The Bright Side of Multiple Scattering

or

Medical Imaging via electronCT

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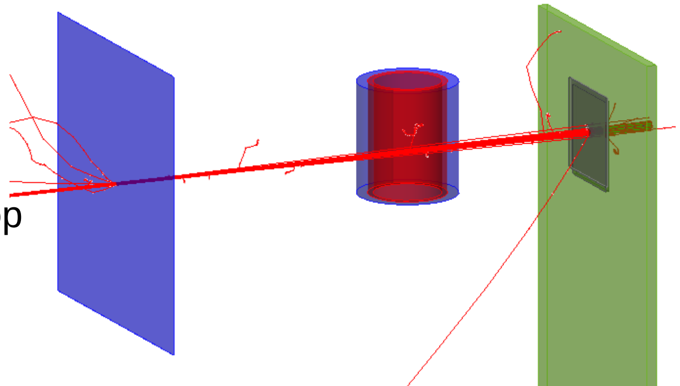

12th Beam Telescopes and Test Beams Workshop

17th April 2024

DESY.

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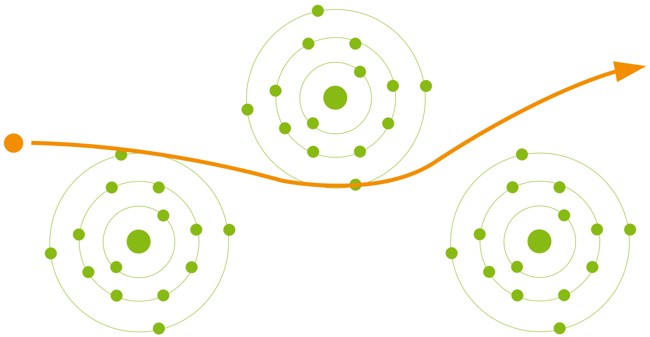
RESEARCH FOR GRAND CHALLENGES

Multiple Coulomb Scattering



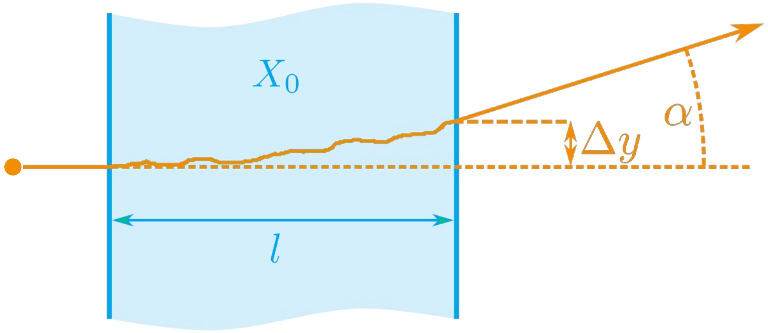
- High-energy particles undergo multiple Coulomb scattering in the electric fields of close by nuclei
  - ➔ Particle is deflected stochastically
  - ➔ Scattering angle distribution
- Total deflection theoretically described by Molière
  - ➔ Approximation on central width by Highland / Lynch / Dahl

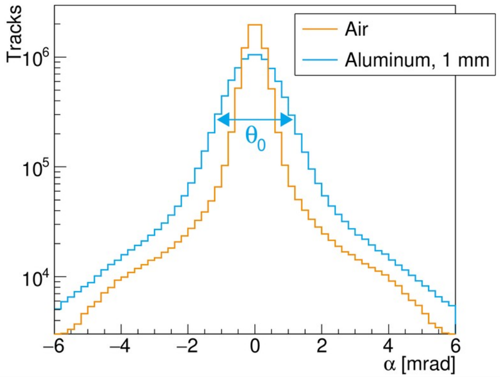
$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p}\sqrt{\frac{l}{X_0}}\left(1 + 0.038\ln\left(\frac{l}{X_0}\right)\right)$$

l : Projected path length in the material

X_0 : Radiation length

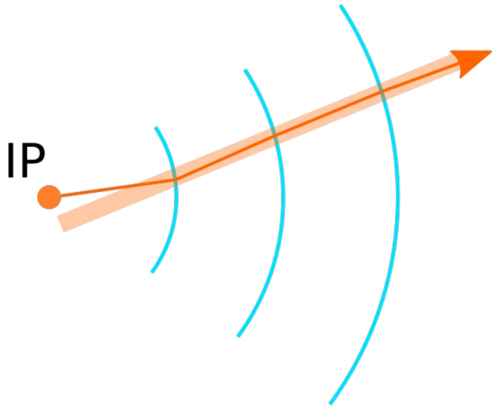
$\varepsilon = l/X_0$: Material budget





Multiple Coulomb Scattering

- 👎 Stochastic deflection leads to deterioration of the position resolution for tracking detectors
  - ➔ Usage of light & thin materials



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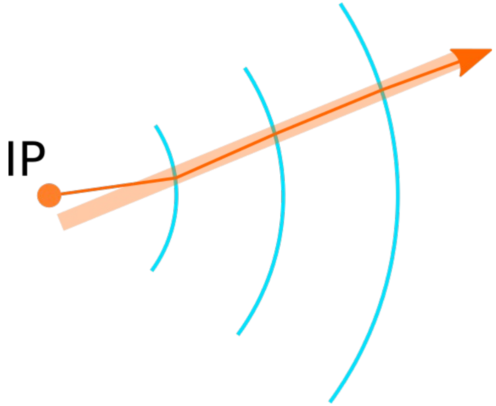
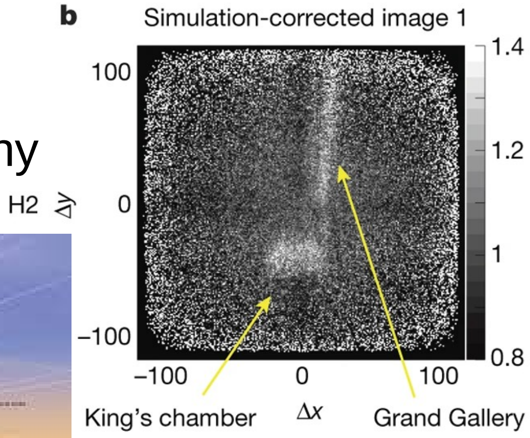


- 👍 Can be used to gain information on traversed objects

➔ Muon Tomography



doi:10.1038/nature24647
#ScanPyramids

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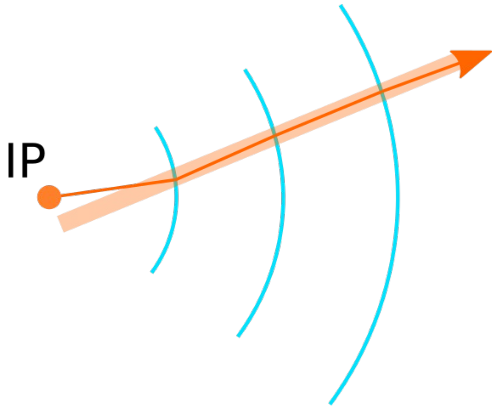

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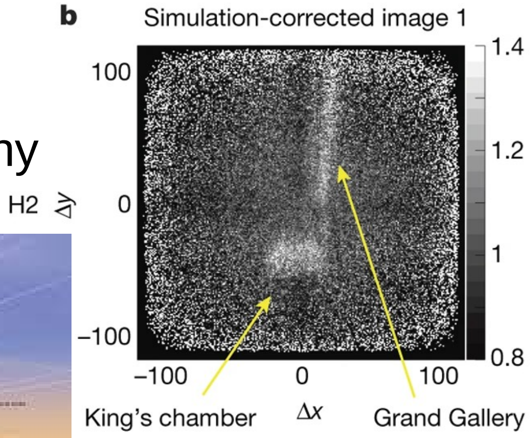

