e-CT – Computed Tomography with Electrons

Scattering / Material Budget based Imaging at Electron Accelerators

Paul Schütze, Simon Spannagel
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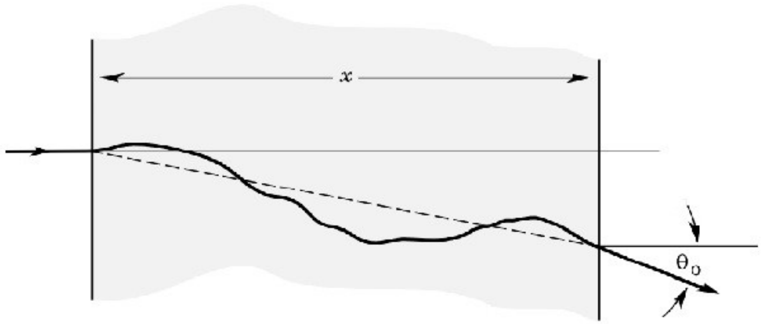
Concept

Multiple Scattering & Material Budget

Coulomb Scattering, Highland Formula



- High-energy particles undergo multiple Coulomb scattering when traversing material

  → Particle is deflected

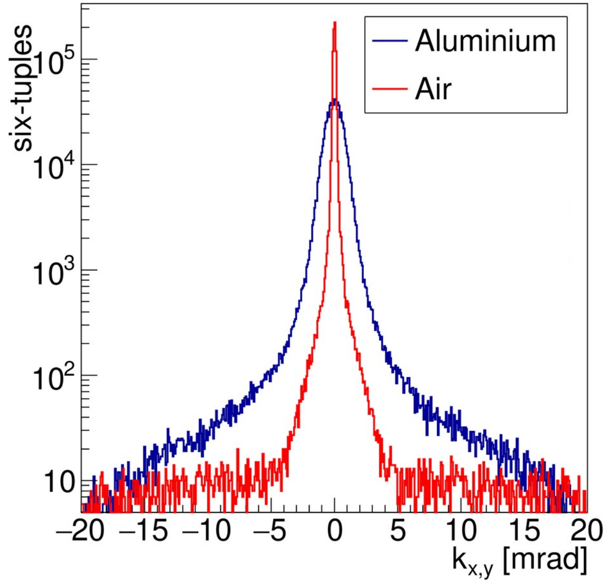
- Scattering angle distribution:
  Gaussian-like center with tails at larger angles

- Width of Gaussian-like center well predicted by the Highland formula:

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

  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



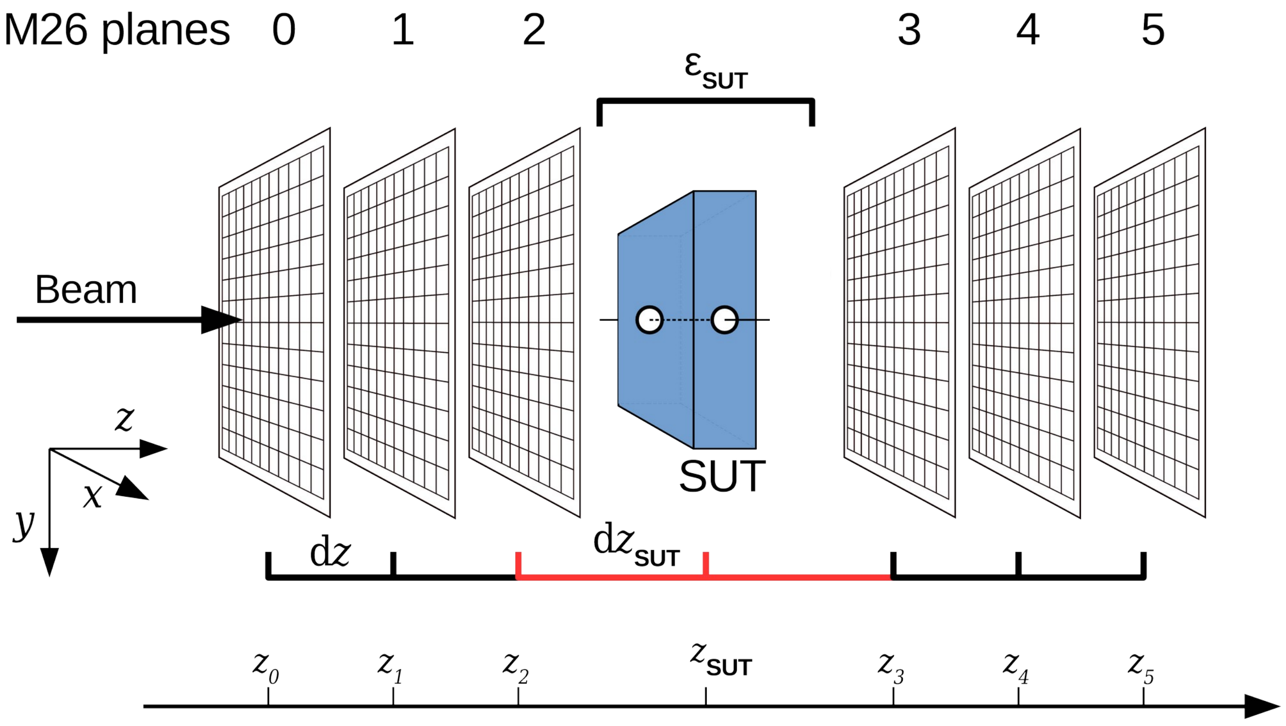
The Work so Far

Track-based Multiple Scattering Tomography

Track-based Multiple Scattering Tomography

Position-resolved measurement of the material budget via the deflection angle

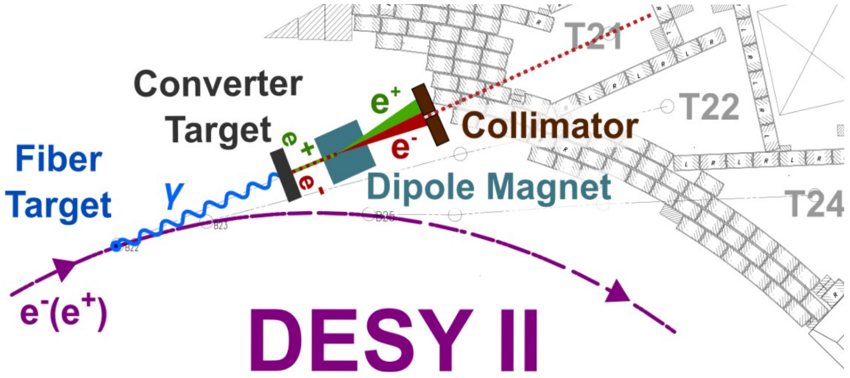
- Single-particle tracking before and after the sample under test (SUT) using so-called beam telescopes – multi-plane (silicon) tracking detectors
- Measurement of the scattering angle at the SUT
- Extrapolation of the track to the position of the sample
- Four steps:
  - Illuminate a sample with a charged particle **beam**
  - Measure the *hits* in the **pixel sensor** planes around it
  - Reconstruct the particle **trajectories** through the telescope
  - Extract the **width** of the kink angle distribution

