eCT – Computed Tomography with Electrons

Scattering / Material Budget based Imaging at Electron Accelerators

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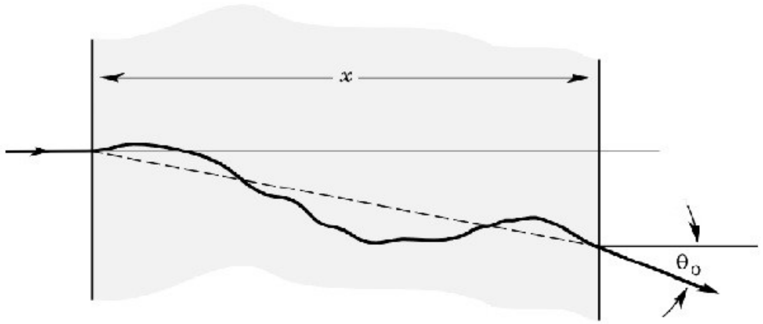
for the eCT and ARES teams

11th BTTB
DESY, Hamburg, 18/04/2023

Measurement Principle

Multiple Scattering & Material Budget

Coulomb Scattering, Highland Formula



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

  → Particle is deflected

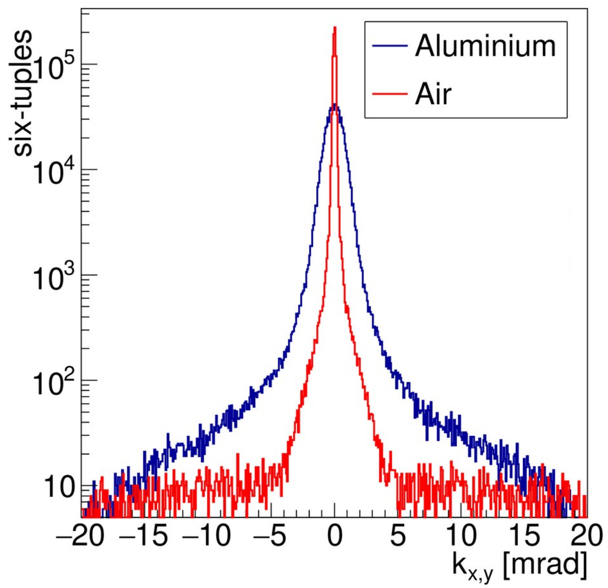
- Scattering angle distribution:
  Gaussian-like center with tails at larger angles

- 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



Initial Feasibility Studies

Track-based Multiple Scattering Tomography

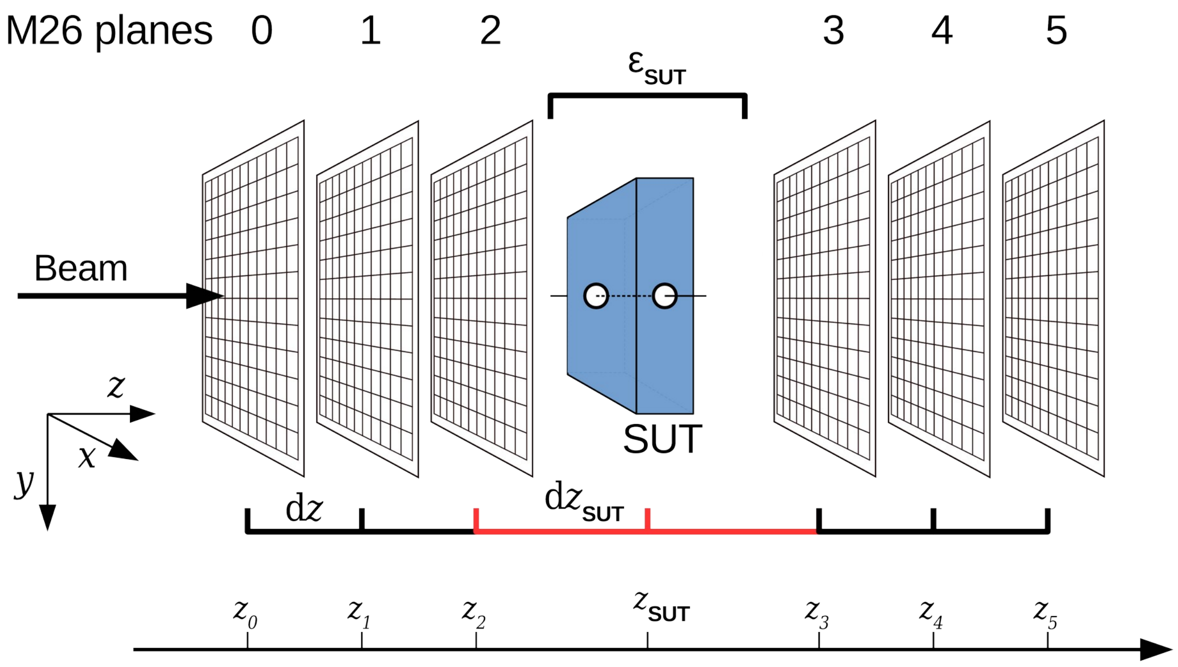
Track-based Multiple Scattering Tomography

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

- Goal: Measurement of the scattering angle at the SUT

- Four steps:
  - Illuminate a sample with a charged particle **beam**
  - Measure the *hits* in the **pixel sensor** planes in front of and behind it
  - Reconstruct the particle **trajectories** through the telescope
  - Extract the **width** of the kink angle distribution

