The Bright Side of Multiple Scattering

or

Medical Imaging via electronCT

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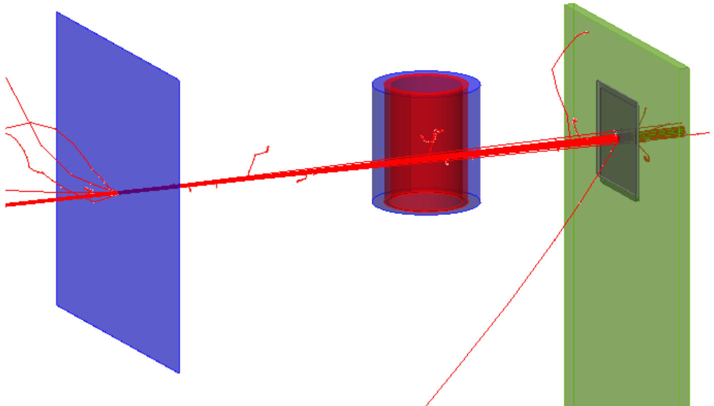
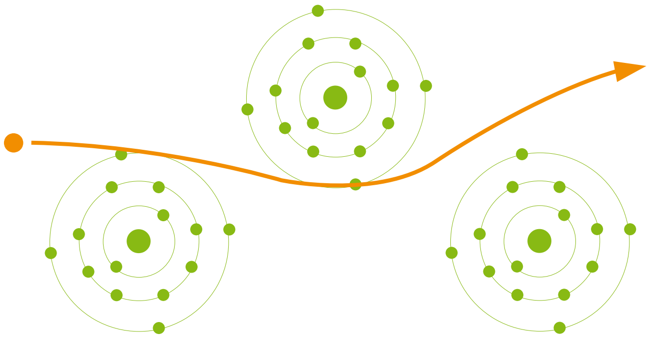
S. Spannagel, S. Ruiz Daza, A. Herkert
FH Detector Platform Retreat
19th January 2024

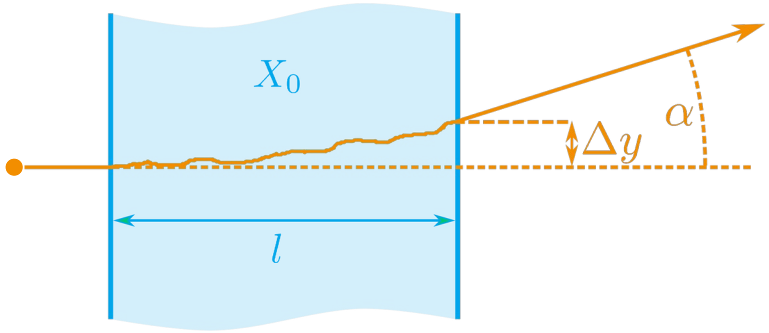


HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Multiple Coulomb Scattering



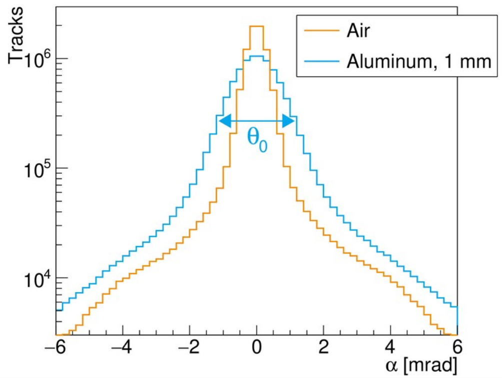
- High-energy particles undergo multiple Coulomb scattering in the electric fields of close by nuclei
  - ➔ Particle is deflected stochastically
  - ➔ Scattering angle distribution



- Total deflection theoretically described by Molière
  - ➔ Approximation on central width by Highland / Lynch / Dahl

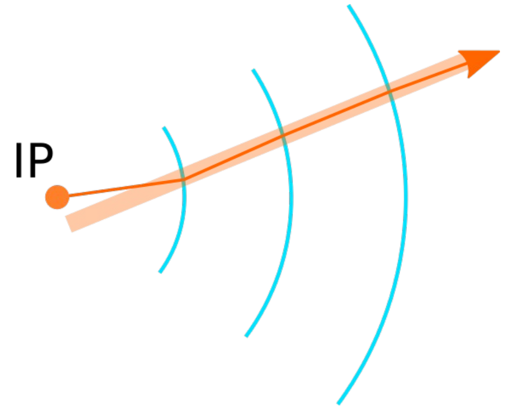
$$\theta_0 = \frac{13.6\,\mathrm{MeV}}{\beta c p}\sqrt{\frac{l}{X_0}}\left(1 + 0.038\ln\left(\frac{l}{X_0}\right)\right)$$

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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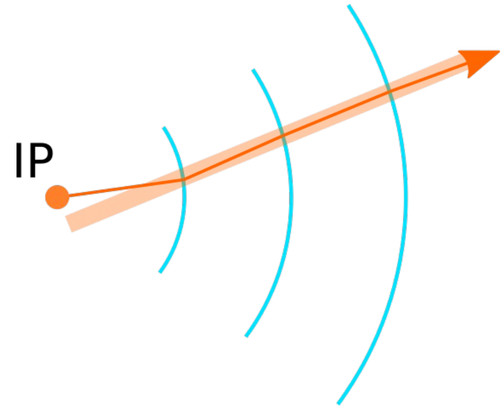
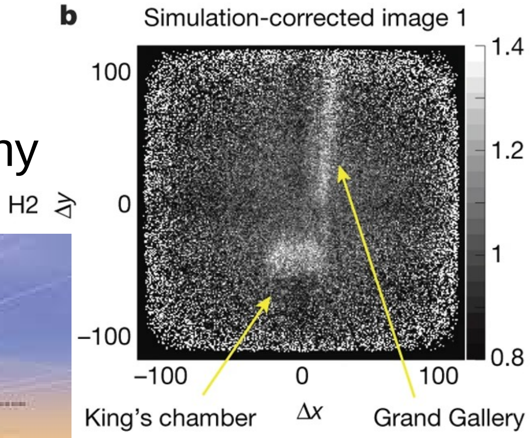


- 👍 Can be used to gain information on traversed objects

➔ Muon Tomography



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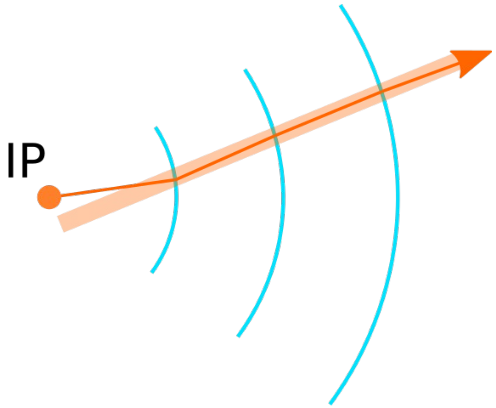