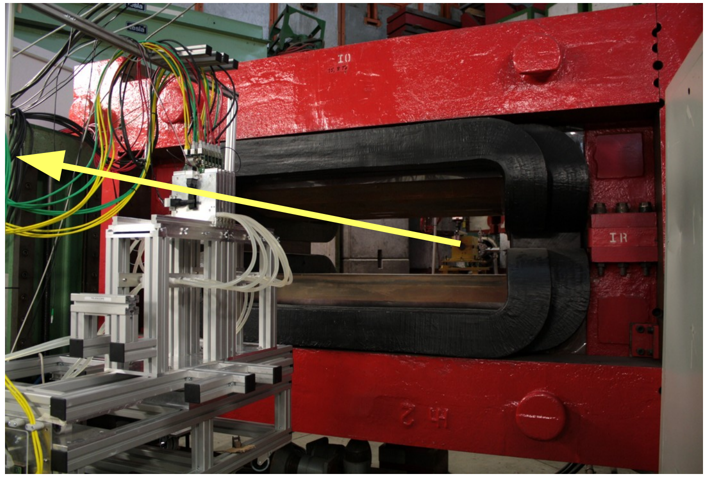


Measurement Setup

Accelerator, beam line & beam telescope

- DESY II Test Beam
  - Positron or electron beams created from primary bunch via bremsstrahlung / pair conversion target
  - Beam energy: 1 – 6 GeV
  - Particle rate: < 50 kHz (energy dependent)
  - Three beam lines available, all equipped with…
- Beam telescopes
  - Six Mimosa26 MAPS sensors
  - Pixel Pitch: 18.4 µm x 18.4 µm
  - Active area: 10.6 mm x 21.2 mm
  - Intrinsic sensor resolution: > 3.24 µm
- Track resolution at SUT: σ ~ 2 µm

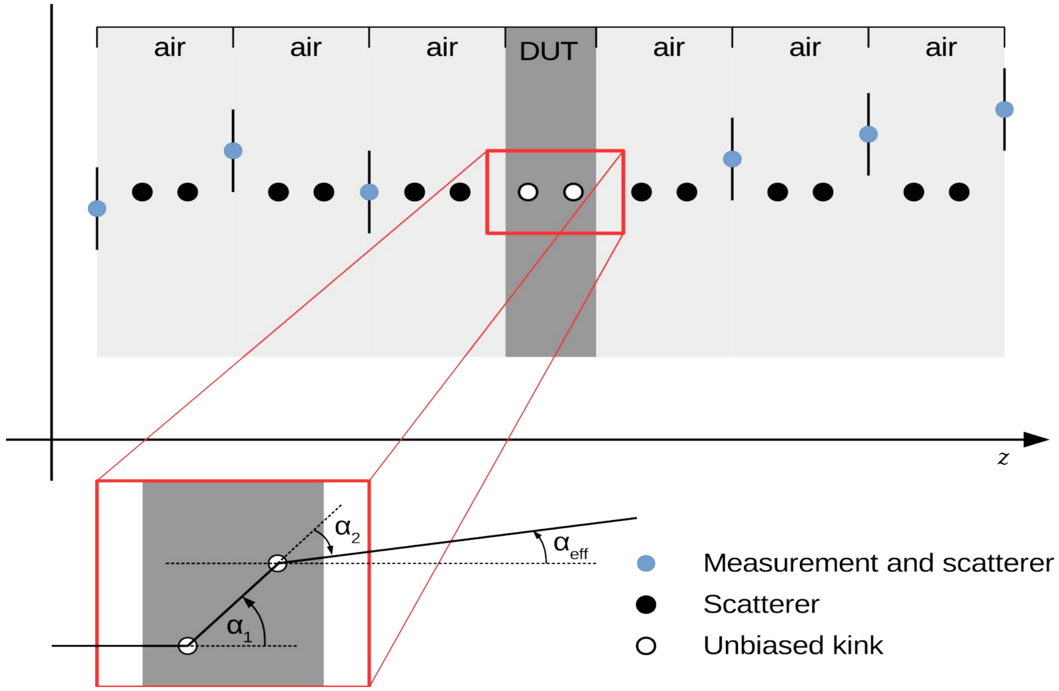




Track Reconstruction & Material Budget Estimators

Combining robustness with contrast

- Track model needs to allow kinks at scatterers
  - Using **General Broken Lines**
  - Find the most probable trajectory based on the measured hits
  - Uncertainties weighted with (known) detector materials to include multiple scattering in telescope
  - Kink angle at the sample: Local, unbiased parameter in the track model
  - Volume scatterer approximated by two thin scatterers
- Estimator for distribution width not straight forward
  - Gaussian shape only approximation
  - Need statistically robust method with high sensitivity for good contrast
  - E.g. **Average Absolute Deviation** of the inner 90% quantile
- Many more parameters: voxel size, required statistics