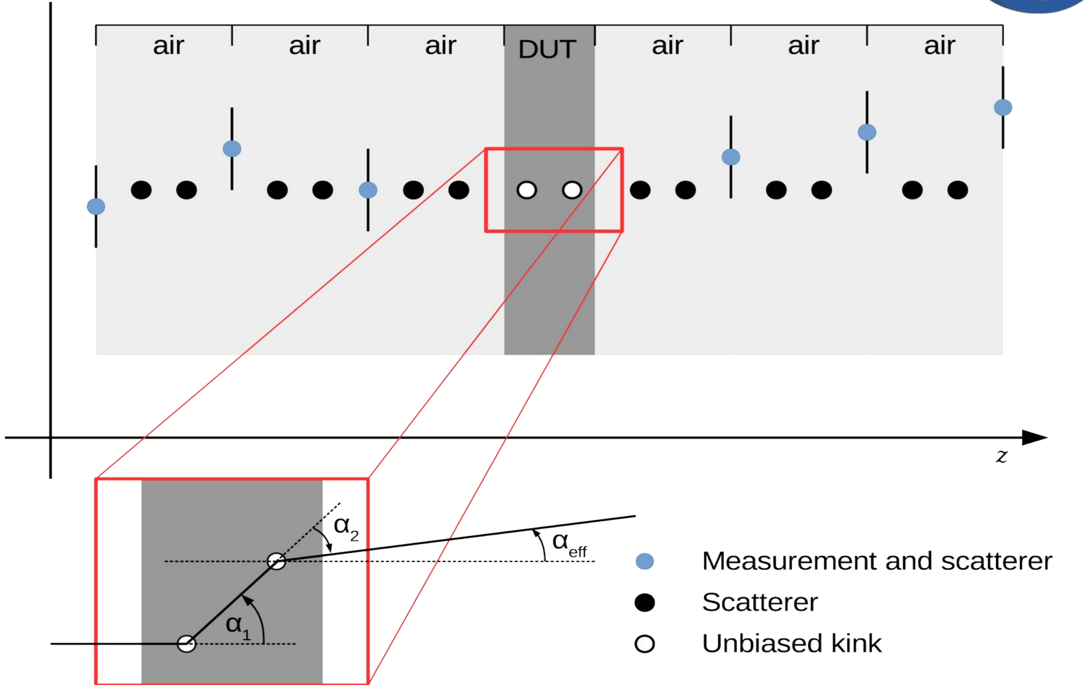


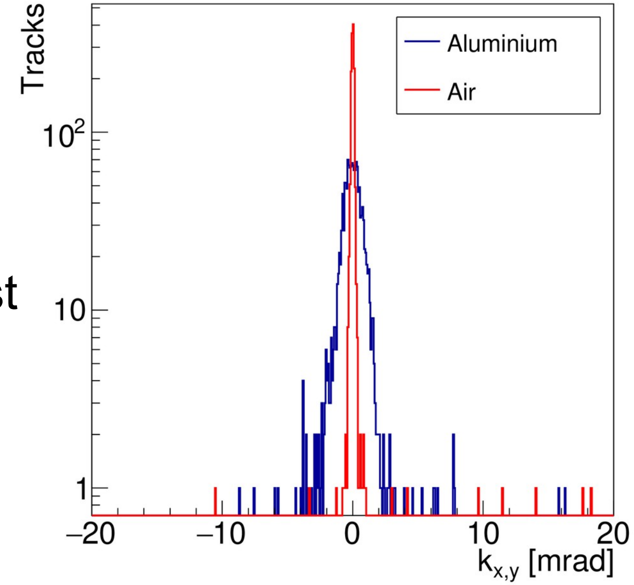
- Using **EUDET M26 telescopes @ DESY-II**

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

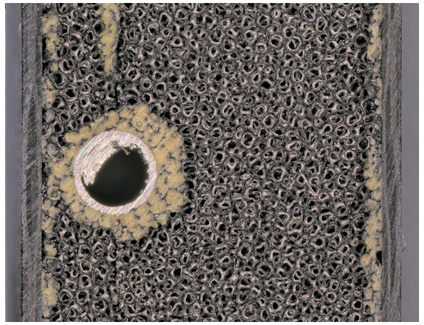


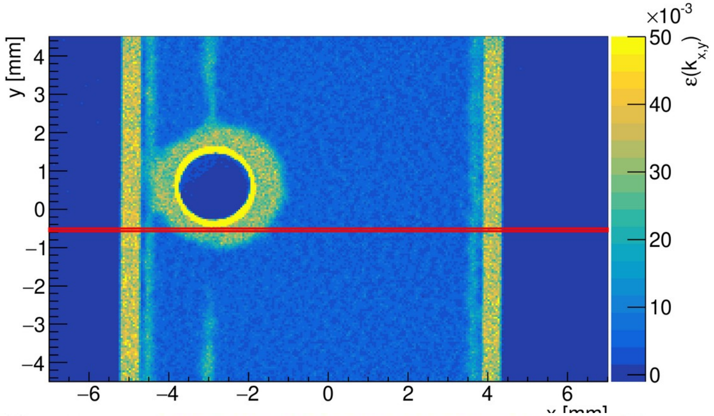


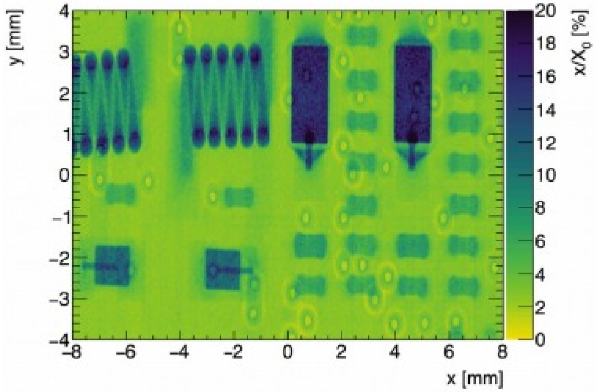
Applications in High-Energy Physics

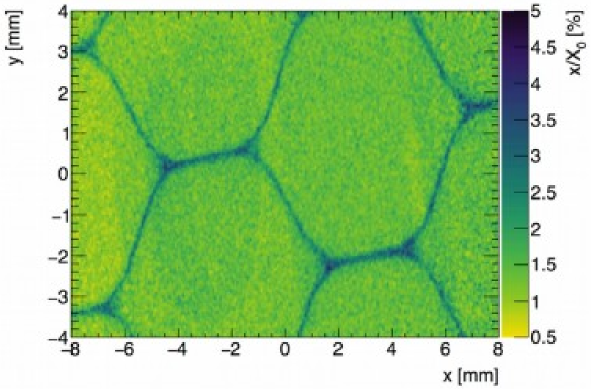
Measurement of detector structures, alignment, …

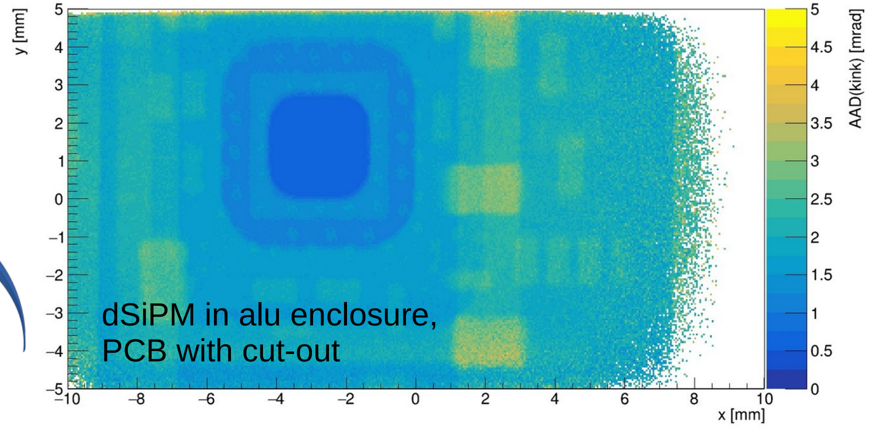
- CMS Phase II Tracker Upgrade
  - CF foam with cooling pipe & face sheets
  - Glue layers visible in material budget
- ATLAS ITk Upgrade
  - Measurement of endcap petal structures
  - PCBs, CF honeycomb structure
- Future Detector R&D: Alignment
  - New prototypes often very small
  - Relative alignment to telescope/trigger difficult
  - Using material budget imaging!
- Fully implemented & available in Corryvreckan (*plug & scatter*)