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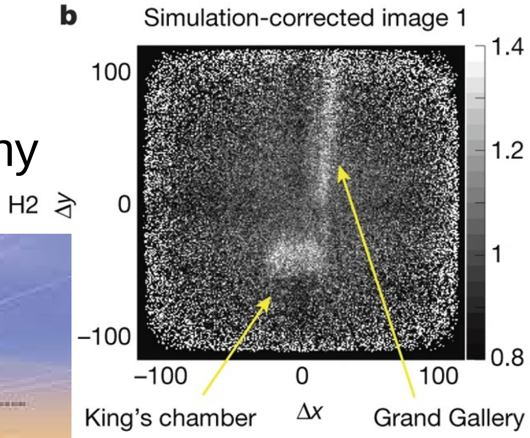
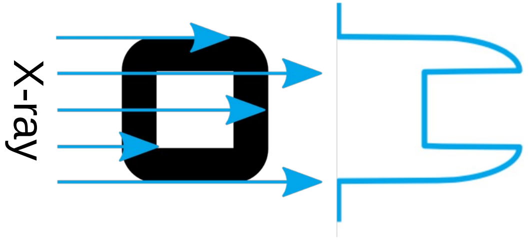


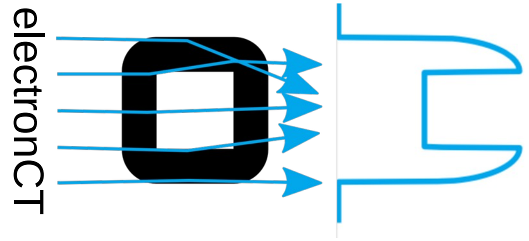
➔ electronCT

Imaging in Radiotherapy

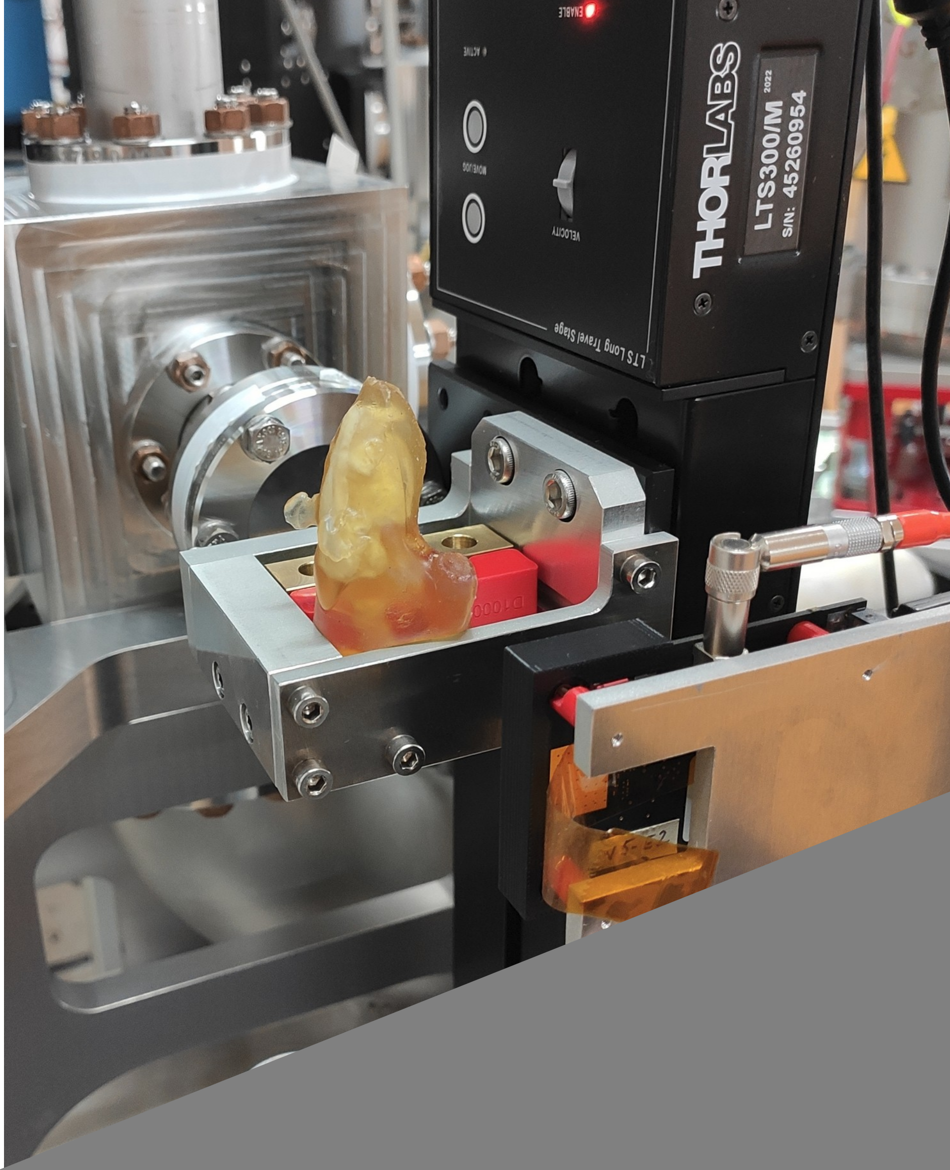
- In the context of radiotherapy, imaging is mostly accomplished via conventional CT or MRI
  - ➔ Change of reference system and/or relocation of patient required



- **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


THORLABS
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2022
S/N: 45260954
LTS Long Travel Stage
VELOCITY
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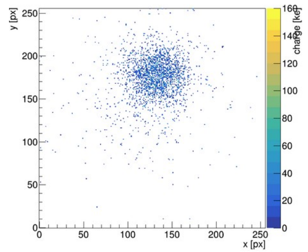
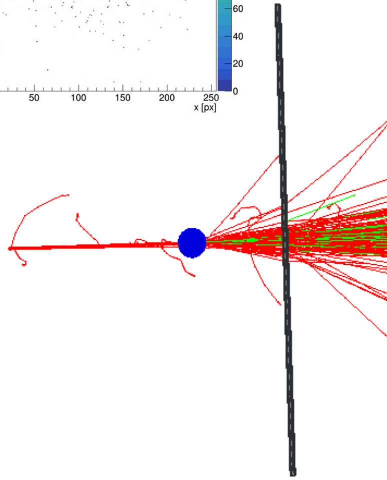
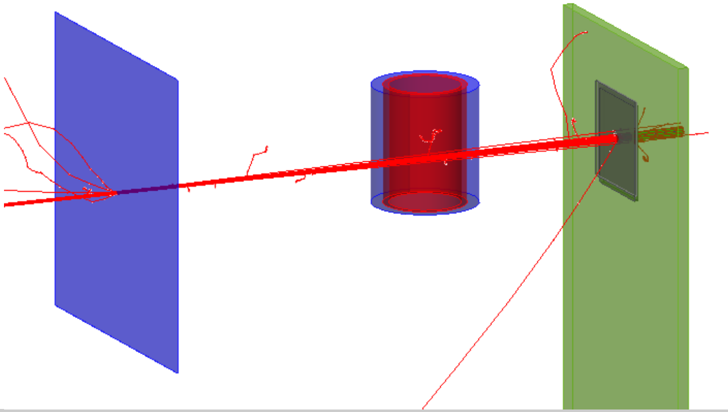
2D electronCT