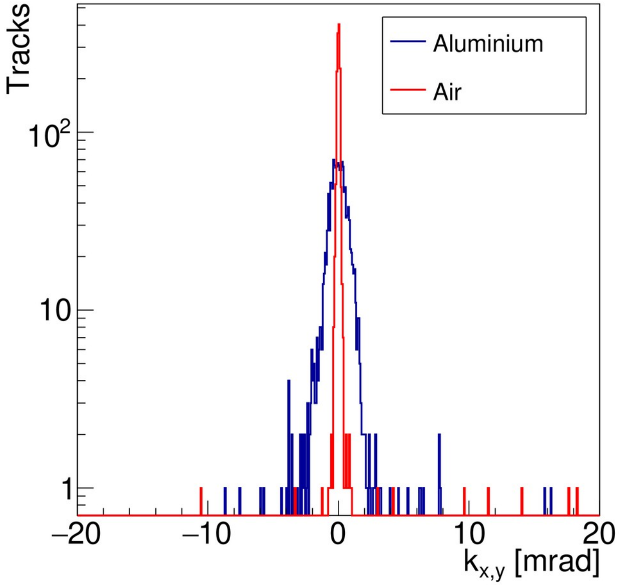
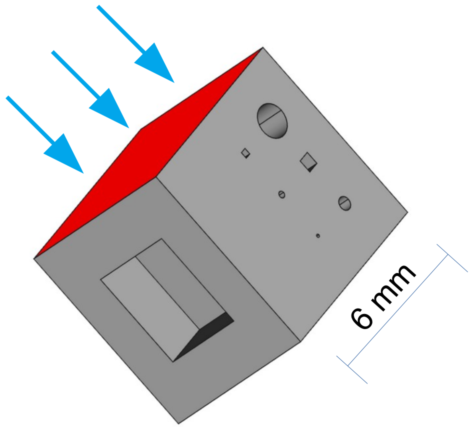
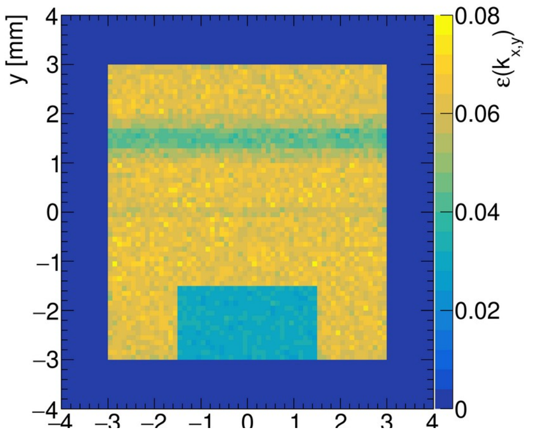


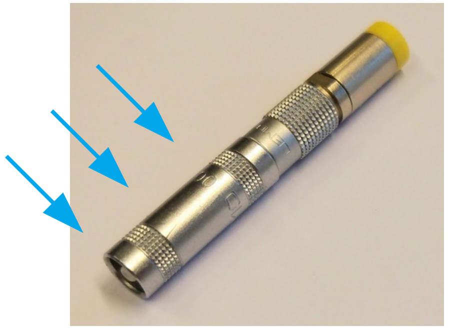
Image Reconstruction

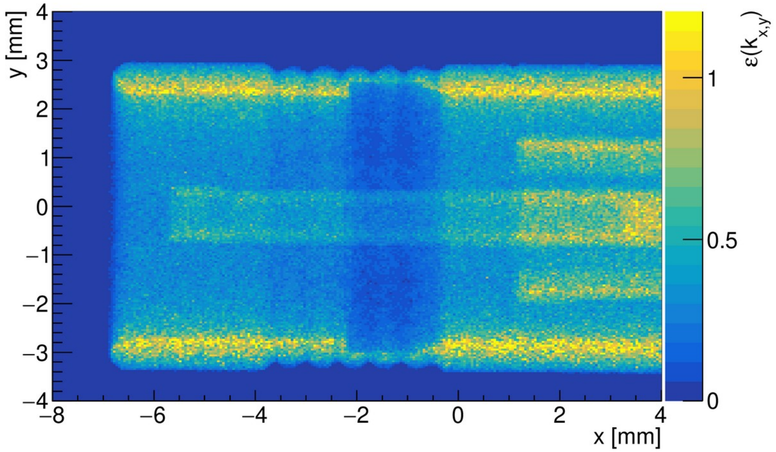
2D measurement of the scatterer material budget

- Illumination of the scatterer, reconstruction of individual particle tracks
- Division of the image plane (SUT) into regions (pixels)
- Calculation of scattering angle for every track, determination of scattering angle distribution width individually for each pixel
- Calibration of the scattering width to material budget using known-thickness known-material scatterers







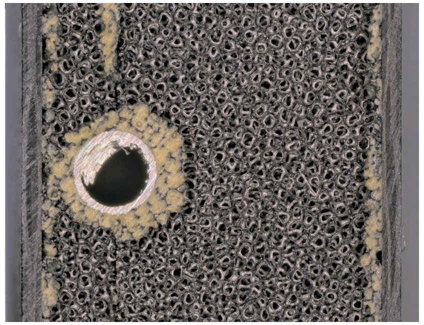


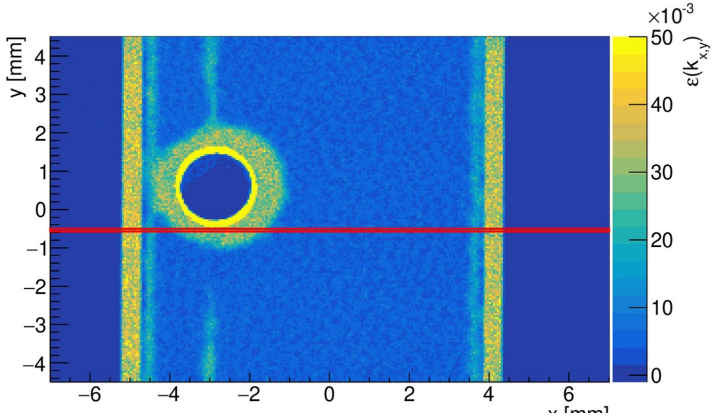
- Result: projection of the material budget Data & simulation compare very well
- Material budget of LHC tracking detector layers (CMS & ATLAS upgrades, complex CF with glue)

First Applications in High-Energy Physics

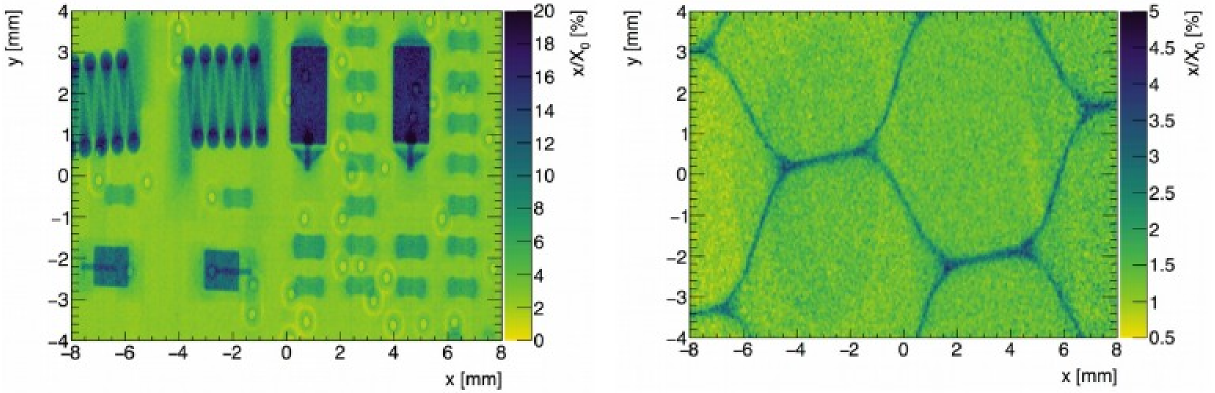
Measurement of detector structures & comparison with simulations