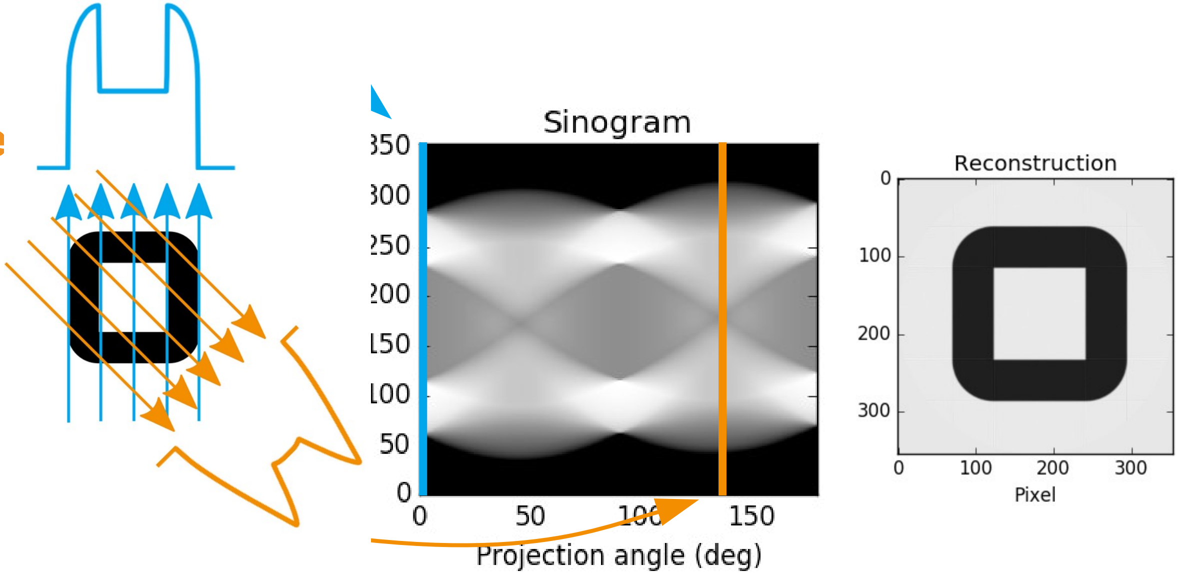






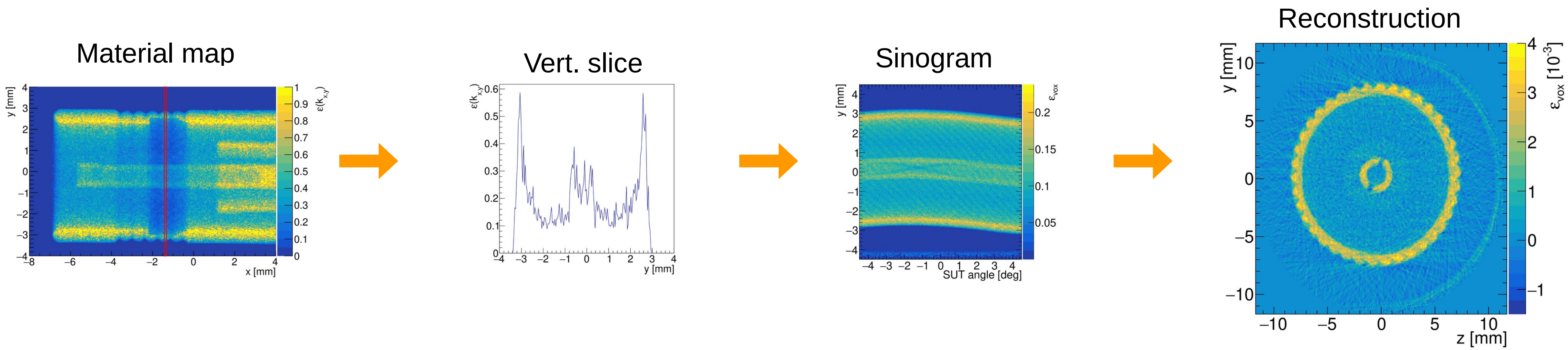
3D Computed Tomography

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
- Can probe thicker material compared to X-rays (e.g. lead)



Track-based Tomography in a Nutshell

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 by 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?

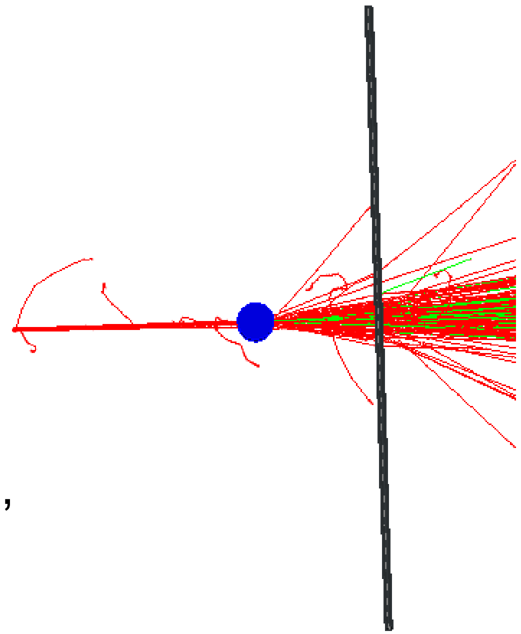
eCT at VHEE Accelerators

Integrated-intensity-based Multiple Scattering Tomography

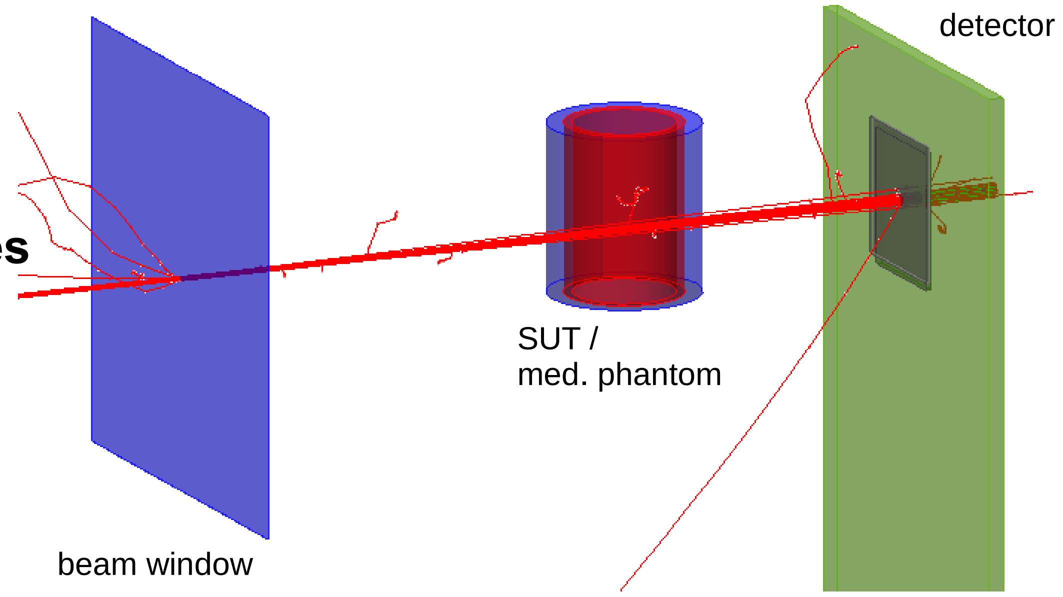
Intensity-Based Measurements

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 - **ARES**
  - Controlled relative movement beam ↔ sample - **Stages**
  - High repetition rate for fast image recording
  - Fast detectors with large dynamic range - **Timepix3**