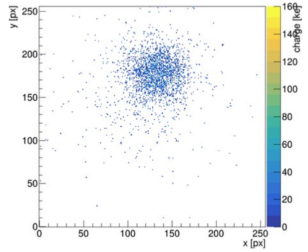


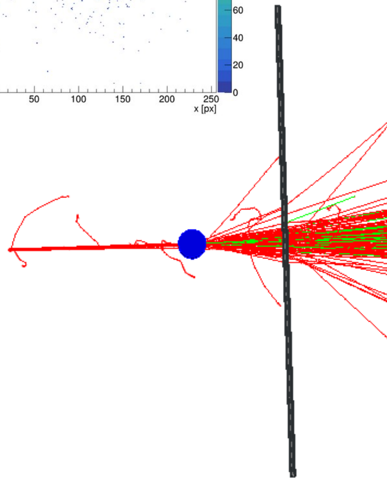
- Technique: Use pencil beam to raster the sample & perform beam profile measurement downstream of the sample
  - **Beam** and/or **sample position** define pixel of obtained image
  - Measured quantity: **width of beam profile** for given beam position

- Requirements:
  - Well-controlled, small beam spot @ sample
  - Precise relative movement beam vs. sample
  - High repetition rate for fast image recording
  - Fast detectors with large dynamic range



2D electronCT





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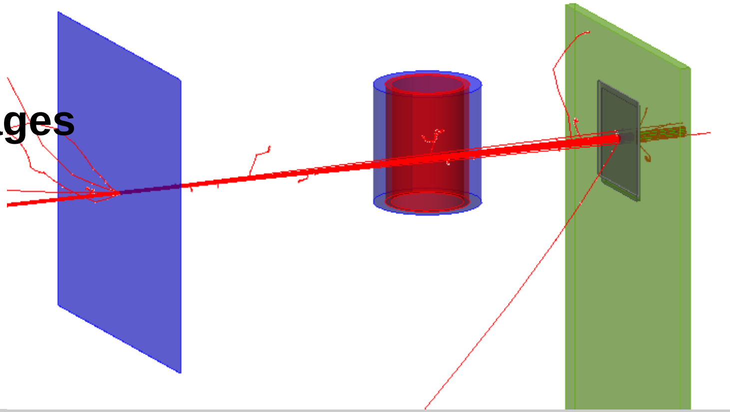
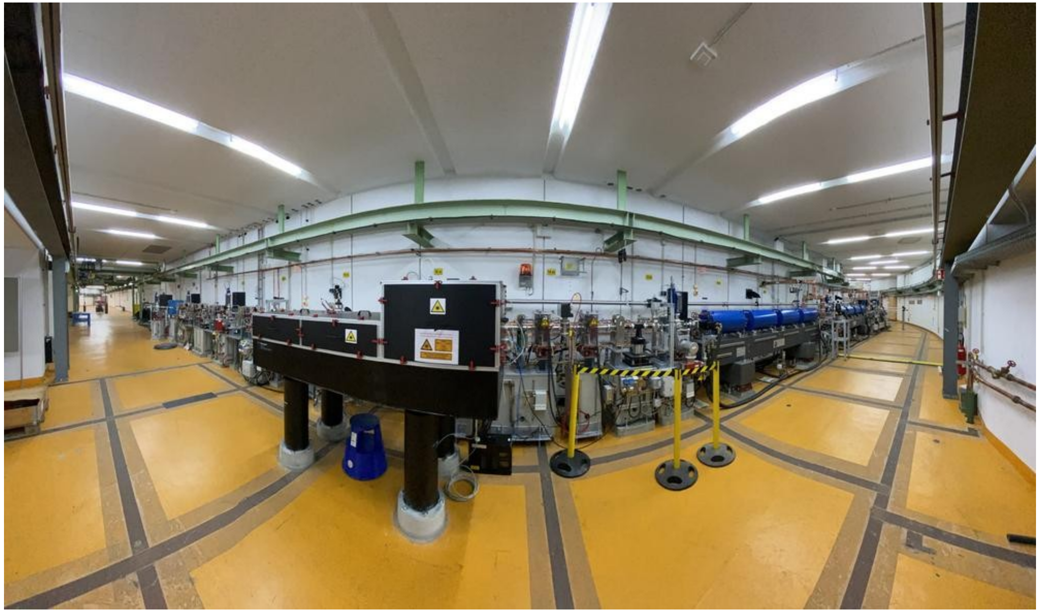
- Requirements:
    - Well-controlled, small beam spot @ sample – **ARES**
    - Precise relative movement beam vs. sample – **Motion Stages**
    - High repetition rate for fast image recording
    - Fast detectors with large dynamic range – **Timepix3**



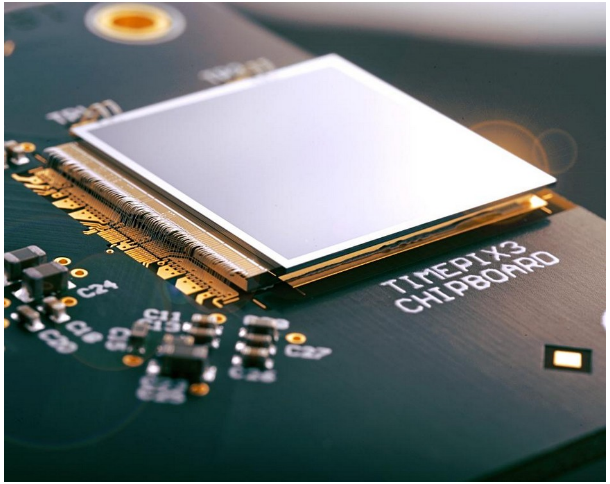
The ARES Accelerator

- **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
- See Talk by Florian Burkart this afternoon