- CMS Phase II Tracker Upgrade
  - CF foam with cooling pipe & face sheets
  - Glue layers visible in material budget

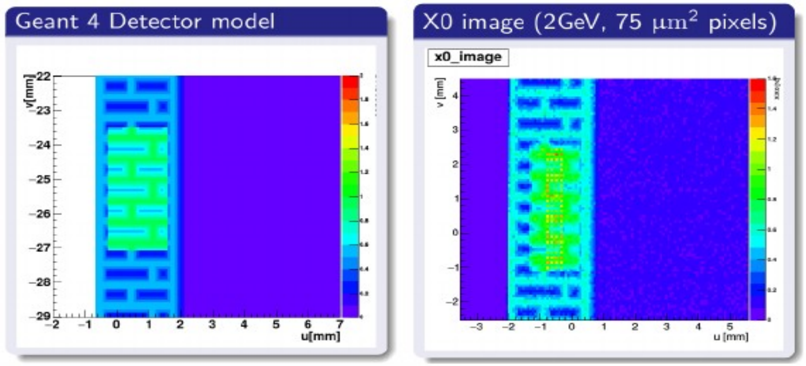




- ATLAS ITk Upgrade
  - Measurement of endcap petal structures
  - PCBs, CF honeycomb structure



- Belle-II Silicon Vertex Detector
  - Comparison of material budget measurement with detailed simulations

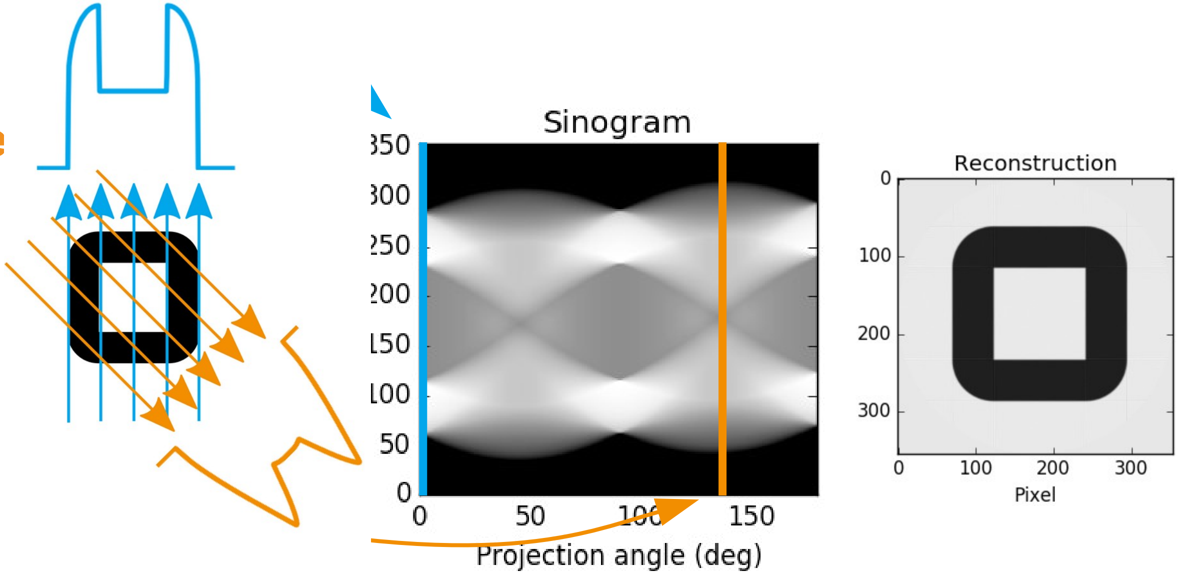


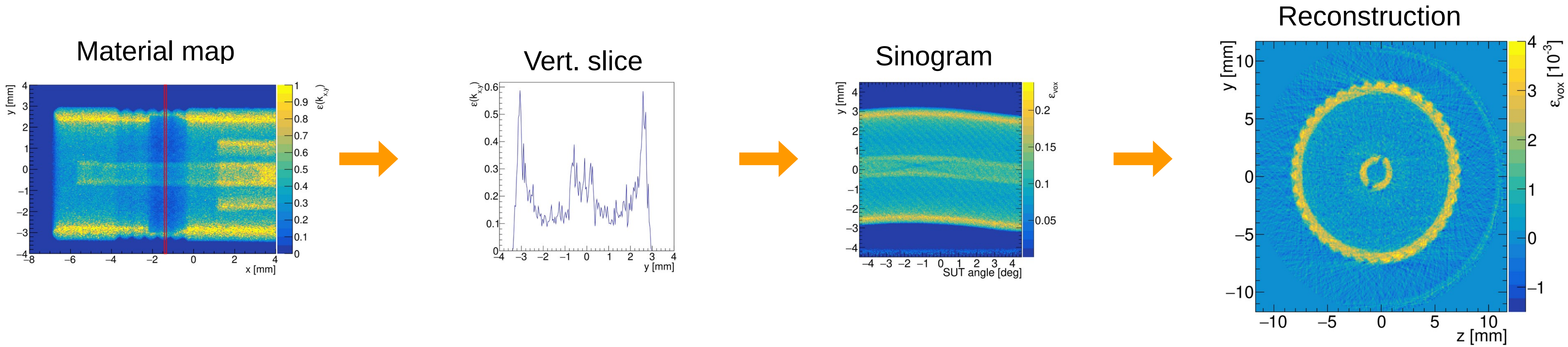
3D Computed Tomography

Reconstruct the 3rd dimension from repeated measure

- Repeated projection measurement at different angles
- Generate sinogram from individual images
- Perform inverse radon transform to reconstruct internal material budget distribution