The ARES Accelerator

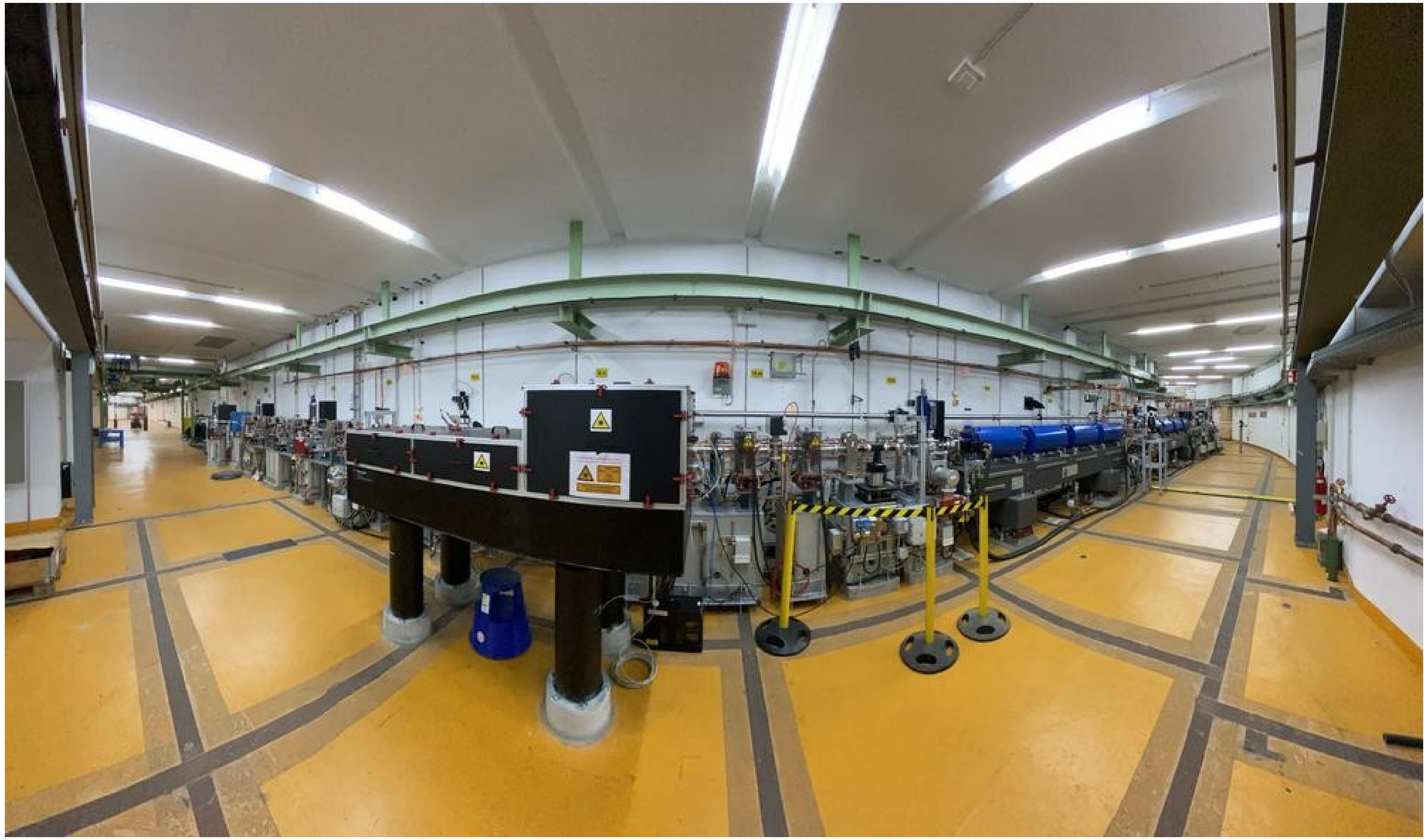
155 MeV LINAC – Accelerator Research Experiment at SINBAD

- Using new accelerator at SINBAD facility (Short and INnovative Bunches and Accelerators at DESY)

  → **ARES** (Accelerator Research experiment at SINBAD)

- Conventional electron S-band linear RF accelerator
  - Ultra-short electron bunches (FWHM < 10 fs)
  - Bunch charge 0.5pC - few pC
  - **155 MeV energy**
  - 10 Hz repetition rate

- See Talk by Florian Burkart on Friday



Individual Bunches – Simulations & Measurements

Shots at different phantom positions

- Medical phantom ***Alfred****
  - 3D printed bone structure, gelatinous tissue
  - Simulation approximated: cylinder, Ø 18 mm (tissue), Cylinder shell, aluminum, 6 mm < Ø < 7 mm (bone)
- Beam traverses phantom at different positions
- Widths calculated from fits to projections: $(\sigma_x+\sigma_y)/2$
  - w/o phantom: saturation of front-end, beam spot ~320 um
  - w/ phantom: no saturation, still room on the sensor