https://kt.cern/technologies/timepix3

Timepix3 Detector

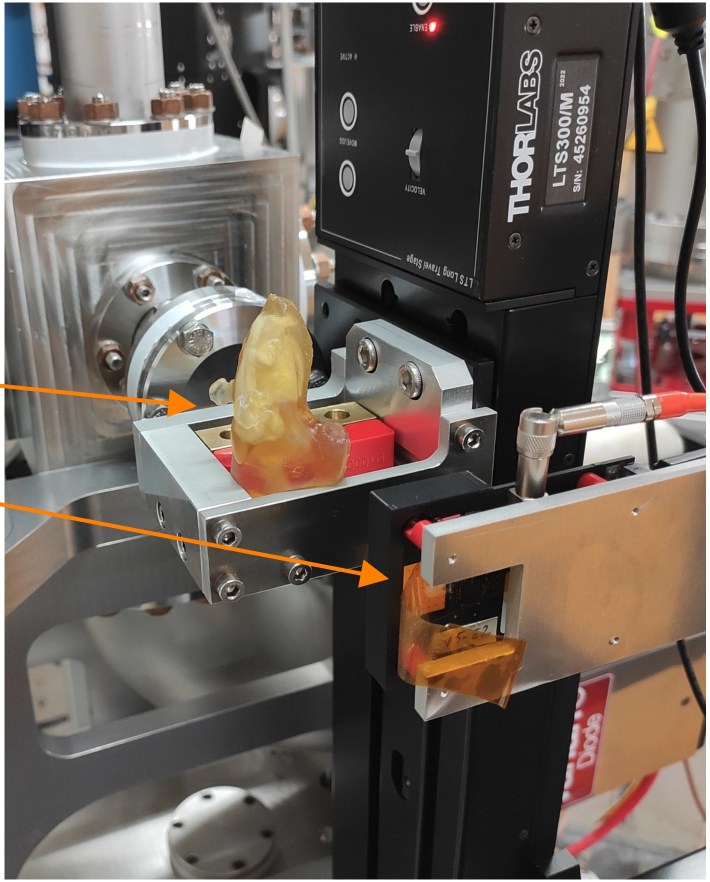


- Detector readout ASIC by CERN, NIKHEF, Uni Bonn
  - Pixel Pitch: 55 x 55 µm
  - Pixel Matrix: 256 x 256
  - Total Area: 14 x 14 mm
- Used in both High Energy Physics and Medical Applications
- Here:
  - Bump bonded to 100 µm thick, planar silicon detector
  - Readout mode options:
    - Frame-based: detector shutter triggered by ARES bunch clock → 10 µs frame
    - Data-driven: continuous readout → event building in post-processing
  - Data acquisition systems:
    - SPIDR Readout System, custom software
    - Katherine Readout System, TrackLab software

electronCT Setup I

Setup for first 2D eCT measurements

- Rat phantom “Alfred” on XY motion stage
  - Medical phantom –
    3D printed skull, gelatinous tissue
  - Fixed on motion & rotation stages
- Timepix3 assembly mounted on fixed stand downstream
- Minimising distances for beam size & detector occupancy
  - Limited by mechanics

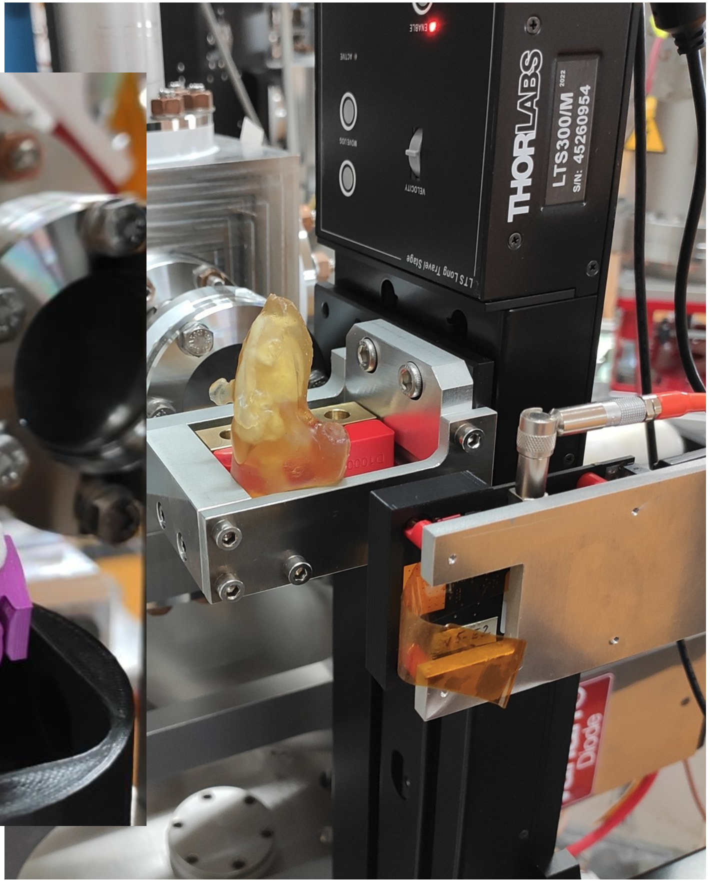


* **A L**ittle **F**urry **R**at for **e**lectronCT **D**evelopment

electronCT Setup I

Setup for first 2D eCT measurements

- Rat phantom “Alfred” on XY motion stage
  - Medical phantom –
    3D printed skull, gelatinous tissue
  - Fixed on motion & rotation stages
- Timepix3 assembly mounted on fixed stand do
- Minimising distances for beam size & detector
  - Limited by mechanics
- Received “Berta” through a DESY-M ↔ UKE collaboration
  - Solid, more detailed skeleton