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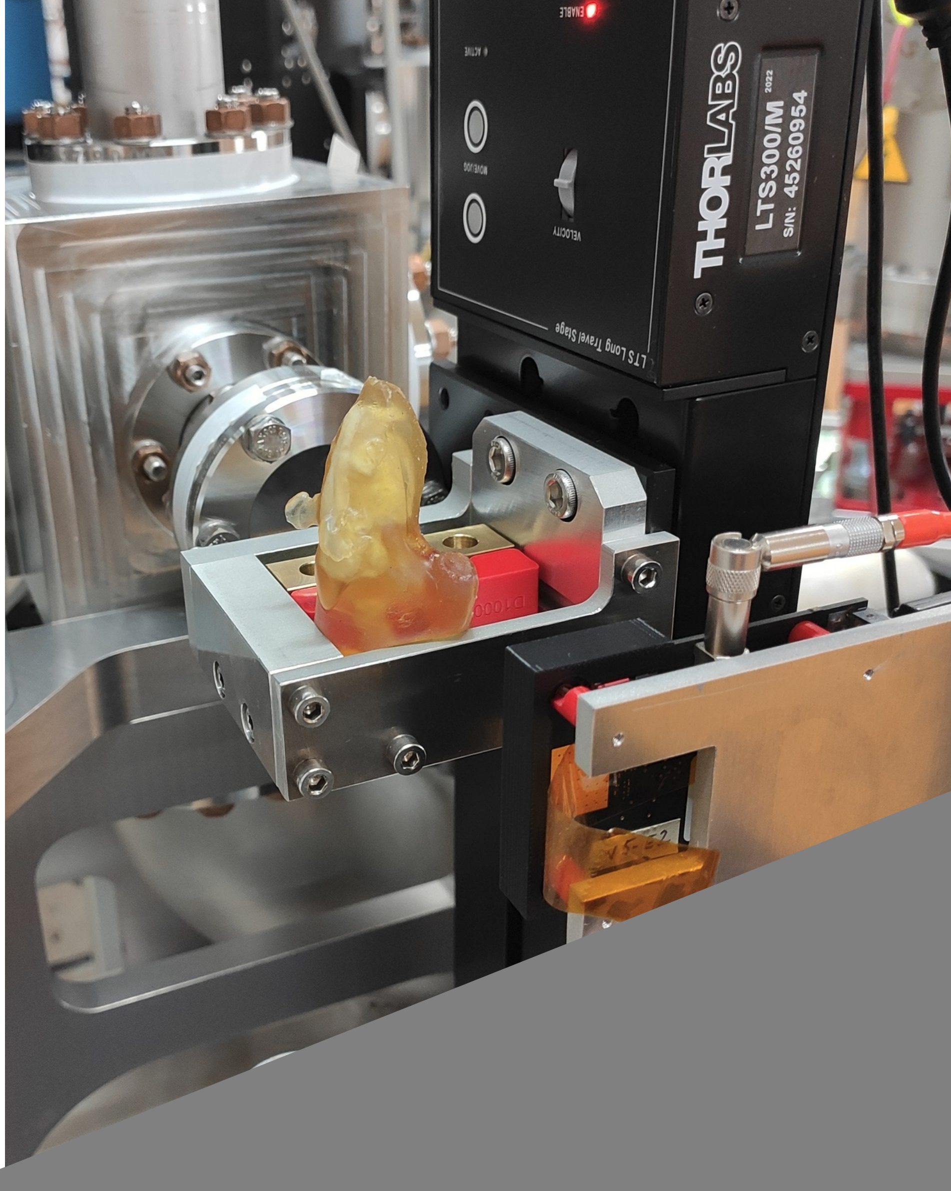
➔ electronCT

electronCT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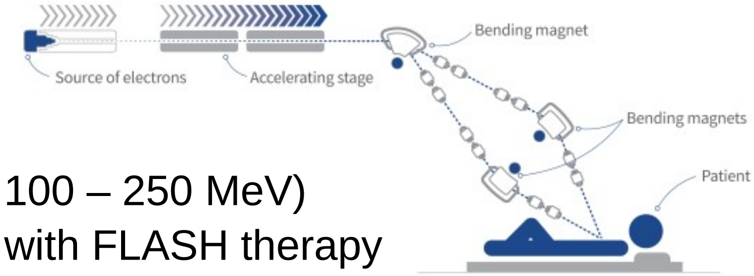
LTS300/M
2022
S/N: 45260954
LTS Long Travel Stage
VELOCITY

electronCT

- Goal: Perform imaging (medical/industrial) of macroscopic objects using electrons



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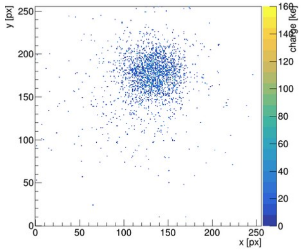
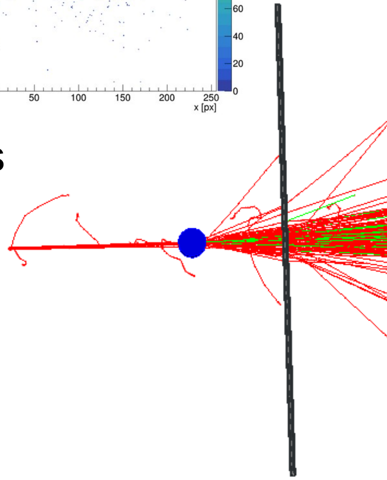
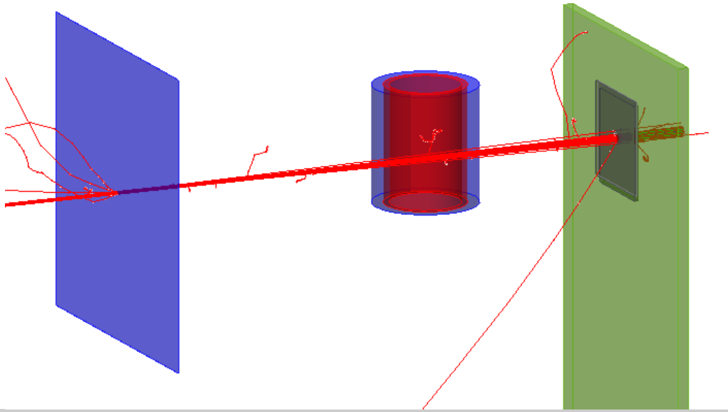
- Motivation:
  - Radiotherapy using Very-High Energy Electrons (VHEE, 100 – 250 MeV) under wide investigation – powerful tool when combined with FLASH therapy
  - Imaging is mostly accomplished via conventional CT or MRI
    - ➔ Change of reference system
  - **electronCT** uses energies applied also in treatment for medical imaging
    - ➔ Synergy: use the same accelerator for imaging and treatment
    - ➔ Accuracy: obviate change of reference system or patient relocation
    - ➔ In-situ: tumor location via eCT

electronCT

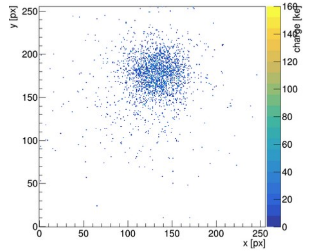


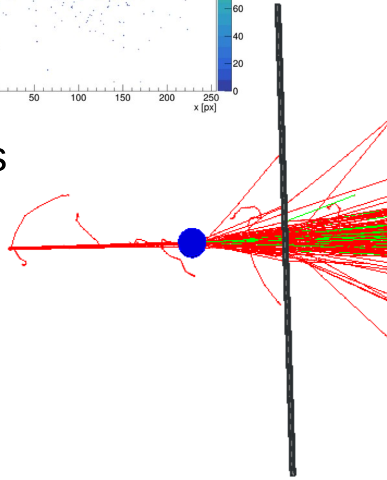


- Goal: Perform imaging (medical/industrial) of macroscopic objects using electrons
- Technique: Use pencil beam to raster the sample &
  perform beam profile measurement downstream of the sample
  - **Beam** traversal **position** at sample defines pixel of obtained image
  - Measured quantity: **width of beam profile** for given beam position
    - ➔ Calibration to **material budget** traversed by beam