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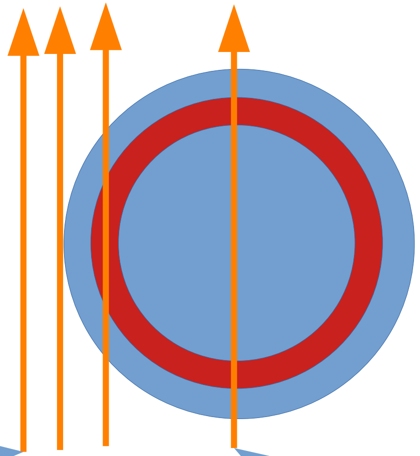
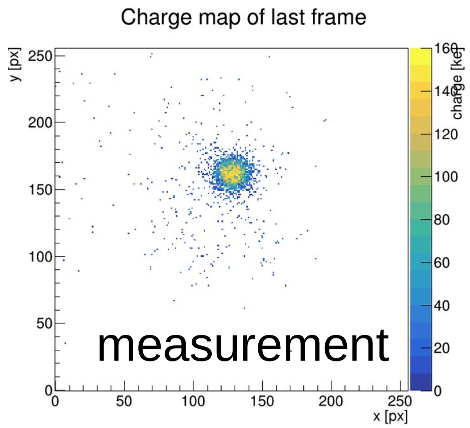
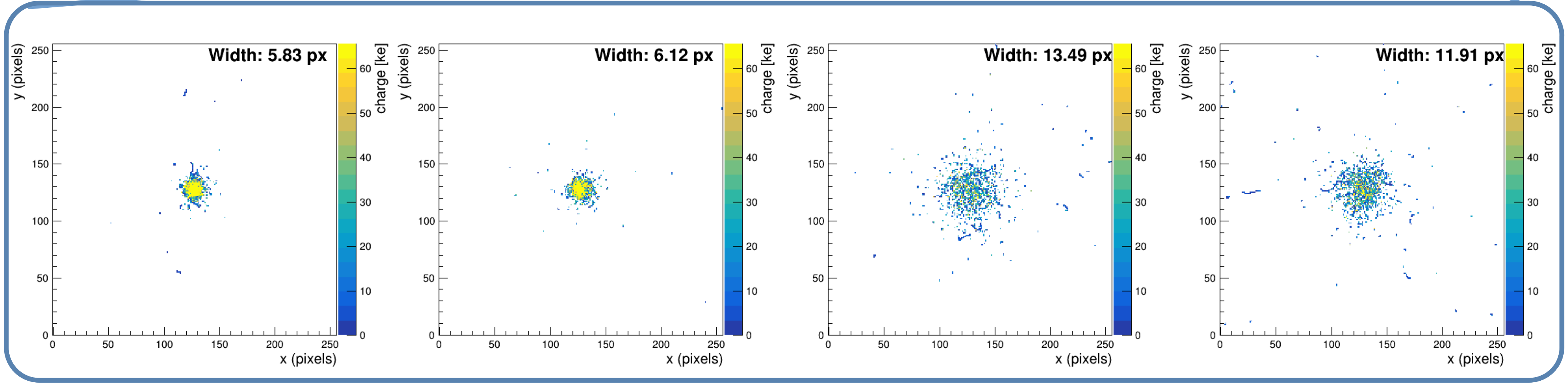


simulations

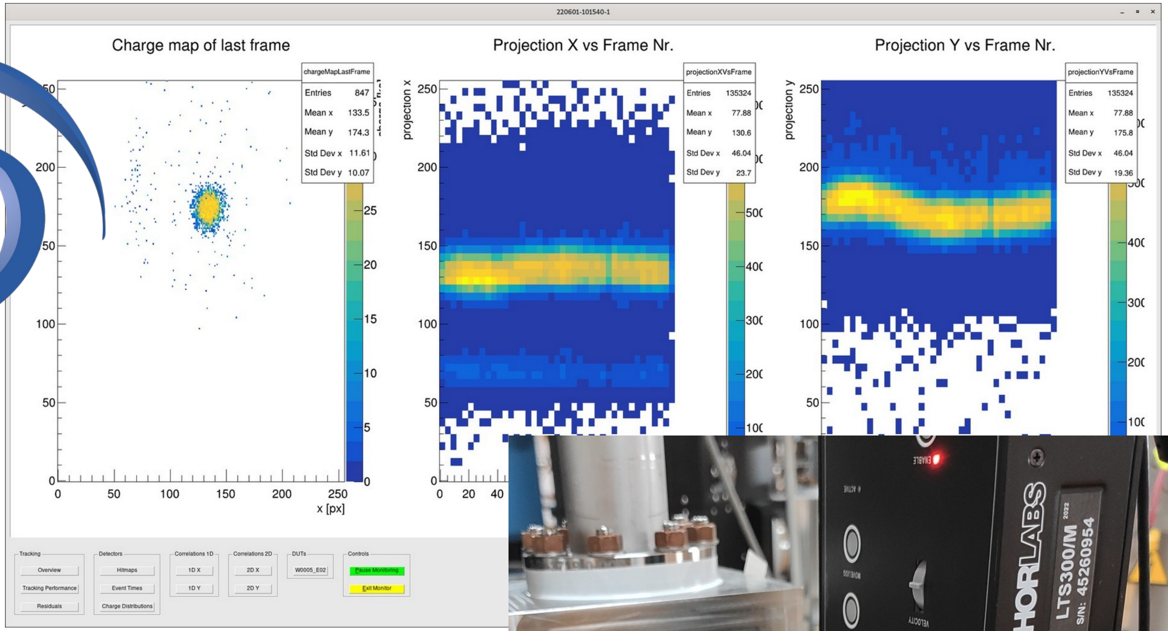




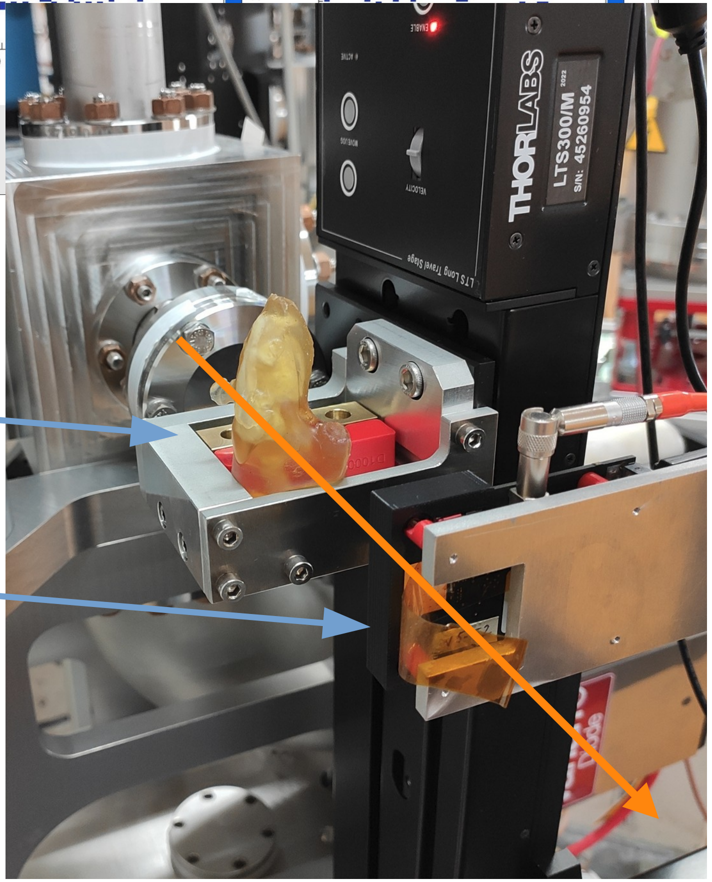
* **A** **L**ittle **F**urry **R**at for **E**lectron-CT **D**evelopment