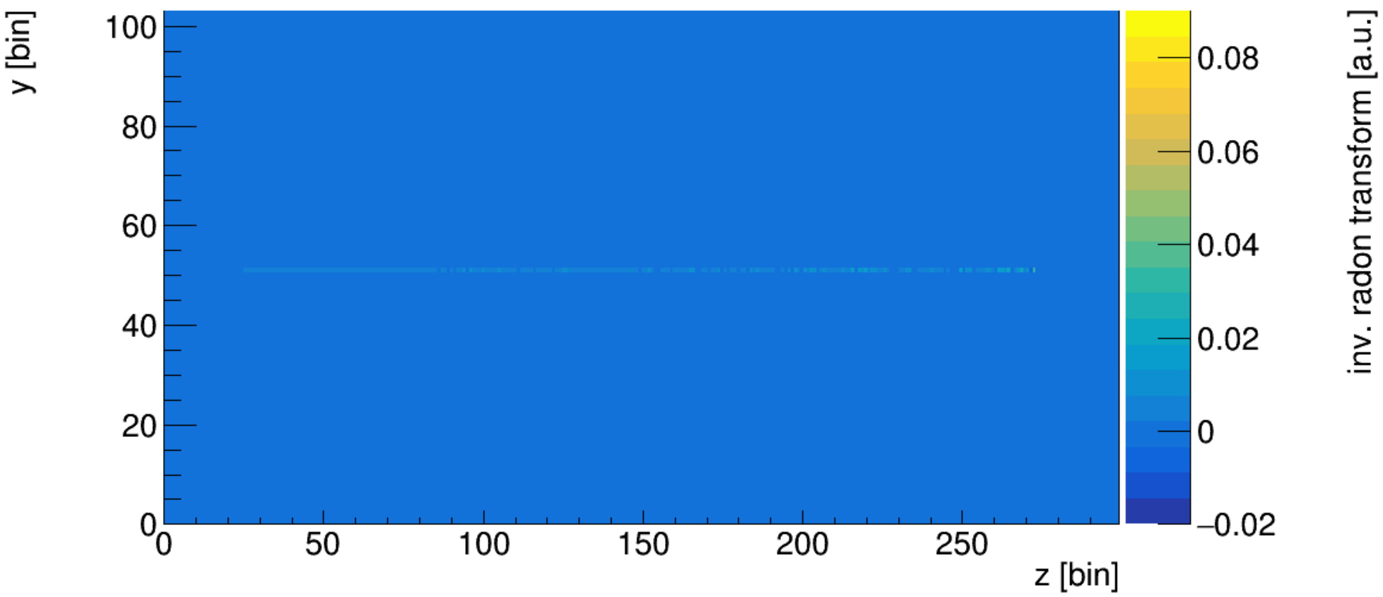
  → Computed tomography

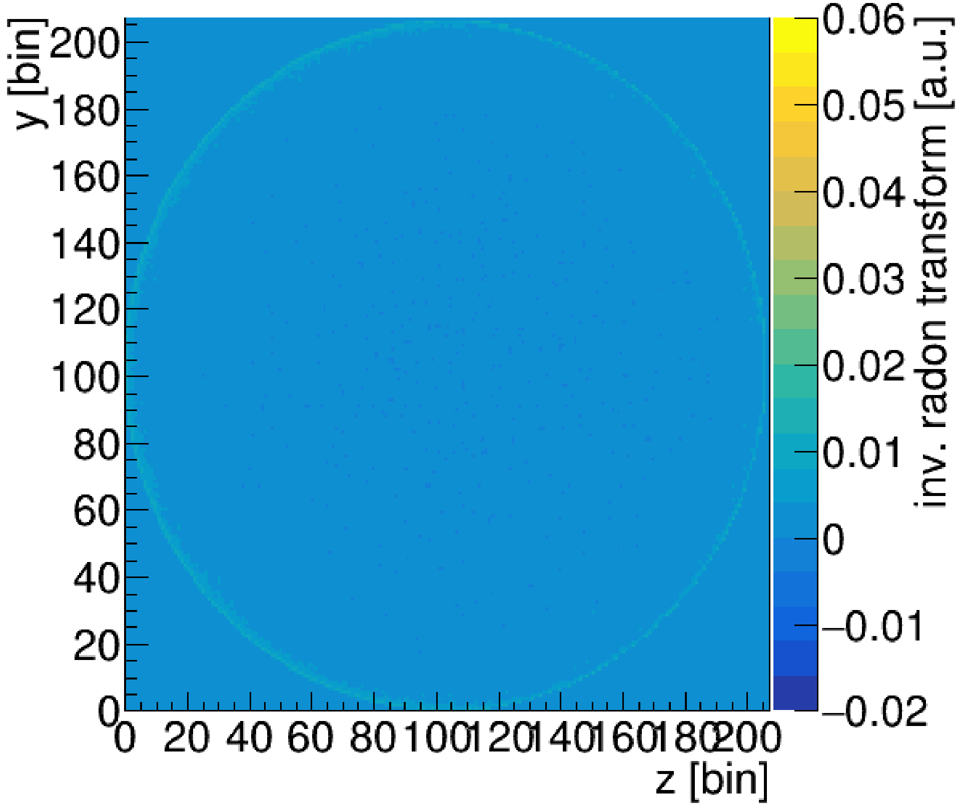




3D Images: Animations

Computed tomography via scattering distribution of electrons

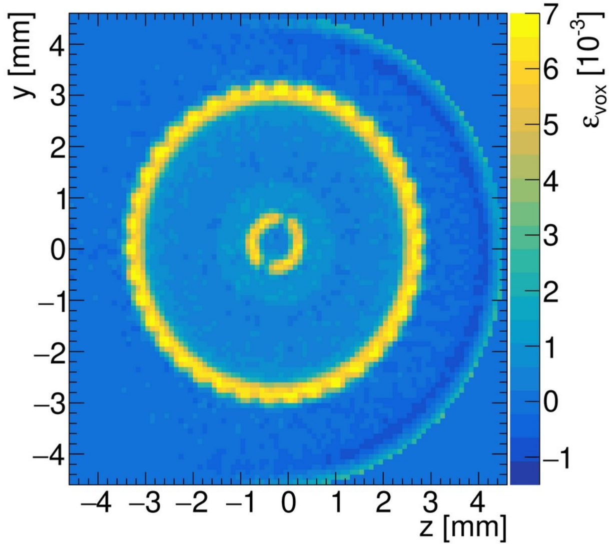


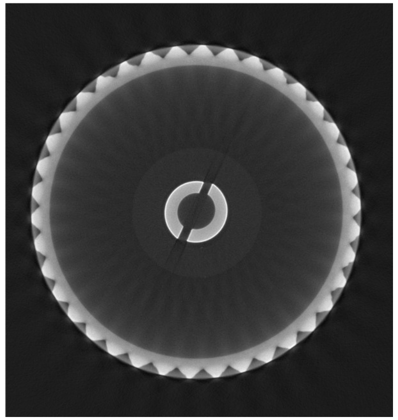


Comparison: X-Ray CT

Pros and cons to conventional computed tomography

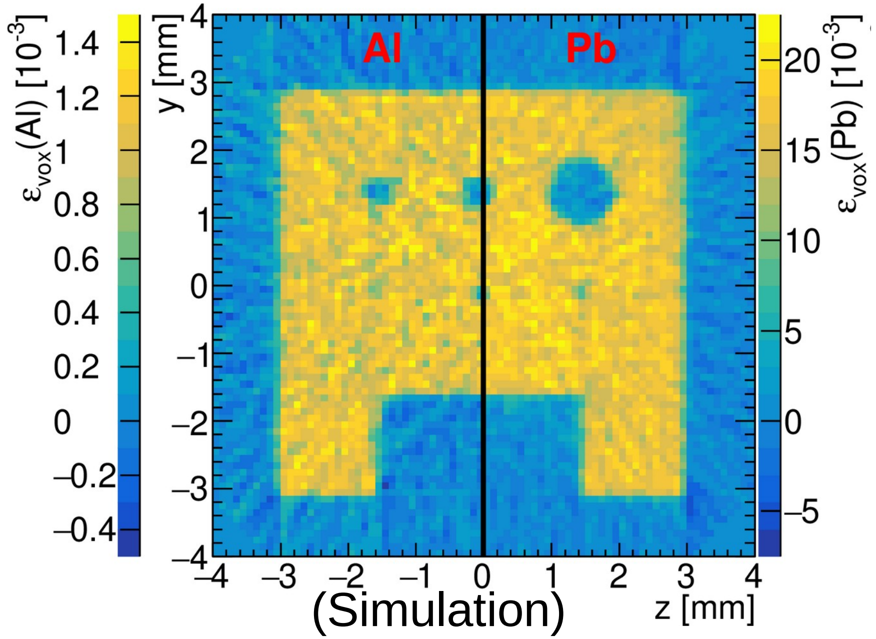
- X-rays attenuation length significantly shorter than radiation length of high-energy particles – example: **Lead**
  - X-ray attenuation length:
    ~0.1 mm (50 keV) / ~0.7 mm (200 keV)
  - Radiation length (GeV electrons): 5.6 mm





Helmholtz-Zentrum Geesthacht
Zentrum für Material- und Küstenforschung

- GeV electrons can serve as probe for thicker materials
- High-Z materials can be probed with high precision
  - Simulation: after calibrating for material,