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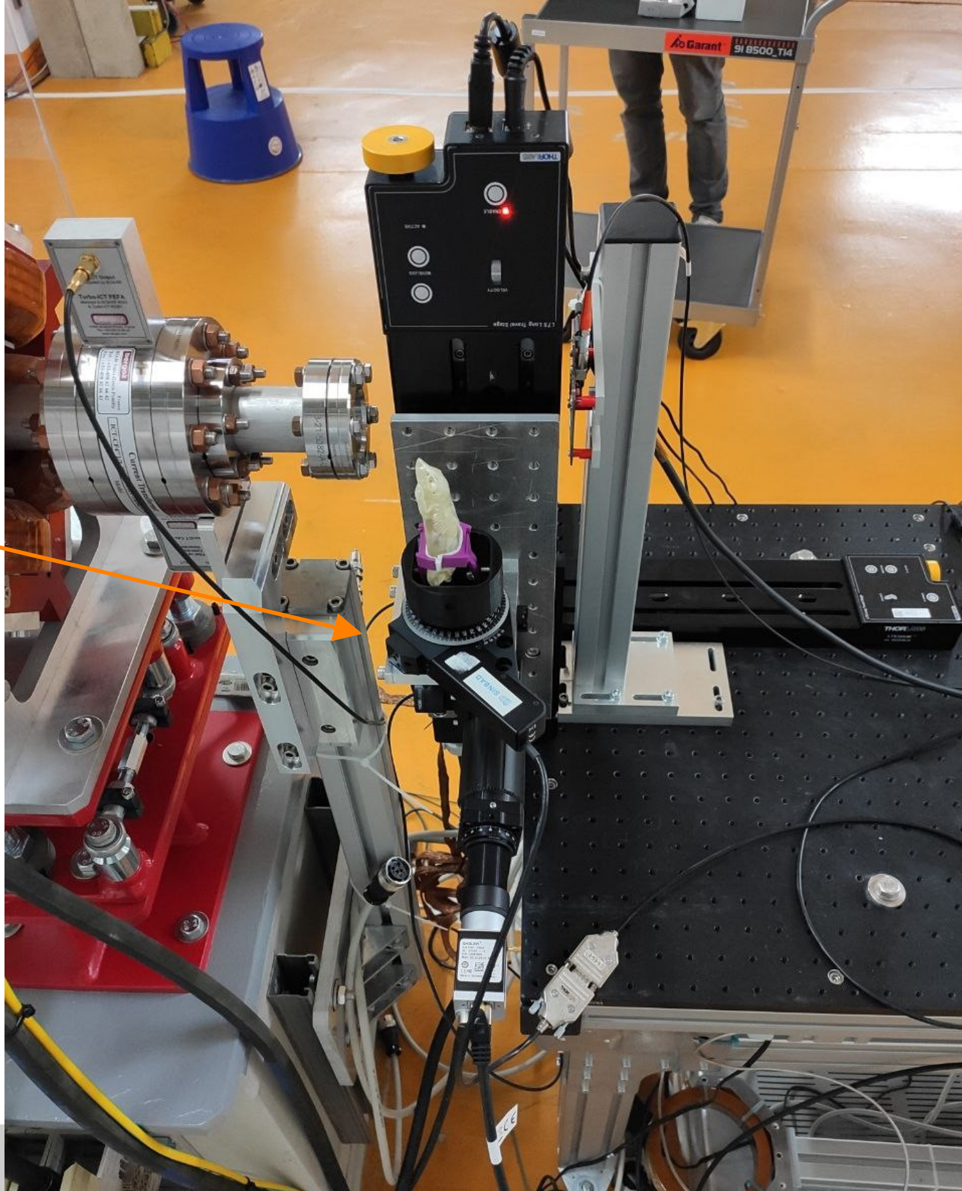
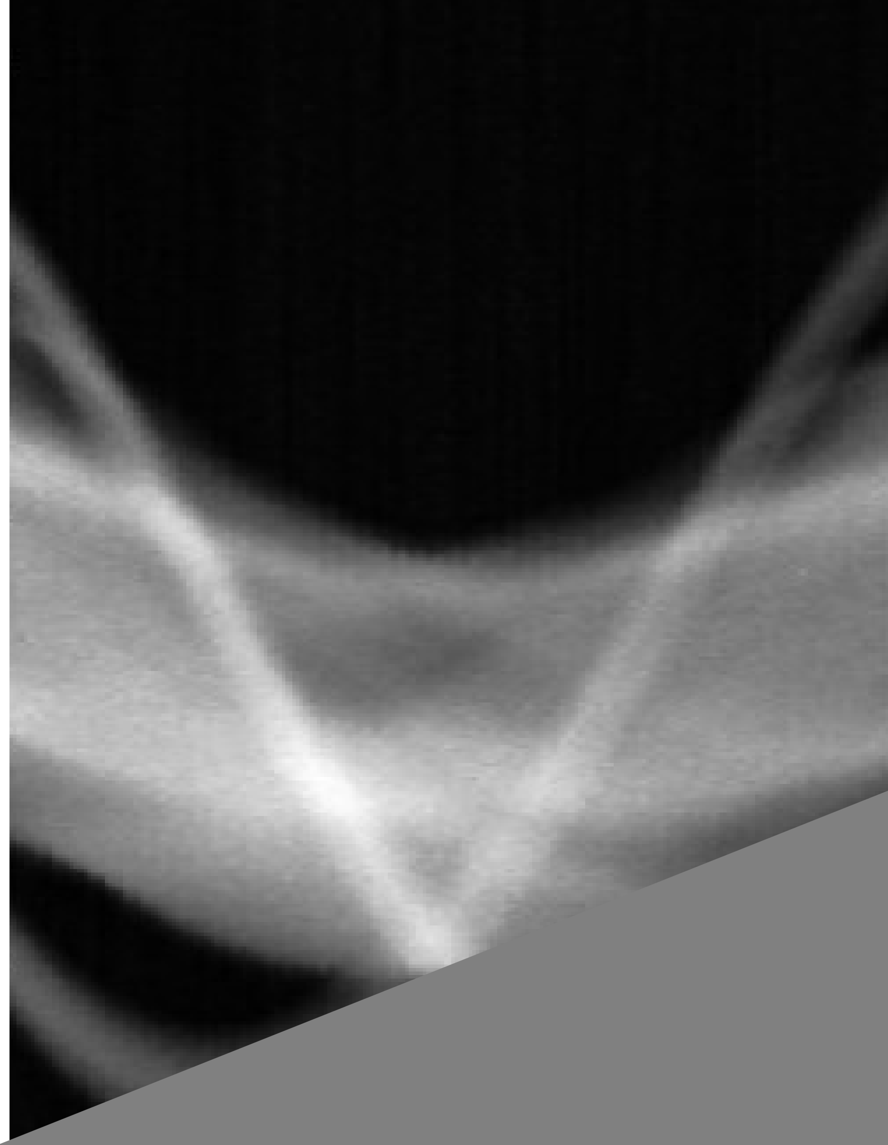
** **B**rave **E**xperimental **R**odent for **T**omographic **A**pplications

electronCT Setup II

- Tomographic reconstructions require multiple projections at different incidence angles
  - ➔ Add rotation stage
- Scan tool was implemented to perform two- or three-dimensional scans:
  - 2D: x + y
  - 3D: x + y + φ
- Continuous motion at defined velocity along x
  - ➔ 10 Hz repetition rate defines resolution
- Steps along y and φ
  - Defines resolution directly