electronCT





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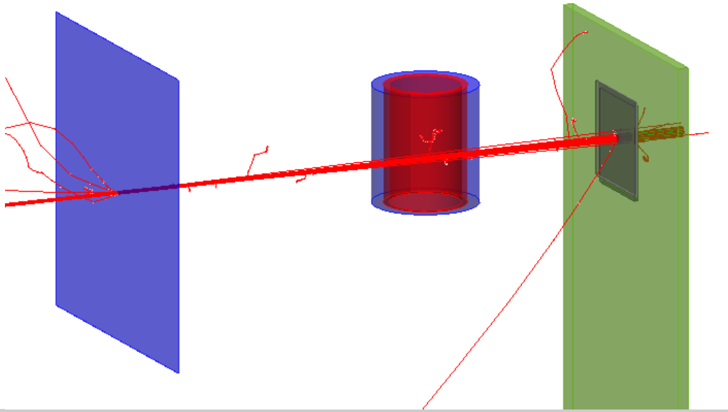
  - Measured quantity: **width of beam profile** for given beam position
    - ➔ Calibration to **material budget** traversed by beam
- Requirements:
  - Well-controlled, small beam spot @ sample – **ARES**
  - Precise relative movement beam vs. sample – **4D Stage**
  - High repetition rate for fast image recording
  - Fast detectors with large dynamic range – **Timepix3**

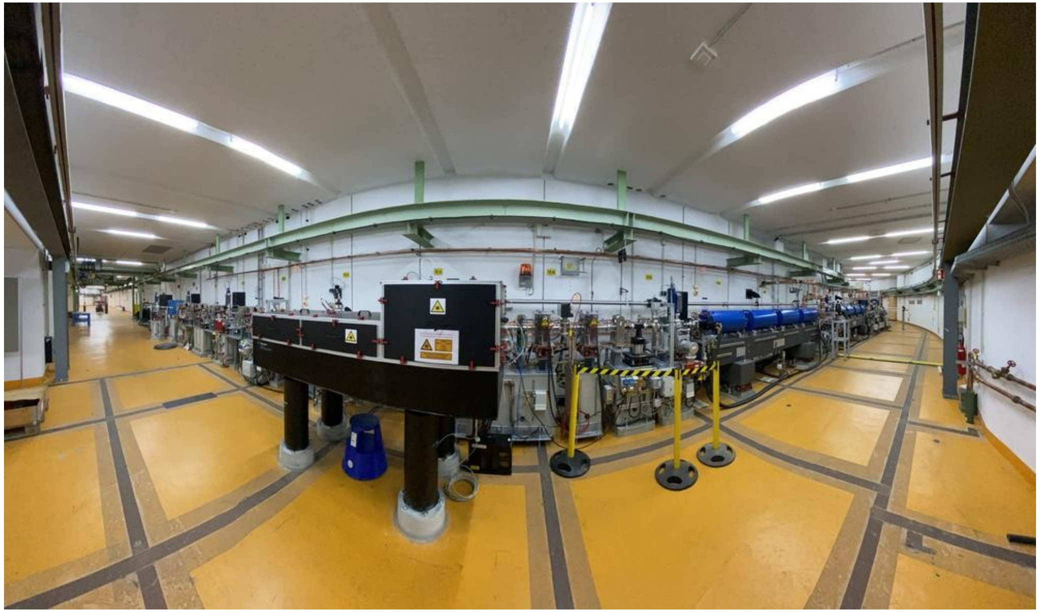


The ARES Accelerator

- **ARES** (Accelerator Research experiment at SINBAD) as an excellent facility for proof-of-concept measurements

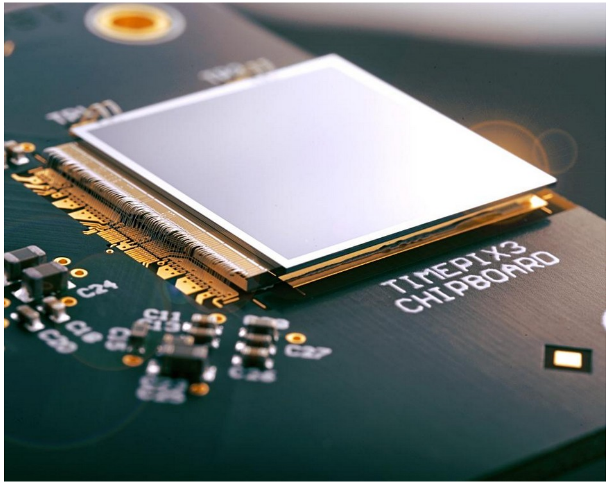
- Conventional electron S-band linear RF accelerator
  - Ultra-short electron bunches (FWHM < 10 fs)
  - Bunch charge 0.5 pC - few pC (and lower)
  - **155 MeV energy**
  - **10 Hz repetition rate**

- In-air experimental area
  - $\mathcal{O}$(250 µm) beam spot at sample, dominated by scattering at beam window



Timepix3 Detector

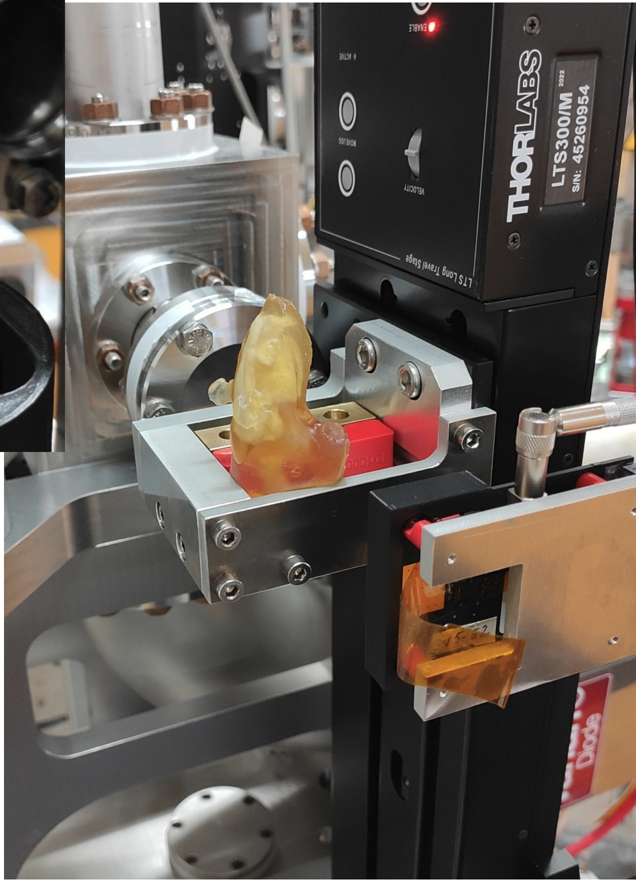
https://kt.cern/technologies/timepix3



- Detector readout ASIC by CERN, NIKHEF, Uni Bonn
  - Pixel Pitch: 55 x 55 µm
  - Pixel Matrix: 256 x 256
  - Total Area: 14 x 14 mm
- Used in both High Energy Physics and Medical Applications
- Here:
  - Bump bonded to 100 µm thick, planar silicon detector
  - Readout mode options:
    - Data-driven: continuous readout → event building in post-processing
    - Frame-based readout tested with few issues, requires further testing
  - Data acquisition systems:
    - Katherine Readout System, TrackLab software

