) **detector developments**
→ study high-Z material assemblies (not accessible by photon CT) for **industry application**
→ use of imaging technique as electron CT method in **medical applications**

Acknowledgements

The measurements leading to these results have been performed at the Test Beam Facility at DESY Hamburg (Germany), a member of the Helmholtz Association.

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

References

[1] ATLAS Collaboration., Technical Design Report for the ATLAS Inner Tracker Strip Detector, ATLAS-TDR-025 (2017)

[2] R. Diener *et al.*, The DESY II test beam facility, NIMA, vol. 922, pp. 265-28 (2019)

[3] H. Jansen *et al.*, Performance of the EUDET-type beam telescopes, EPJ, vol. 3, no. 1, p. 7 (2016)

[4] T. Bisanz, JHA *et al.*, EUTelescope: A modular reconstruction framework for beam telescope data, JINST, vol.15, p.09020 (2020)

[5] J.-H. Arling, Detection and Identification of Electrons and Photons, DESY-THESIS-2020-022 (2020)

[6] P. Schütze *et al.*, Feasibility of track-based multiple scattering tomography, APL vol.112, p.144101 (2018)

12th International Conference on
POSITION SENSITIVE DETECTORS