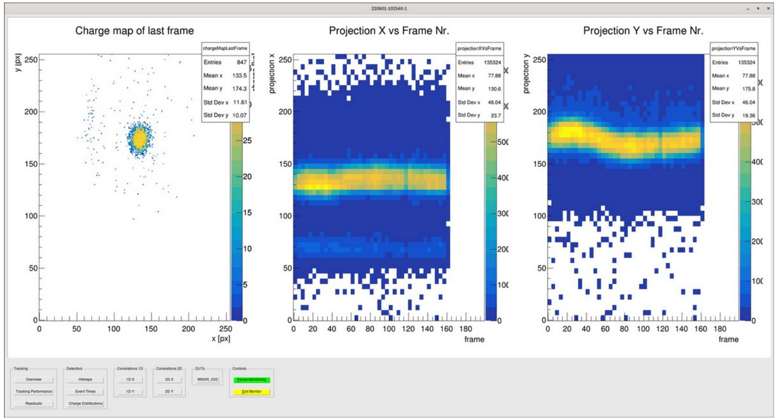
Results

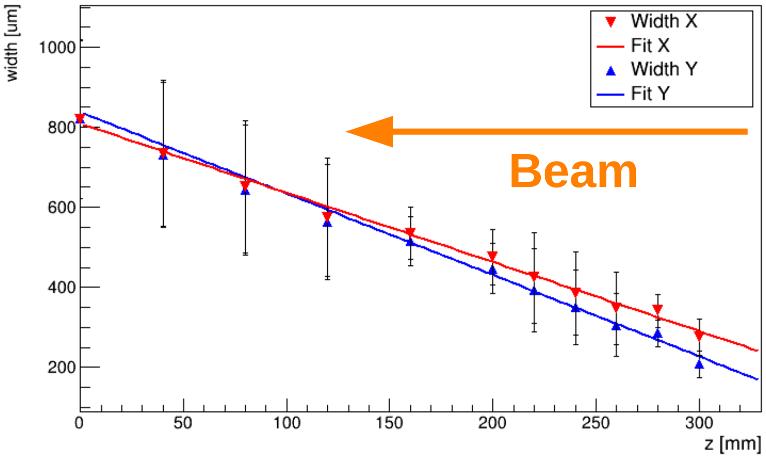


Beam Profile Measurements

Corryvreckan beam monitor

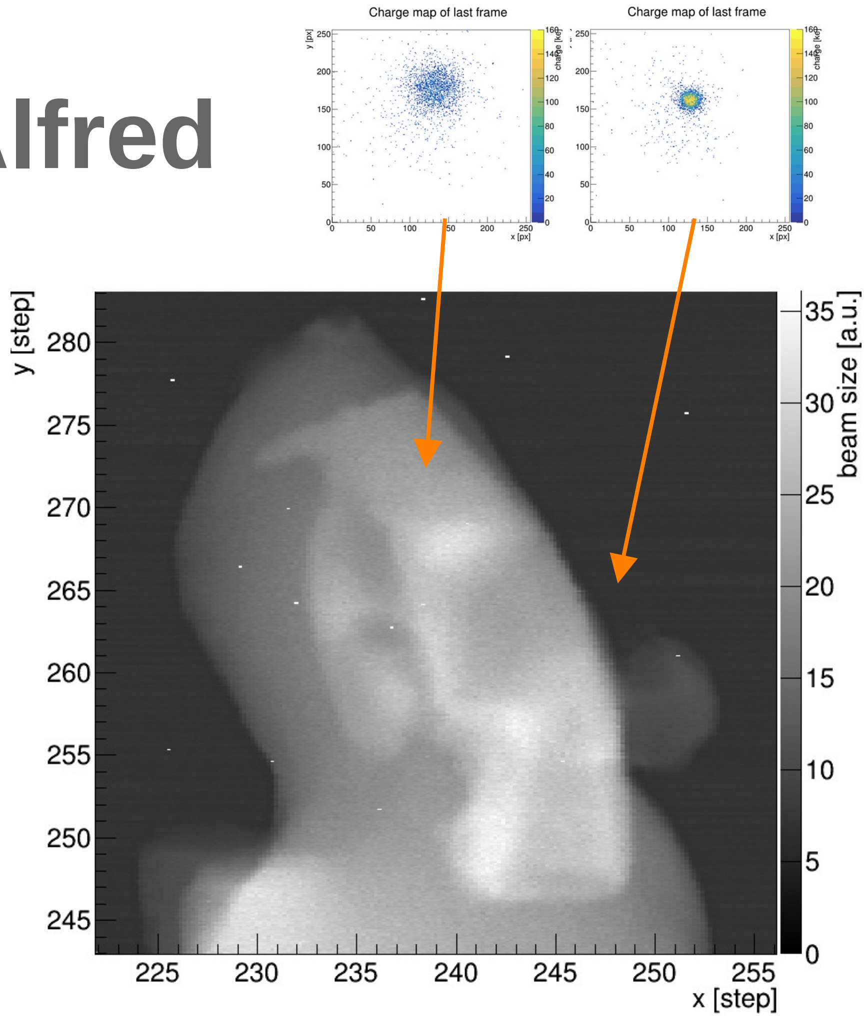
- Bunch-by-bunch beam monitoring from TPX3 data
- Beam parameter optimisation
  - **Low charge**
    - ➔ Low dose to sample or patient
    - ➔ Prevent saturation of detector
  - **Low emittance**
    - ➔ Transverse bunch profile dominates spatial resolution for small samples and affects the sensitivity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





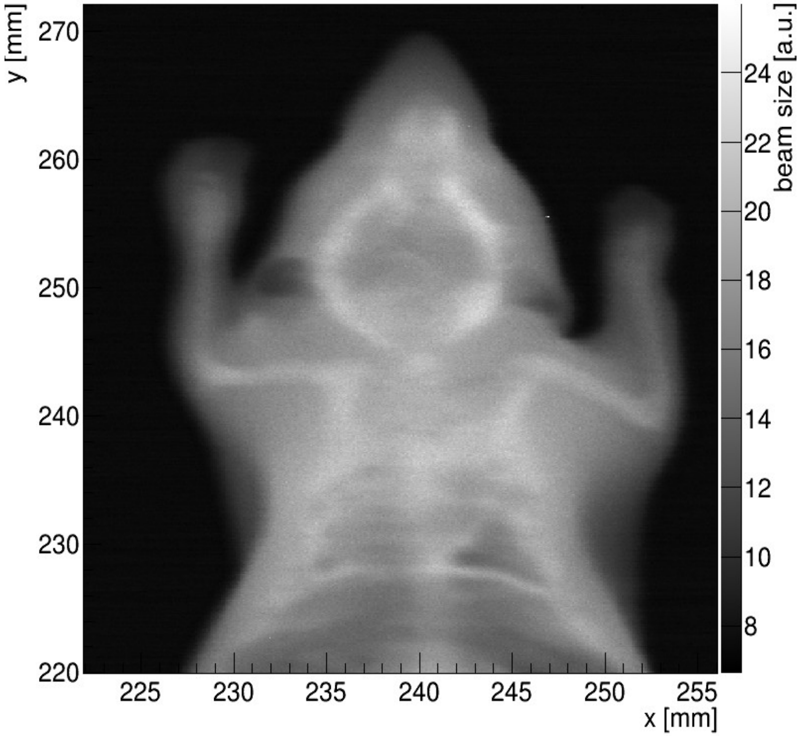
eCT 2D Measurement – Alfred

- Each data point in image represents width of beam at detector at a given phantom 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)