doi:10.1088/1361-6560/acc566

electronCT Setup



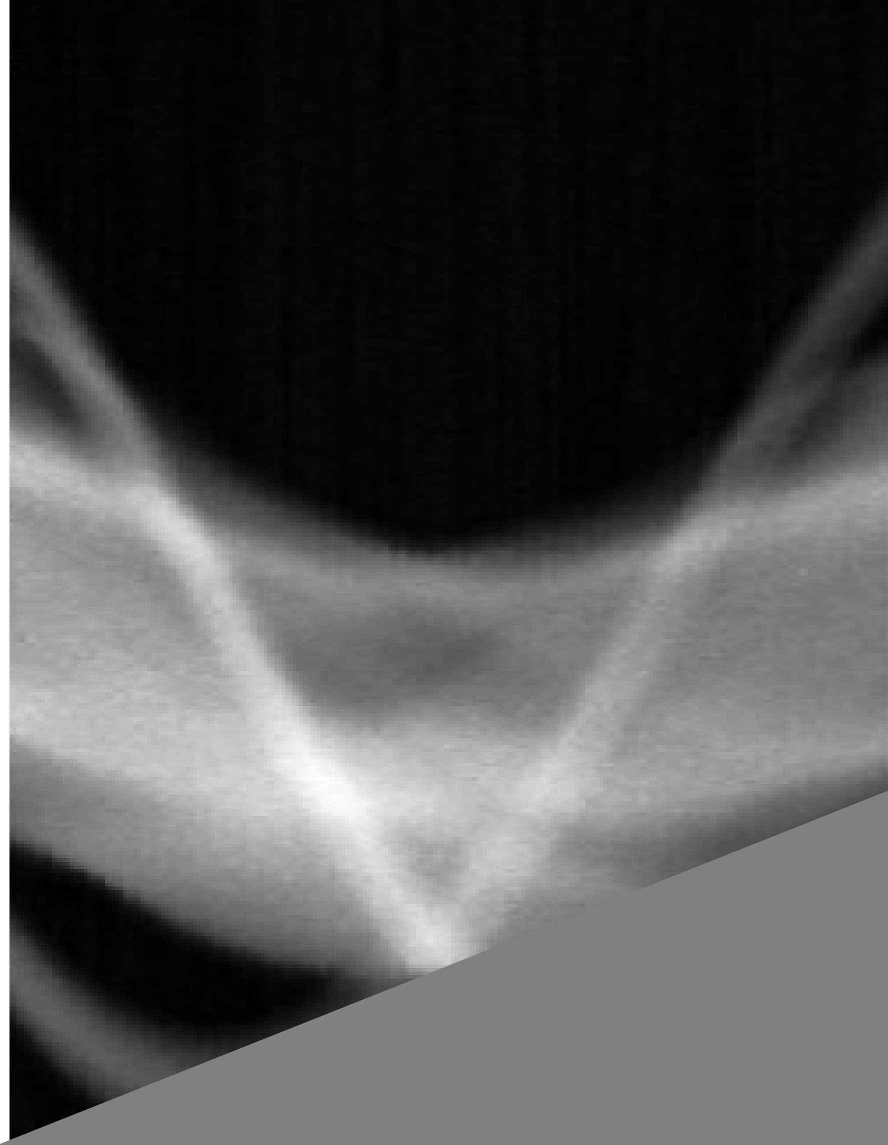
- Medical phantoms on x-y-φ motion/rotation stage
  - “Alfred”: gelatinous tissue, solid skull
  - “Berta”: solid (resin), detailed skeleton
- Timepix3 assembly on fixed stand downstream
- Minimising distances for beam size & occupancy
  - Limited by mechanics – divergence influences spatial resolution

Scanning techniques

- Scan tool implemented to perform two- or three-dimensional scans:
  - 2D: x + y
  - 3D: x + y + φ
- Continuous motion along x, steps in y and φ

* **A** **L**ittle **F**urry **R**at for **e**lectronCT **D**evelopment
** **B**rave **E**xperimental **R**odent for **T**omographic **A**pplications

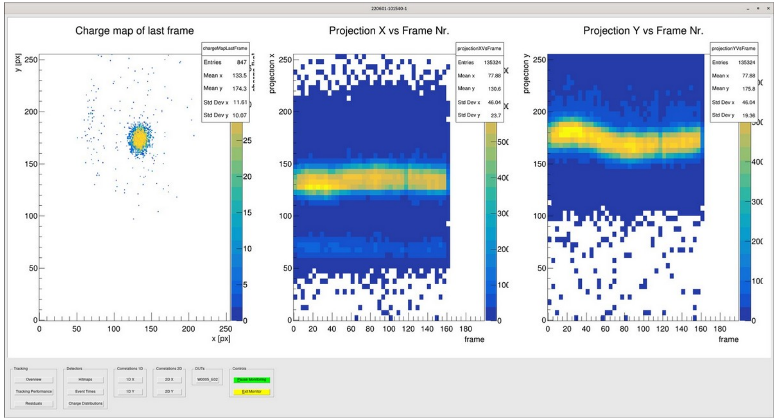
Results

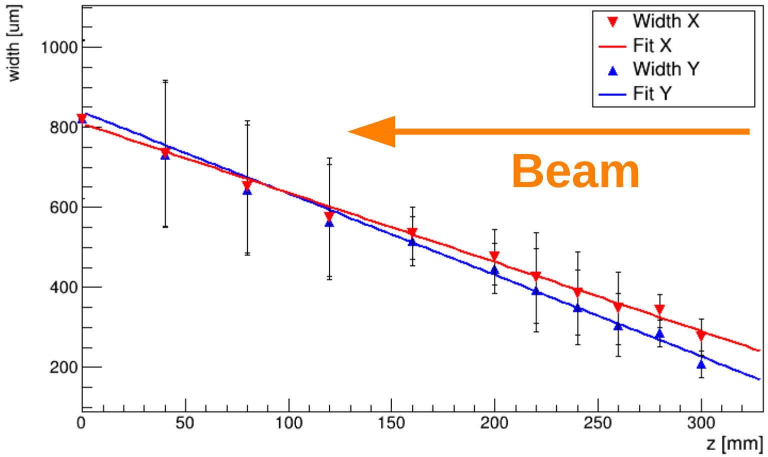


Beam Profile Measurements

Corryvreckan beam monitor

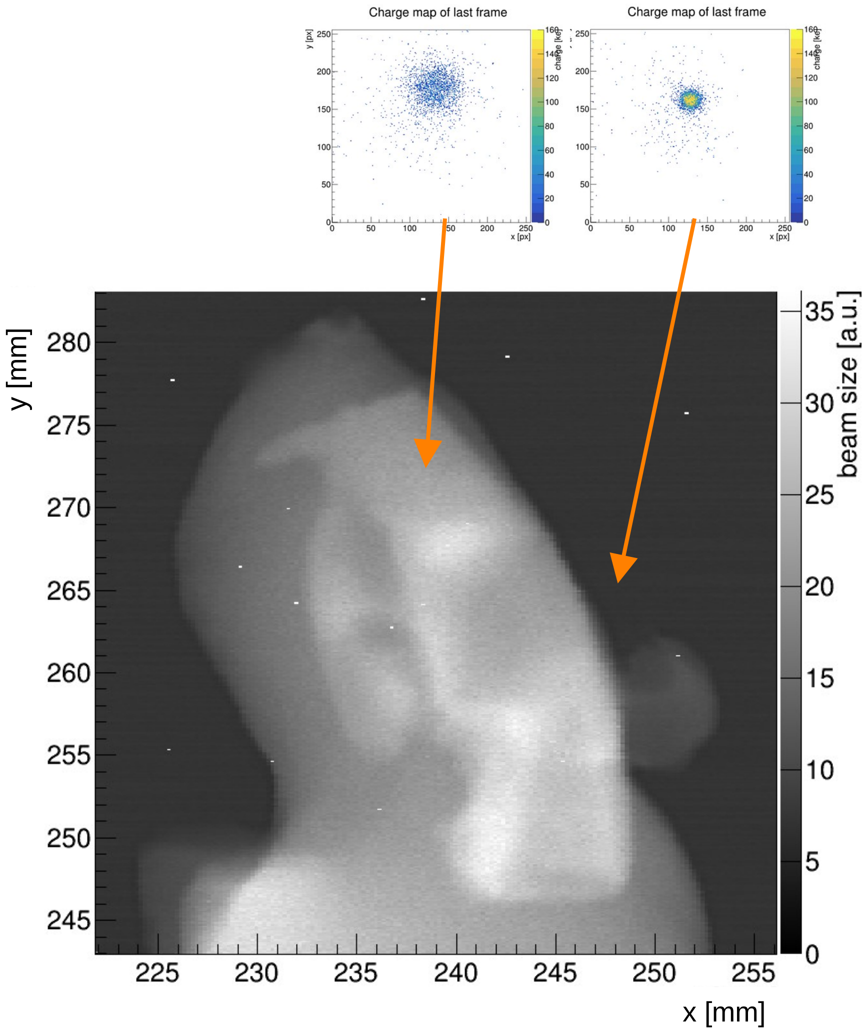
- Bunch-by-bunch beam monitoring from TPX3 data
- Beam parameter optimisation
  - **Low charge**
    - ➔ Low dose to sample or patient
    - ➔ Prevent saturation of detector
  - **Low emittance**
    - ➔ Transverse bunch profile dominates spatial resolution for small samples and affects the sensitivity
- Beam characterisation
  - Transverse bunch size as a function of longitudinal position