    even higher contrast achieved for lead samples than aluminum
- Strongly reduced beam hardening effects



Status Quo

Computed tomography via scattering distribution of electrons

- Reconstruction of 3D material structure using multiple scattering distributions achieved, both from simulation and measured data
- Computed tomography achieves good contrast, better for larger material budget
- Acceptance area limited to telescope sensors to ~ 1 cm x 2 cm
- Limited by statistics
  - Individual particle tracking
  - Measurement time for one sample ~ 3 days

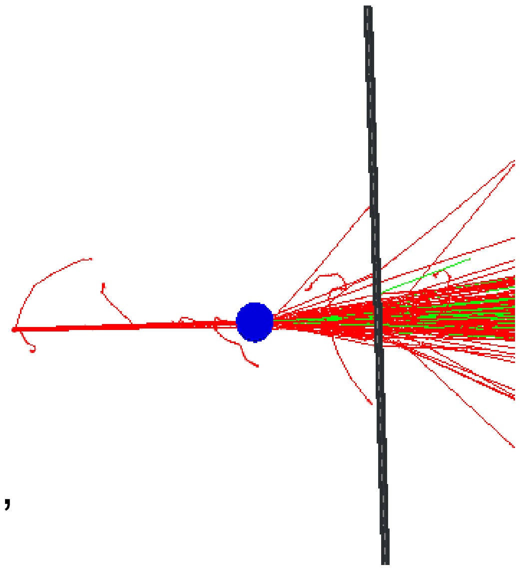
- With faster response, could this method be of broader interest?
- Industrial & clinical applications / diagnosis tool?
- Can we decrease measurement time by orders of magnitude?

A New Approach

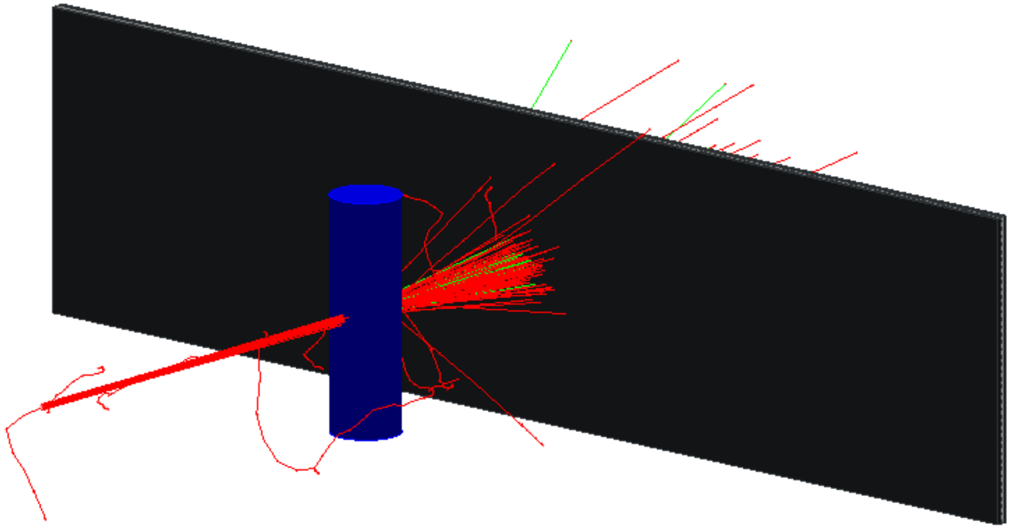
Integrated-intensity-based Multiple Scattering Tomography