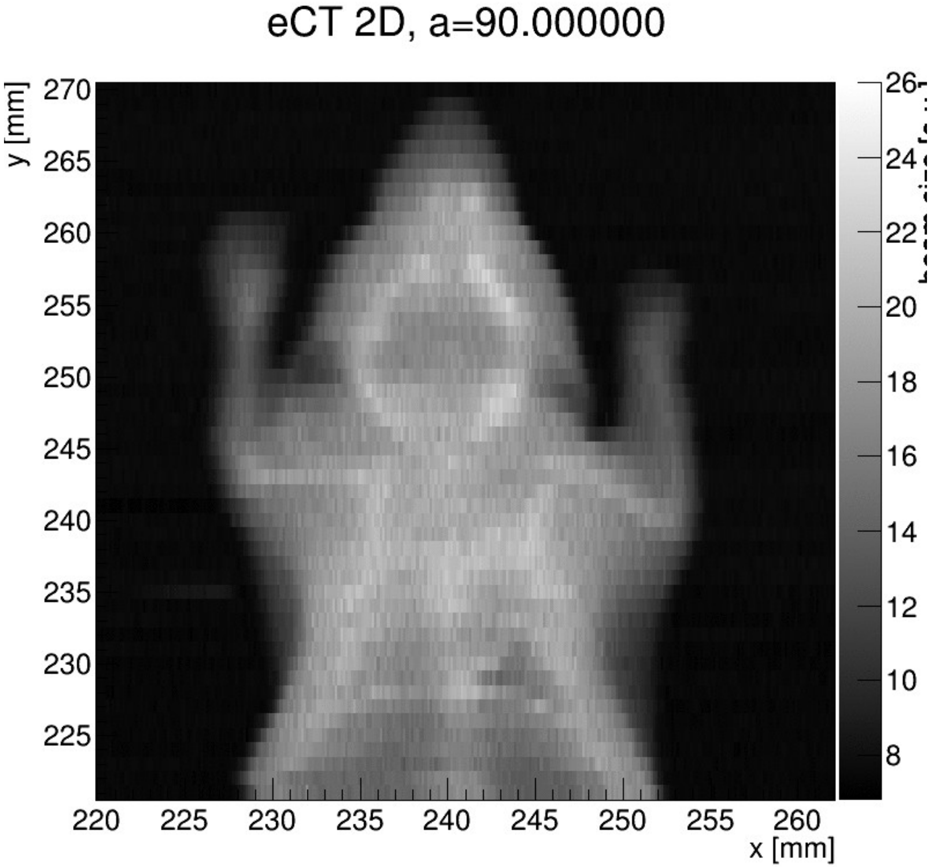
eCT 2D Measurement – Berta

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



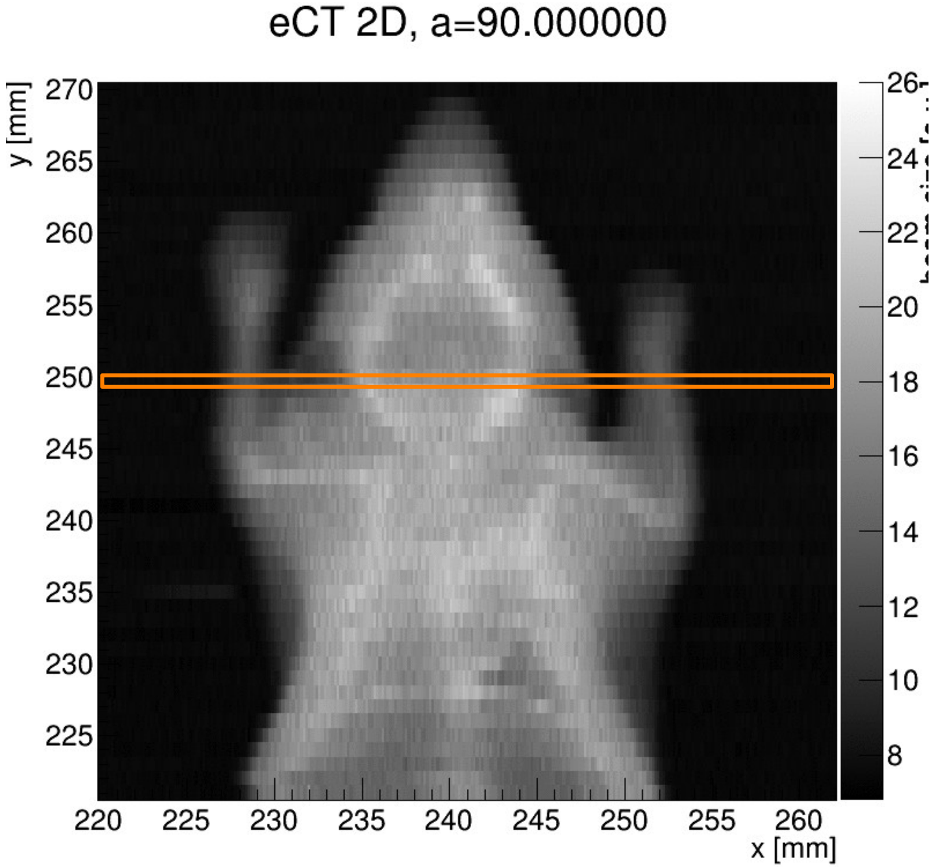
Towards the Third Dimension

- 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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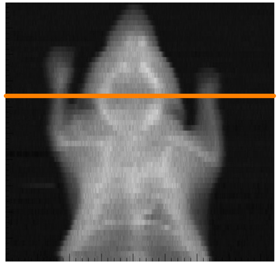
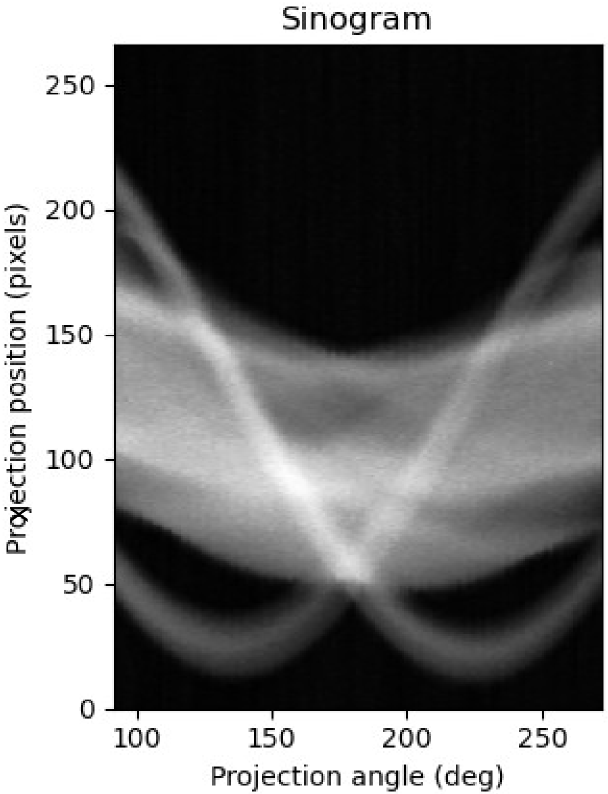


- Repeat 2D imaging at various rotation angles …
- For each row of the parameter space
  plot the pixel value vs x-φ (“Sinogram”)