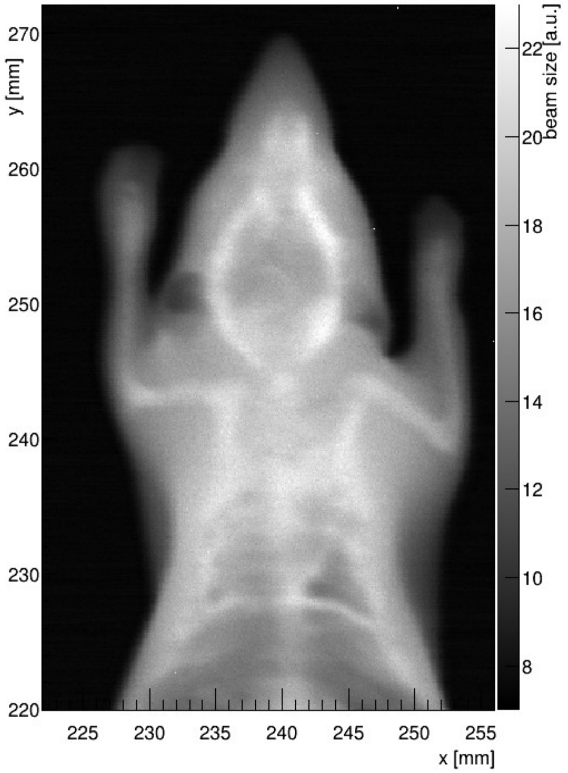
eCT 2D Measurement

- Each data point in an image represents the width of the beam at the detector for the given stage position
- Good contrast reached
  - Skull distinguishable from tissue
  - Features like ears, eyes and teeth visible
- High resolution achievable
  - Here limited by beam size (~0.2 mm)
- Empty bins correspond to missing frames (DAQ issue)



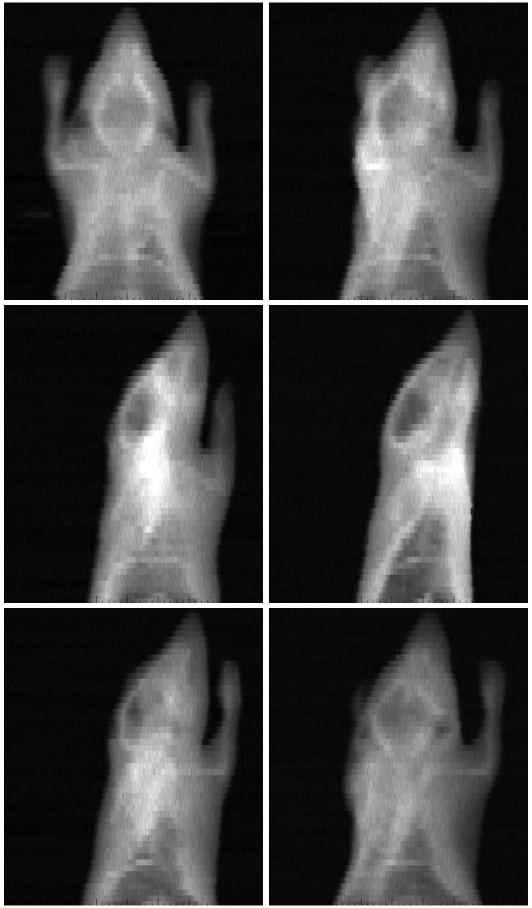
eCT 2D Measurement – Berta

- High resolution 2D scan: 100 x 100 µm
  - Resolve ribs, arms and skull
  - Skeleton distinguishable from tissue
  - No organs or tumours inserted



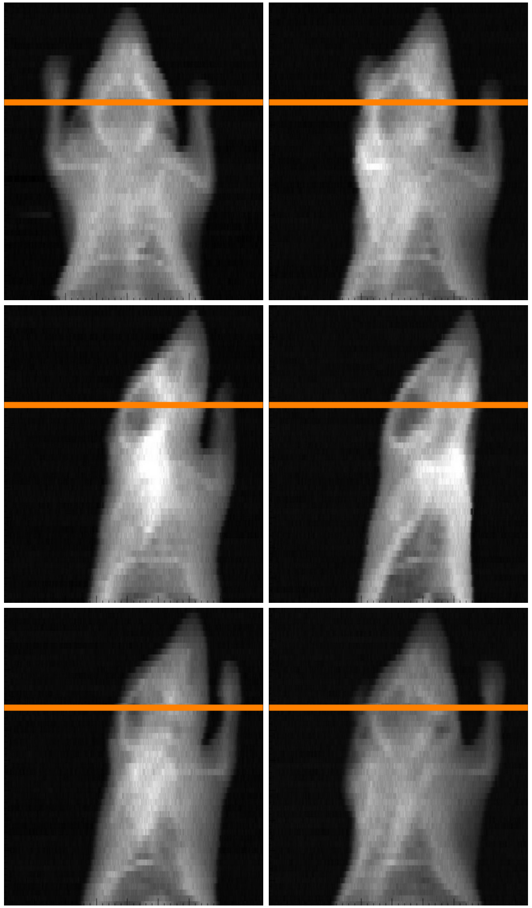
Towards the Third Dimension

- Repeat 2D imaging at various rotation angles …
  - The sequence of motions doesn't matter – in the end we require the time-resolved information from the x-y-φ stage to assign each data frame (bunch) to a point in the 3D parameter space



Towards the Third Dimension

- Repeat 2D imaging at various rotation angles …
- For each row of the parameter space …



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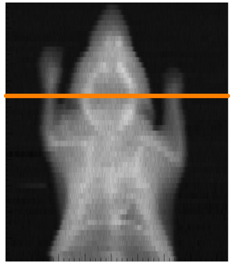
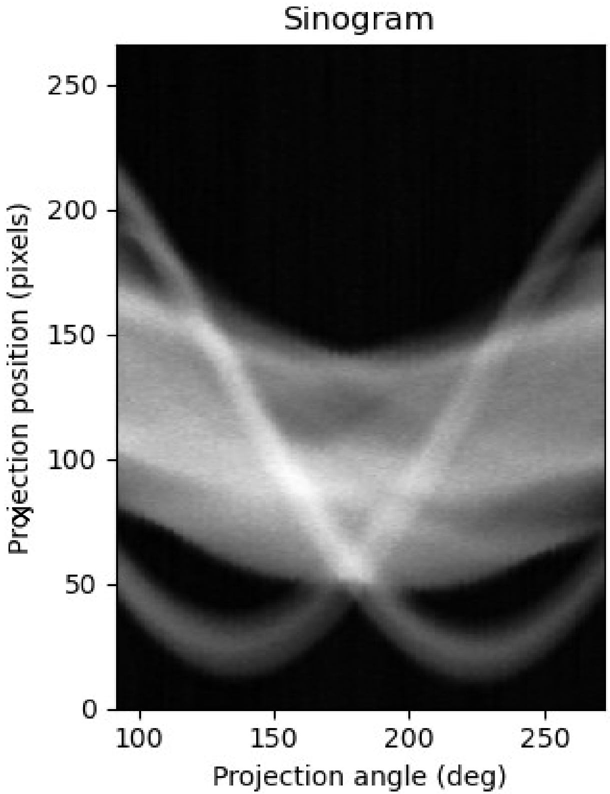