Scanning Alfred

First single-shot eCT measurements



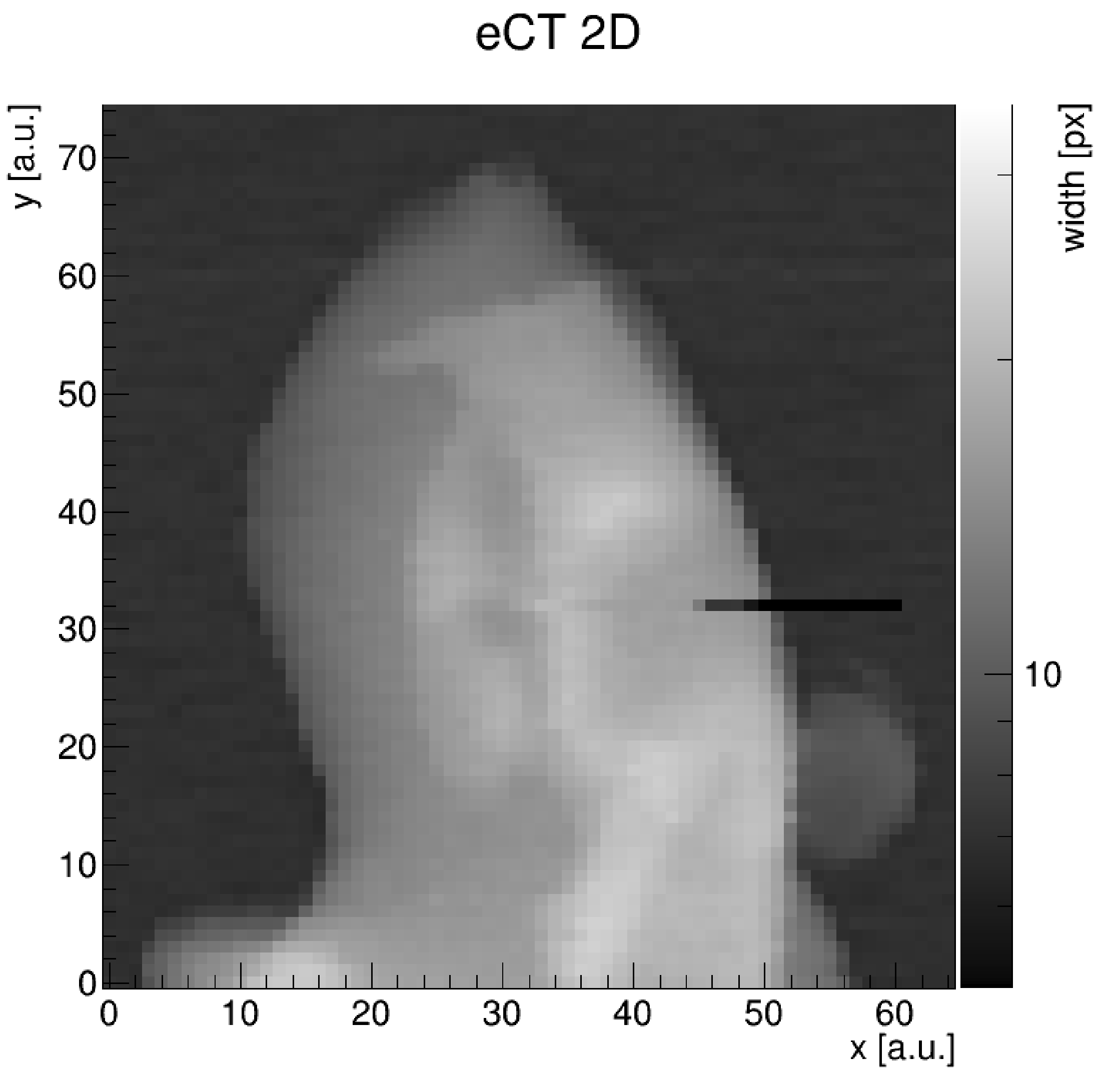
- First beam time in 2022
- Optimization of beam parameters
  - Very low charge – using Timepix3 as beam monitor
  - Corryvreckan Onlinemonitor for bunch-by-bunch feedback
- First 3D eCT images of Alfred
  - Alfred affixed on moving stages
  - Beam incident from side
- Timepix3 mounted on fixed stand behind, minimized distances as much as possible
- Performed several scans
  - Some limitations from mechanics
  - Approx. 10 bunches per image point
  - Reconstruction & synchronization “by hand”



Single-image (2D) Scan of Alfred

Synchronized with ARES bunch clock

- Each point in final image represents width of beam widening at given Alfred position
  - Synchronize every scan line
    with position information from stages
- Scan with ~ 10 bunches per position
  - Very good contrast reached already,
  - Tissue features such as ear, teeth, eyes visible
  - Skull clearly distinguishable from tissue
- Artifact close to eye understood,
  Beam loss upstream for part of scan-line
- Proof of principle: resolution here limited by stage steps
  - Technically: resolution limited by beam size at sample currently O(200um)