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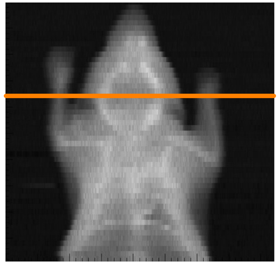
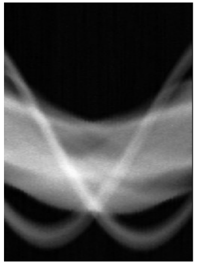
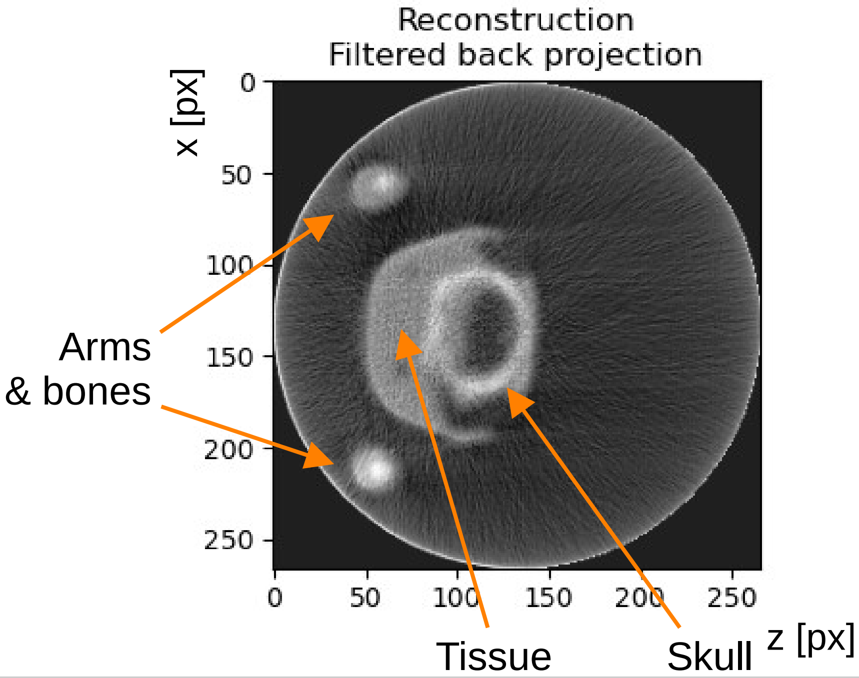


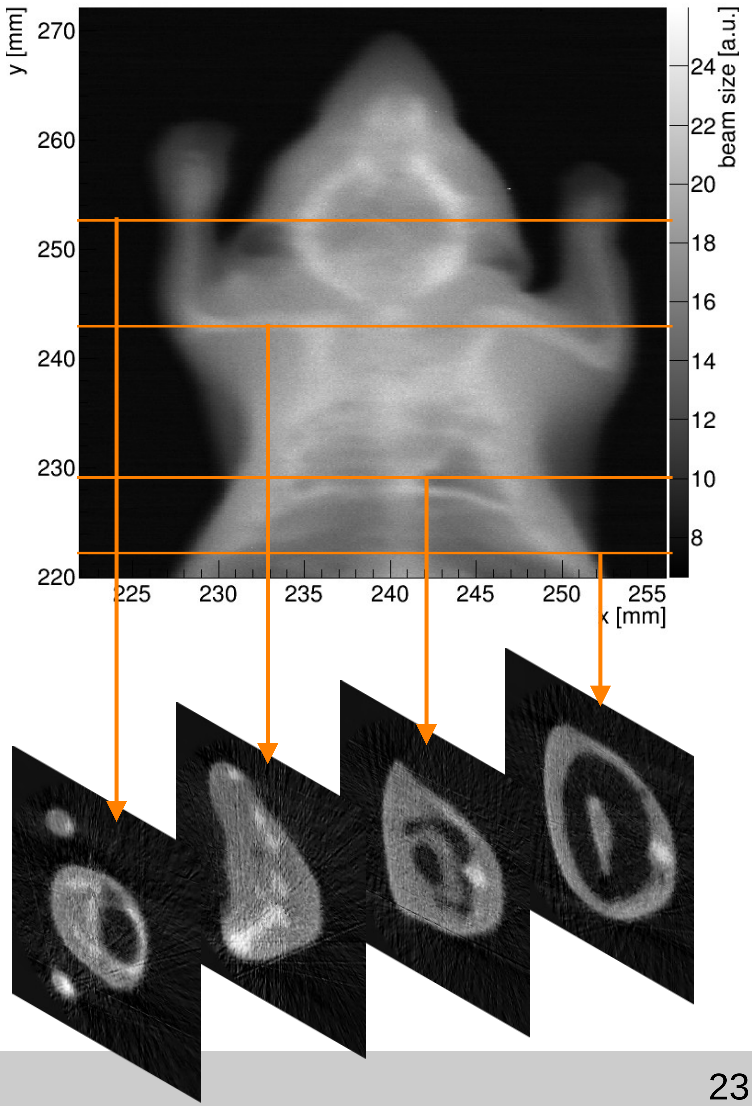


- Repeat 2D imaging at various rotation angles …
- For each row of the parameter space
  plot the pixel value vs x-φ (“Sinogram”)
- Perform an *inverse radon transform*
  (here: filtered back projection)
  to obtain a single slice (x-z) of the sample

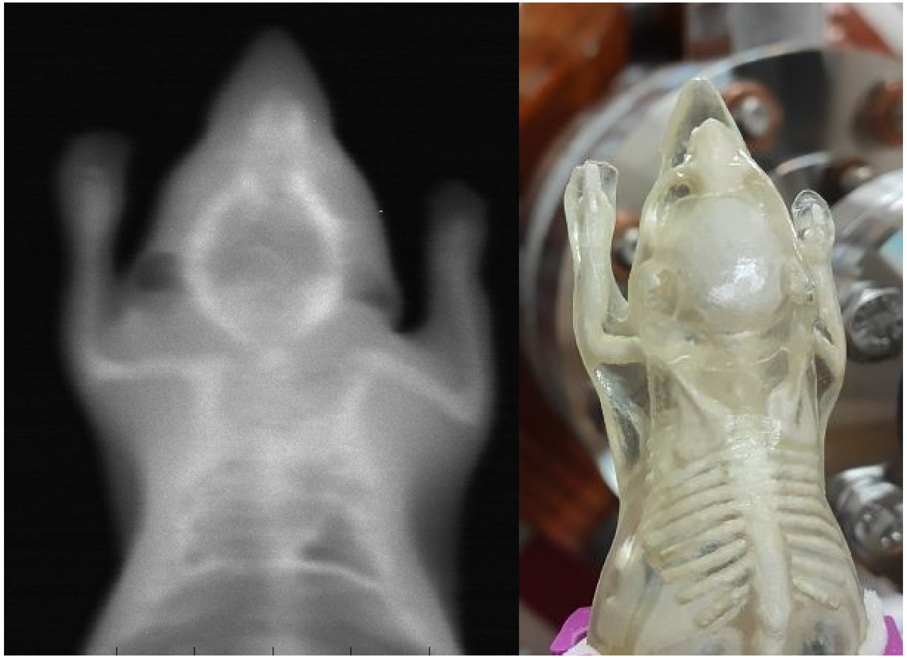


electronCT – 3D

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



Conclusions



Status Quo & Outlook

We appreciate the support and efforts of the ARES team over the past years!
Thank you!

- **electronCT** concept studied @ARES
  - Measurement of beam widening from scattering
  - Drastically reduce measurement time
  - Concept proven via 2D & 3D measurements

- ARES will not be to our availability in the future
  - ➔ Looking for a new home
  - ➔ Made contact to CLEAR @CERN

- Towards medical imaging …
  - Simulations to benchmark analysis & reconstruction, dose, contrast, …
  - Calibration & characterisation measurements