- Repeat 2D imaging at various rotation angles …
- For each row of the parameter space
  plot the pixel value vs x-φ (“Sinogram”)



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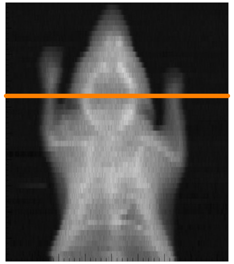
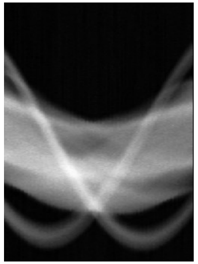
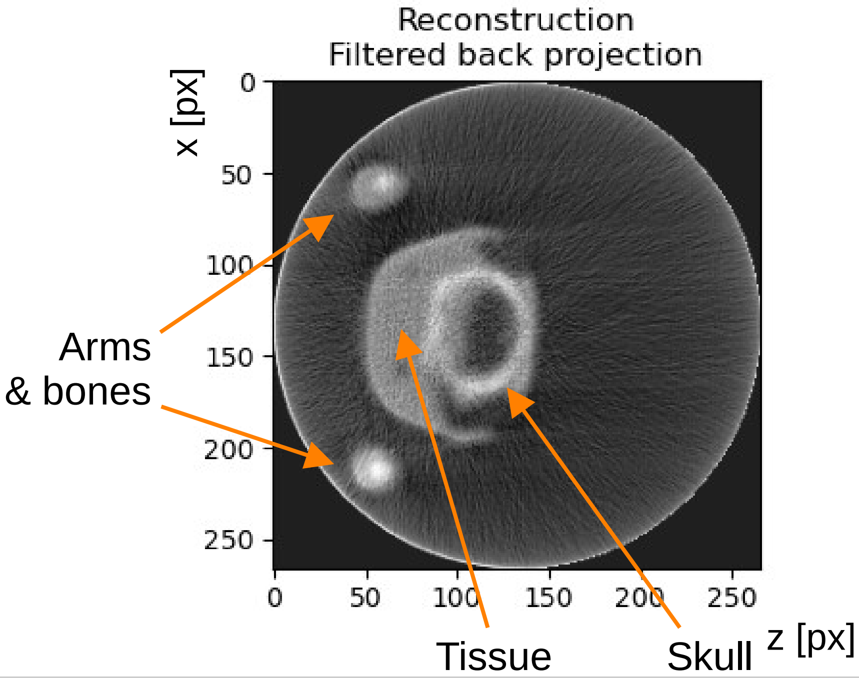




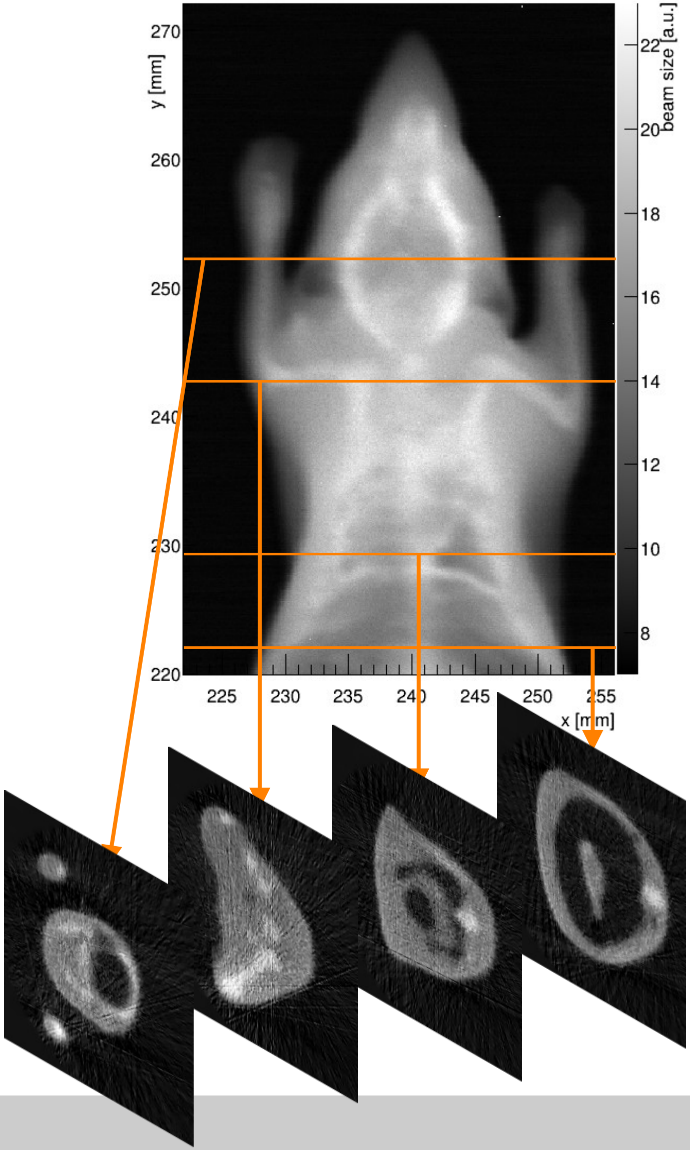
- Repeat 2D imaging at various rotation angles …
- For each row of the parameter space
  plot the pixel value vs x-φ (“Sinogram”)
- Perform an *inverse radon transform*
  (here: filtered back projection)
  to obtain a single slice (x-z) of the sample
- Image artefacts under investigation
  Potential sources:
  - Non-linearity of beam width as a function of material budget
  - Variation of incoming beam parameters throughout measurement



electronCT – 3D

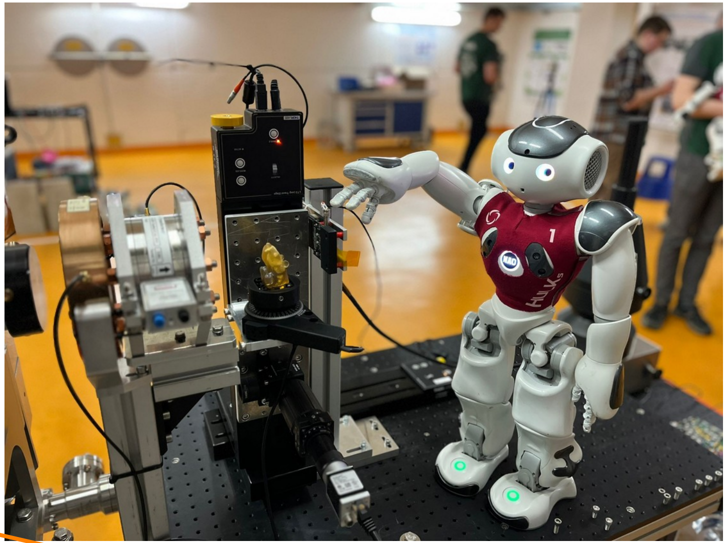
- Phantom features well visible from tomographic reconstruction (f.l.t.r.):
    - Skull (no brain inserted) + paws
    - Shoulder + spine
    - Lung + spine
    - Abdomen (empty) + spine