Towards 3D eCT

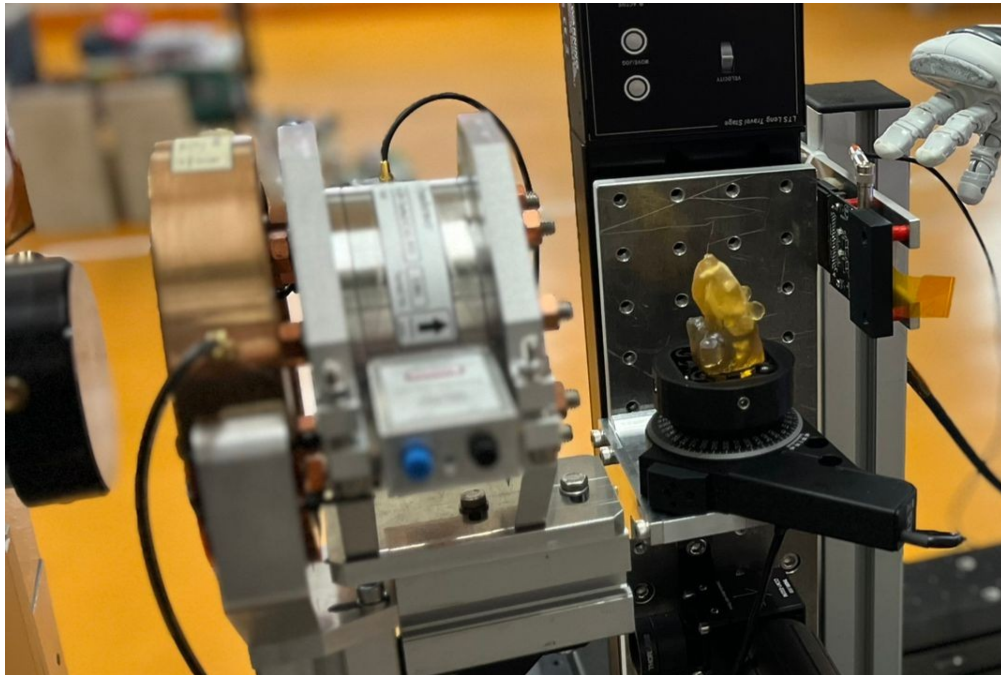
3D electronCT

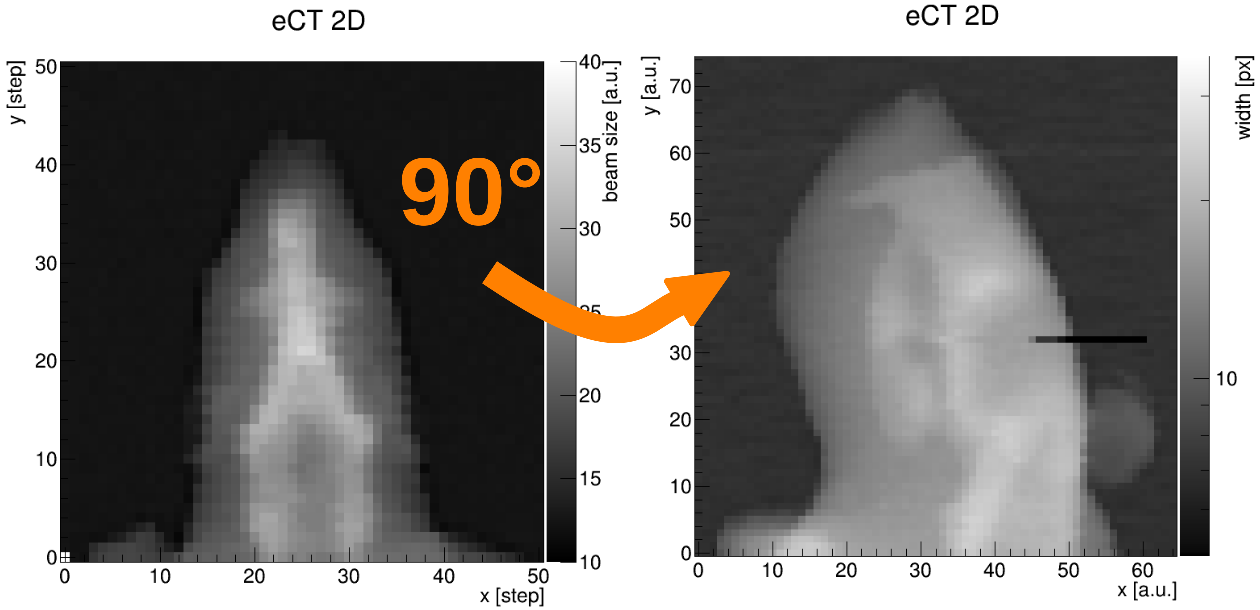
Towards Medical Imaging using High Energy Electrons

- Added rotation stage to Alfred
  –> 3D tomography possible

- 2nd test beam campaign conducted in 04/2023
  - ARES linear accelerator: low-charge, low emittance
  - Improvements to scanning procedure
  - Beam optimizations

- Status & Plans:
  - Rotation stage commissioning – rotation scans
  - ARES extension ongoing – lower bunch size expected
  - Open PostDoc position to be filled in Summer 2023





Join us!

Developing electron Computed Tomography

- **We are looking for a PostDoc with**
  - Experience in test beam instrumentation development
  - Possibly silicon detector characterization/operation
  - Interest in imaging methods and detectors for medical applications

- We offer a position to…
  - Work on **Monte Carlo simulations** for setup/beam optimization
  - Develop a **data acquisition system**, integration with accelerators
  - Measure at DESY accelerators and **analyze imaging data**
  - Collaborate closely with accelerator experts
  - Supervise PhD students

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For our location in Hamburg we are seeking:

Postdoc for the Development of an Imaging Method using Silicon Pixel Detectors

Remuneration Group 13 | Limited: 2 years | Starting date: earliest possible | ID: FHPO006/2022 | Deadline: 03.05.2023 | Full-time/Part-time

DESY, with more than 2700 employees at its two locations in Hamburg and Zeuthen, is one of the world's leading research centres. Its research focuses on decoding the structure and function of matter, from the smallest particles of the universe to the building blocks of life. In this way, DESY contributes to solving the major questions and urgent challenges facing science, society and industry. With its ultramodern research infrastructure, its interdisciplinary research platforms and its international networks, DESY offers a highly attractive working environment in the fields of science, technology and administration as well as for the education of highly qualified young scientists.

DESY is developing a new medical and industrial imaging method based on scattering of electrons in matter, which might provide several advantages over conventional X-ray imaging. This research project is supported by the DESY Generator Program (DGP) and aims at establishing this new method using linear electron accelerators with an energy up to a few hundred MeV and conventional silicon pixel detectors. The DGP supports DESY technologies with high application potential in reaching development milestones and launching them on the market. While initial proof-of-concept measurements have successfully been conducted already, DESY is looking for a post-doctoral researcher with a focus on device simulation and test beam integration of pixel detectors. The
will be part of a dynamic, interdisciplinary team working on new imaging methods with
/e the unique opportunity to work closely with experts from the different fields of silicon
n accelerators, and in close collaboration with the department for Innovation & Technology

Apply today (now!)
DESY Career Portal @ https://v22.desy.de/e67416/records188252/index_eng.html

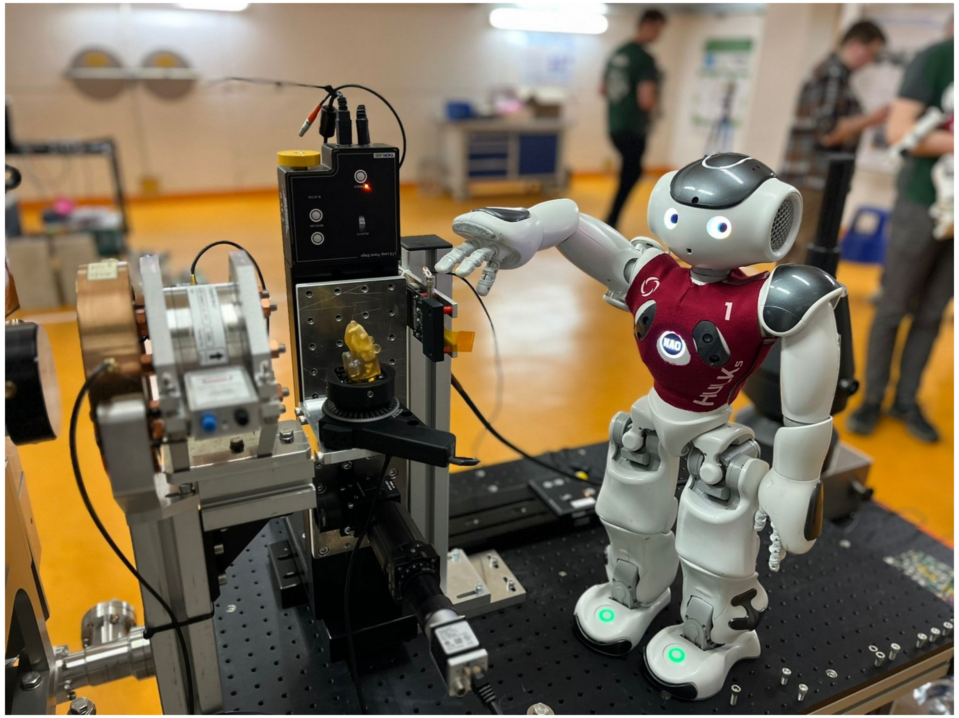
Status Quo & Next Steps

Towards medical imaging with electron Computed Tomography

- **Single-particle tracking eCT** shown to perform well
  - Simulation, calibration, data taking performed at DESY II synchrotron beam lines
  - Already used by high-energy physics experiments: measure detector component properties / alignment