Intensity-Based Measurements

Making use of high-performance beams

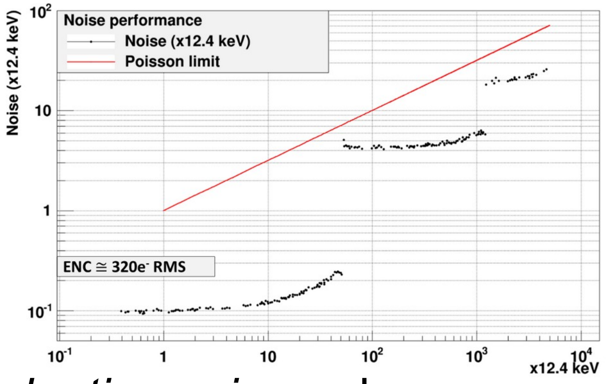


- Up till now, particle track position used to identify relevant pixel / voxel of final image
- Turning things around:
  use pencil beam to raster the sample, beam position dictates voxel size & position
- Single detector records absolute beam size after scattering as function of the position,
  Single-shot many-particle measurement of scattering width
- Requirements:
  - Well-controlled, small beam spot @ sample
  - Controlled relative movement beam ↔ sample
  - High repetition rate for fast image recording
  - Fast detectors with large dynamic range



@ DESY:
PITZ – Zeuthen
ARES – Hamburg

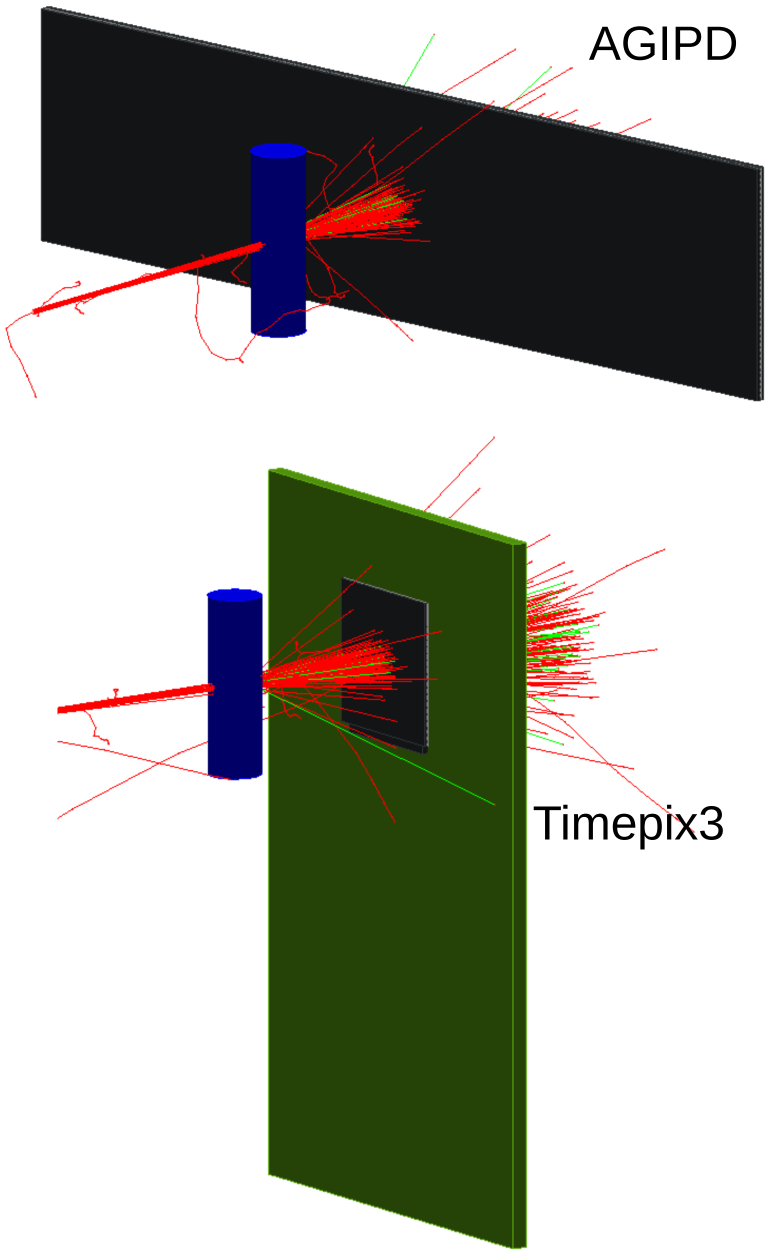
Detector Options



- **AGIPD**
  - Large area
  - High dynamic range, if functioning in *adaptive gain* mode
  - Available on loan by developers @ DESY FS
  - Requires implementation of data acquisition

- **Timepix3**
  - Smaller area
  - Lower, but tolerable dynamic range
  - Available at almost any time @ DESY FH
  - Data acquisition ready

  → Suitable candidate for proof-of-principle measurements



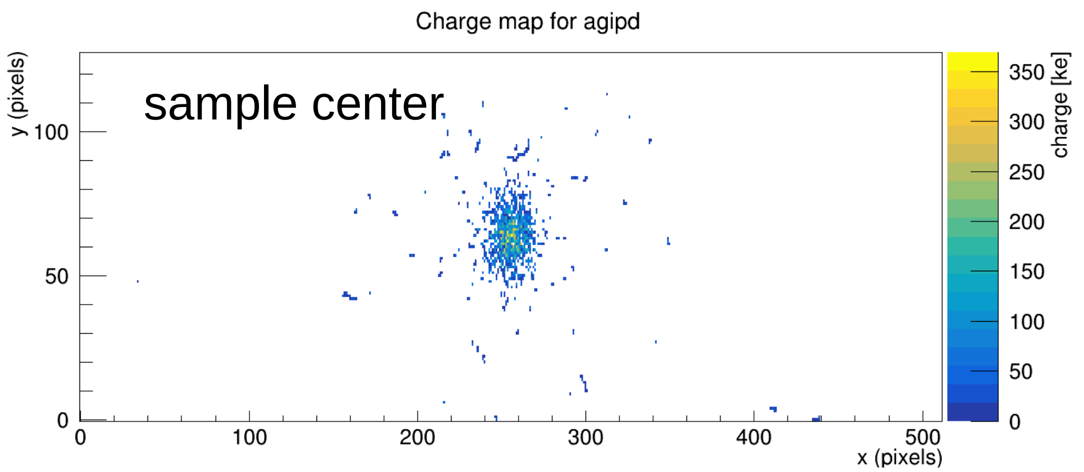
Scattering Distribution & Sample Distance