- Proof-of-concept for small-size phantoms



Conclusions

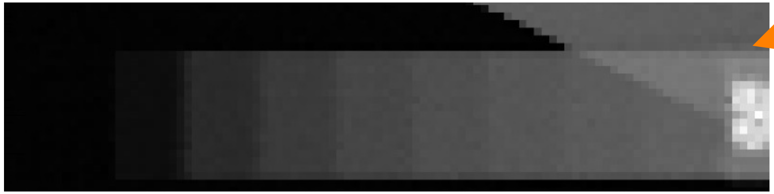
Status Quo & Outlook

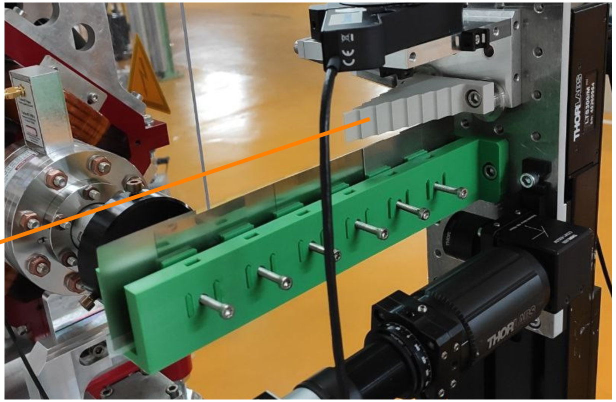


- **electronCT** concept studied @ARES
  - Measurement of beam widening from scattering
  - Concept proven via 2D & tomographic measurements
  - High measurement times ($\mathcal{O}$(few hours)) – limited by acc. repetition rate

We appreciate the support of the ARES team!

- Next steps towards medical imaging …
  - **Simulations**: benchmark/improve analysis & reconstruction, contrast, explore limitations, estimate dose …
  - **Calibration** & characterisation measurements
  - Reduce **measurement time**

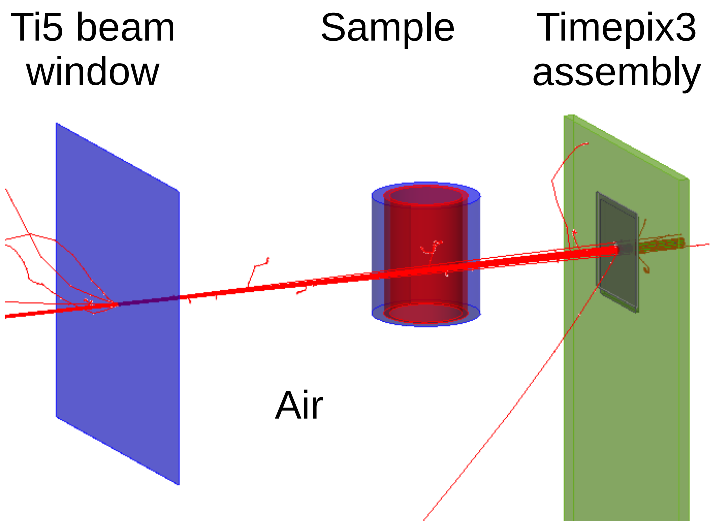


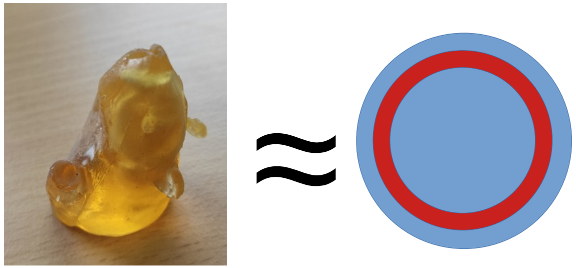


Backup

Simulation Setup

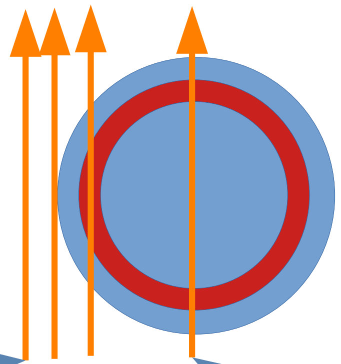
- Allpix Squared Semiconductor Simulation Framework
  - Particle-matter interaction integrated via Geant4
- Beam:
  - Electrons, 155 MeV
  - Beam size: 100 µm
  - Divergence: none (dominated by scattering at window)
  - Particles per bunch: 1000 (0.16 fC)
- Medical rat phantom
  - Simulation:
    - Cylinder, paper, Ø 18 mm (tissue)
    - Cylinder shell, aluminum, 6 mm < Ø < 7 mm (bone)

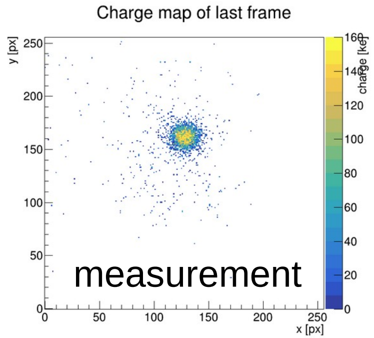


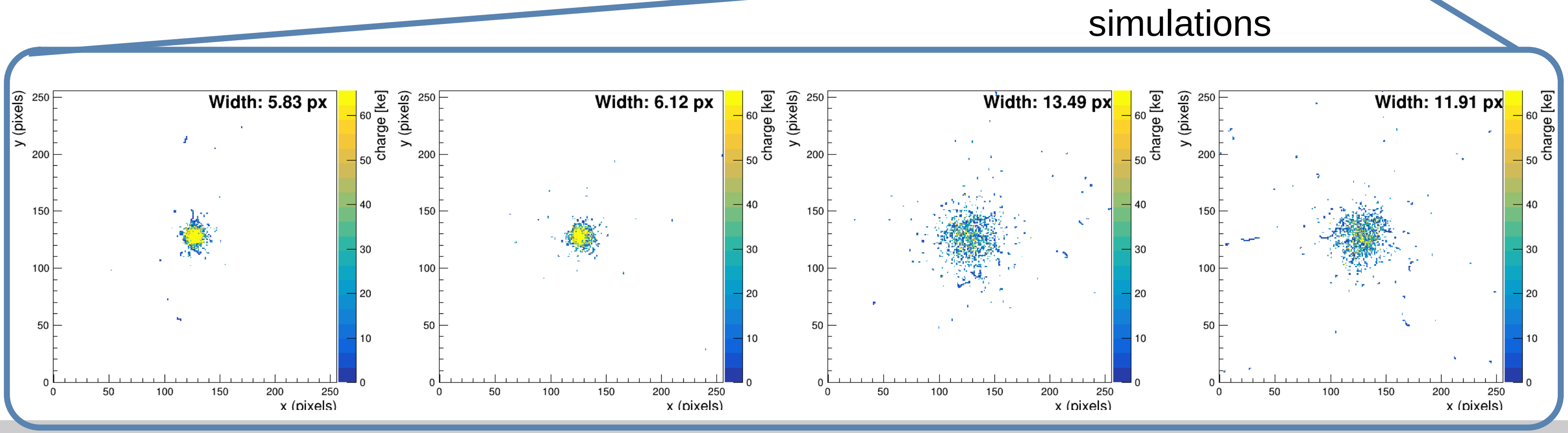


Bunch Profile – Simulation & Measurement

- Simulation setup:
  - 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 sensor
- High resemblance with in-beam measurement







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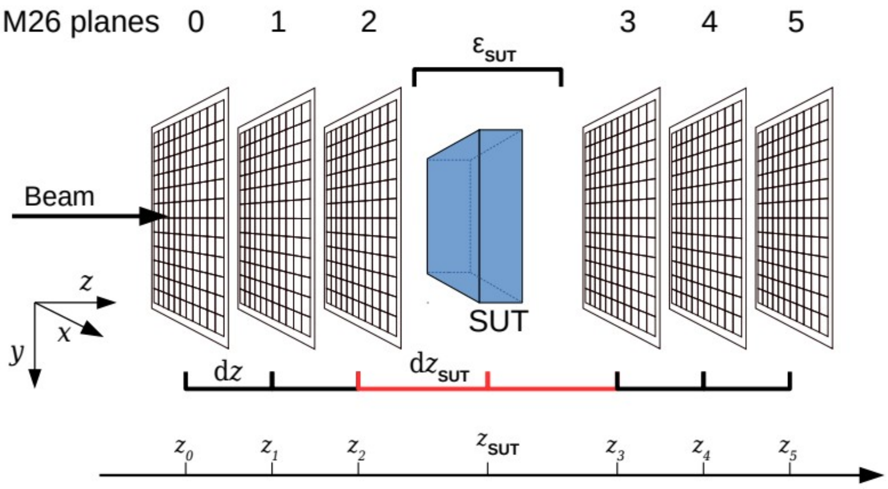
History: Track-based Multiple Scattering Tomography