- Novel approach using **one-shot intensity-based scattering** measurements
  - Reduces required measurement time by orders of magnitude
  - Single detector records widened beam after scattering in sample
  - Proof-of-principle measurements demonstrate viability of method

- Next steps towards medical imaging
  - Simulations to benchmark analysis & reco, dose, contrast, …
  - Measurements for full 3D tomographic reconstruction at ARES
  - Open PostDoc position!



Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

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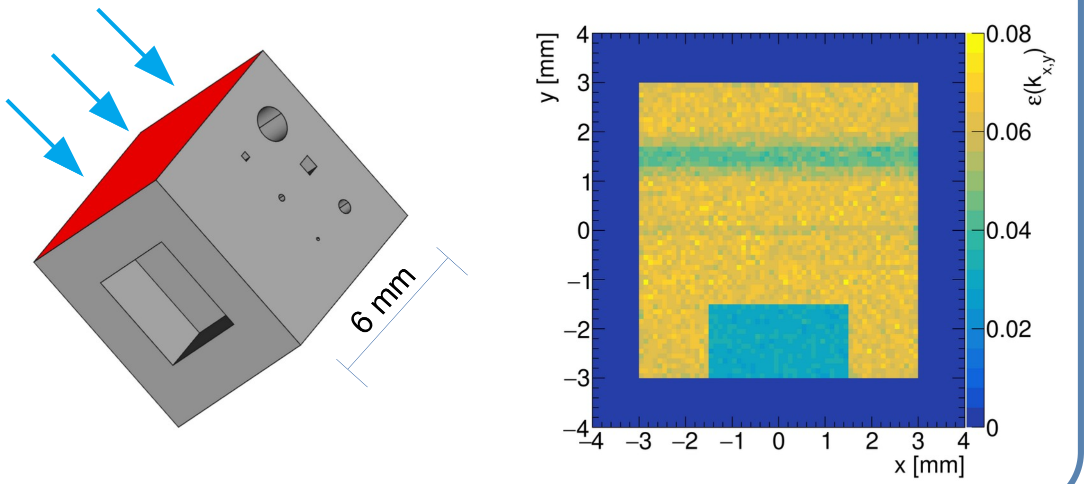
Image Reconstruction

2D measurement of the scatterer material budget

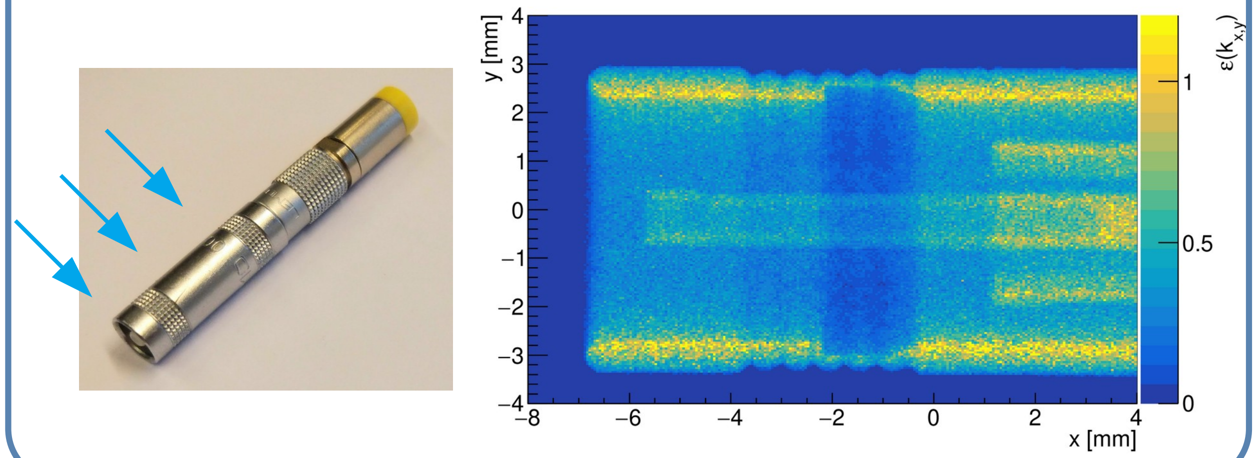
- Illumination of the scatterer,
  reconstruction of individual particle tracks
- Division of the image plane (SUT) into regions (pixels)
- Calculation of scattering angle for every track,
  determination of scattering angle distribution width
  individually for each pixel
- Calibration of the scattering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

Simulation



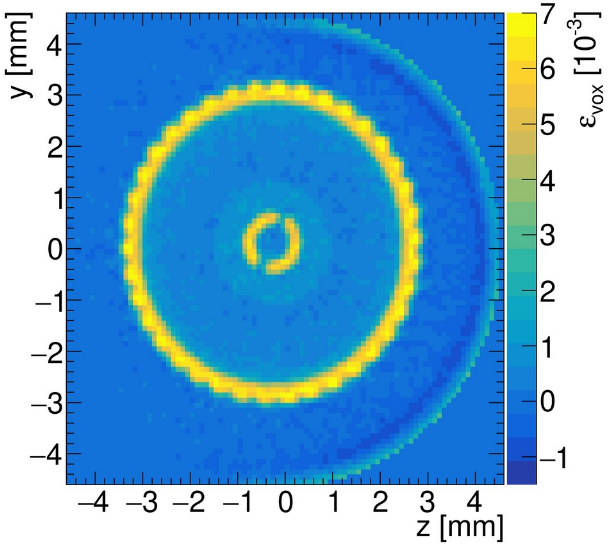
Measurement

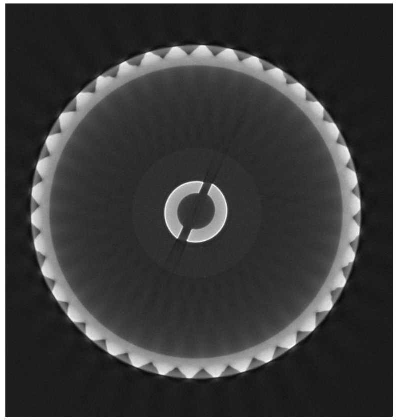


Comparison: X-Ray CT

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