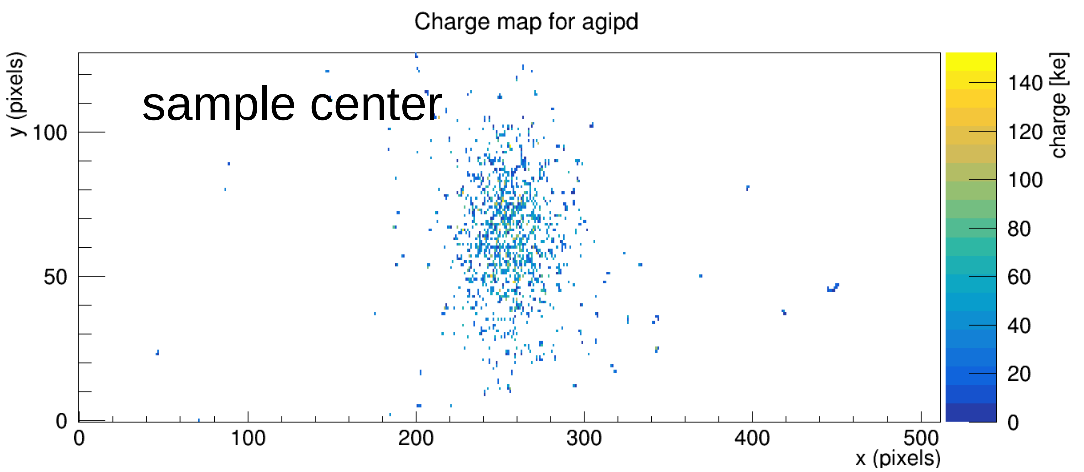
Allpix² Simulations with AGIPD Sensor Geometry

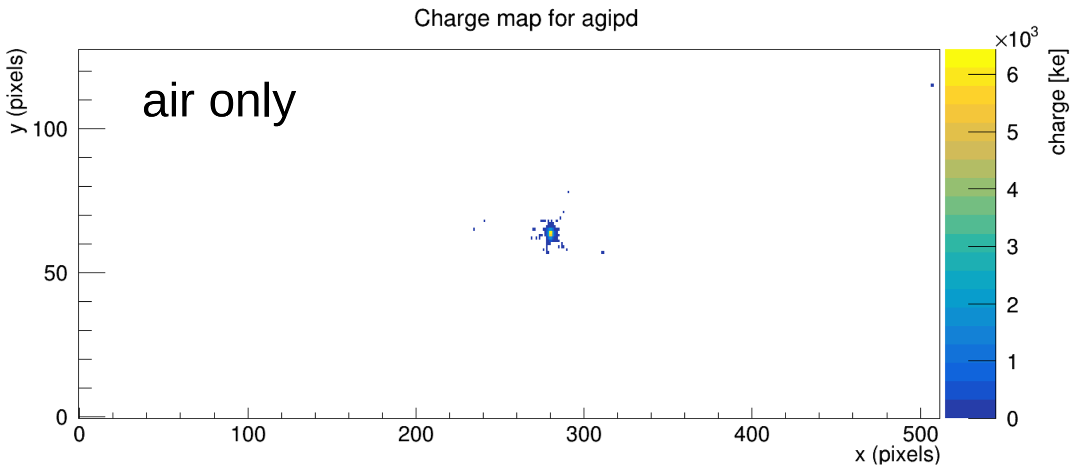
22 MeV, 1000 electrons
100 um transverse size
plexiglass cylinder, 3mm rad.

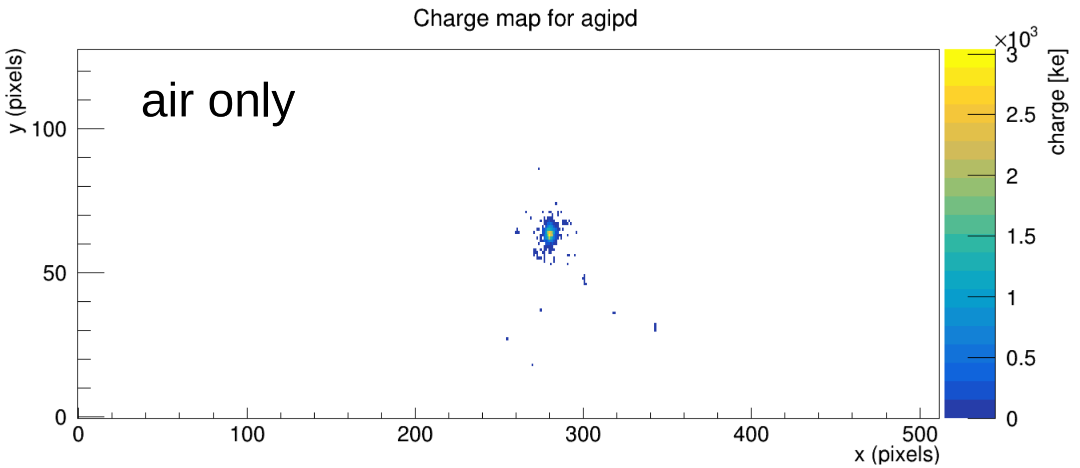
Sample ↔ AGIPD: 20 mm

Sample ↔ AGIPD: 50 mm









Summary

Summary & Outlook

e-CT imaging based on material budget measurements with electrons

- Single-particle tracking e-CT shown to perform well
  - Simulation, calibration, data taking performed at DESY II synchrotron beam lines
  - Already used by high-energy physics experiments to measure detector component properties
  - Measurement time prohibitively long for wider application in industry / medical applications
- Novel approach using one-shot intensity-based scattering measurements
  - Reduces required measurement time by orders of magnitude
  - Rastering of sample either by beam or by motion stage
  - Single detector record widened beam after scattering interaction in sample
- Simulations & detector / DAQ preparations ongoing, funding application for postdoc & PhD student pending
- We are hoping for some first beam time in 2022!

Open Questions / Beam Requirements / …

- How can we synchronize with the accelerator?
  Bunch clock?

- Beam conditions:
  - How does rastering work? Area, stepping, …?
  - Minimal possible bunch current?
  - Transverse bunch size at focal plane?

- Counting room, space for detector DAQ & infrastructure?
- General logistics

Thank you

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Simon Spannagel
FH-ATLAS
Simon.spannagel@desy.de
+49-40-8998-2794