- Goal: Measurement of the scattering angle at the SUT
- Strategy: single-particle tracking before and after the sample under test using so-called beam telescopes
- Four steps:
  - Illuminate full sample with a *GeV* charged particle **beam**
  - Measure the hits in the **pixel sensor** planes
    in front of and behind it
  - Reconstruct **particle trajectories** through the telescope
  - Extract the **width** of the kink angle distribution
    & estimate material budget per image cell
- Initial tests:
  EUDET telescopes (Mimosa26 sensor)
  @ DESY II Test Beam Facility



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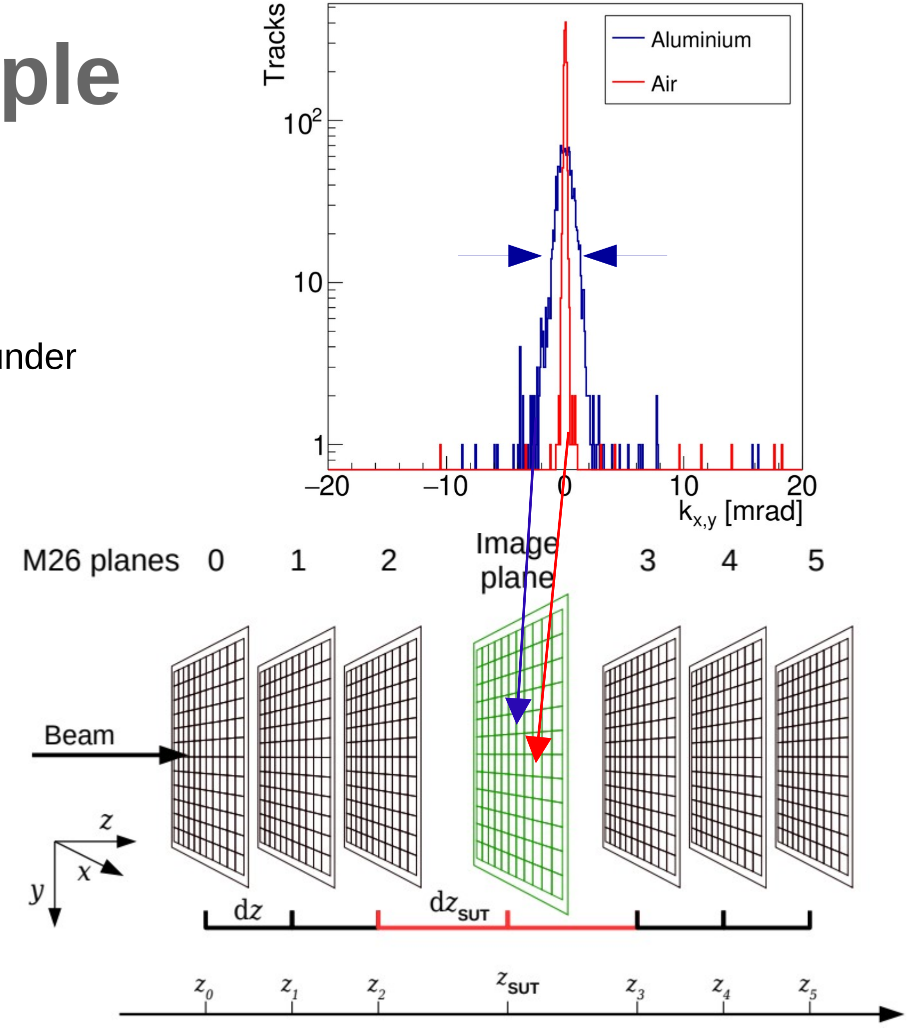
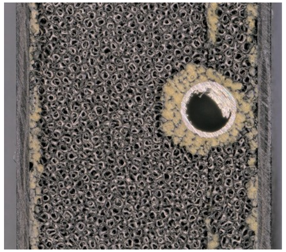
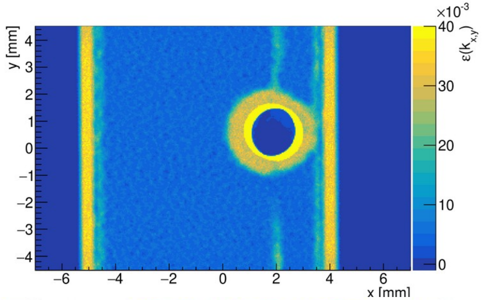
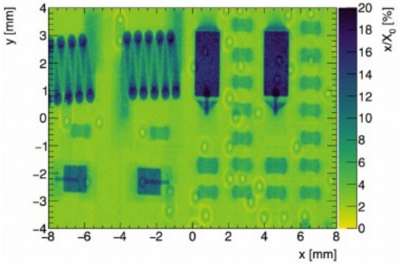


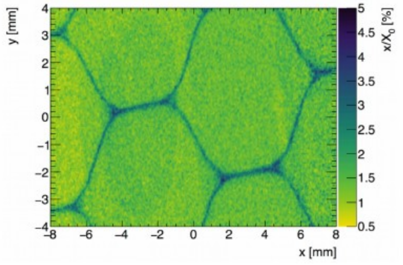
History: Track-based Multiple Scattering Tomography

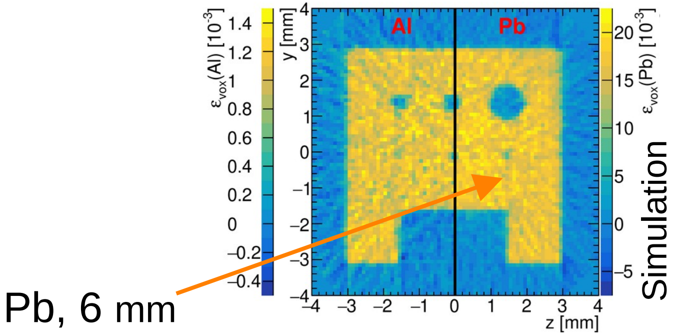
- CMS Phase II Tracker Upgrade
  - CF foam with cooling pipe, CFRP plates & glue joints
  - All features visible & quantifiable
- ATLAS ITk Upgrade
  - Measurement of support structures & electronics
- Potential:
  - Quantification of material budget possible
  - Simulations show good performance for large range of objects up to a few millimeters of lead











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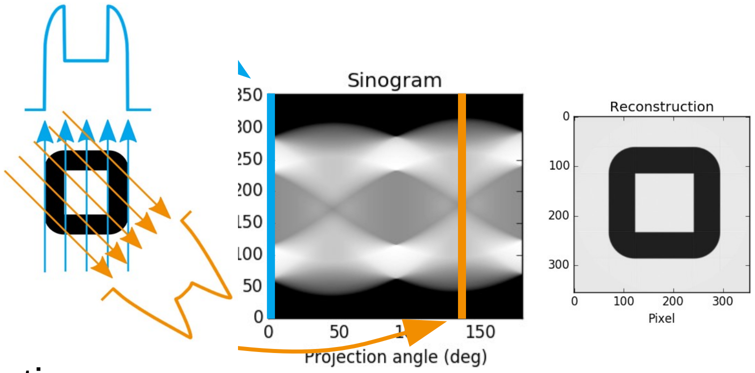

- Repeat projection measurement for various angles
- Generate sinograms from individual images
- Perform inverse Radon transform for tomographic reconstruction

2D Material Budget Image

Vertical Slice

Sinogram

Reconstruction