BEATS

BEAmline for Tomography at SESAME

The Abdus Salam International Centre for Theoretical Physics

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School on Synchrotron Light Sources and their Applications

# SESAME BEATS
# Synchrotron Computed Tomography for the Middle East

**Gianluca Iori**, BEATS Beamline Responsible

Synchrotron Light for Experimental Science and Applications in the Middle East – SESAME

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Funded by the EU's H2020 framew ork programme under grant agreement n°822535

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BEAmline for Tomography at SESAME

# Outlook

## **Part 1:** Advantages of Synchrotron X-ray Computed Tomography

- Computed Tomography with a synchrotron source
- The BEATS beamline of SESAME: equipment and commissioning
- Laboratory VS Synchrotron XCT

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## **Part 2:** Applications of SXCT and first results of BEATS

- Scientific case of the new BEATS beamline of SESAME
- Materials science and engineering
- Health and biology research
- Soil, plant, animal tissue characterization
- Conservation of cultural heritage samples
- Analysis and digitization of historical objects

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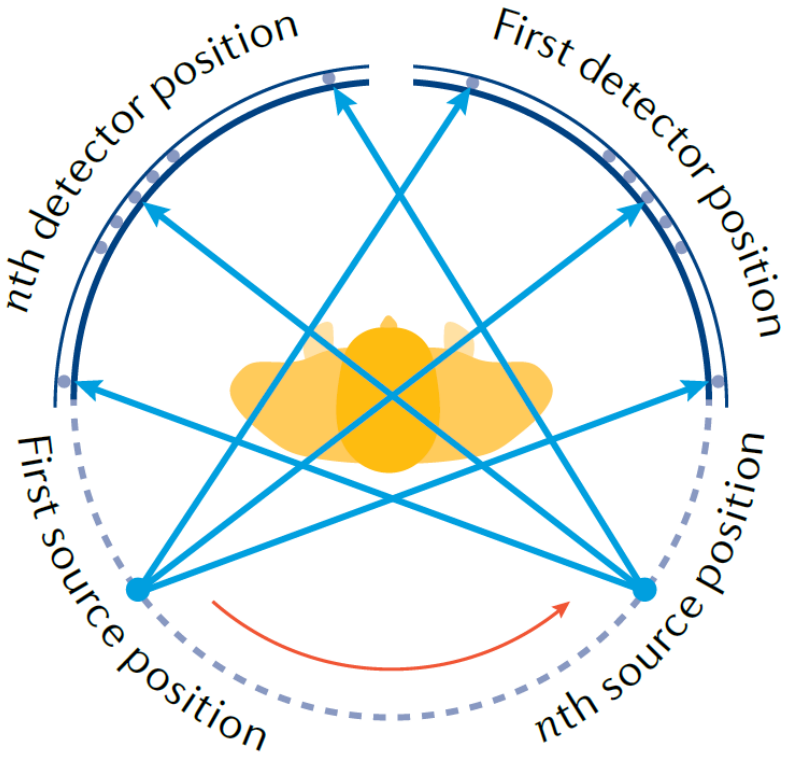
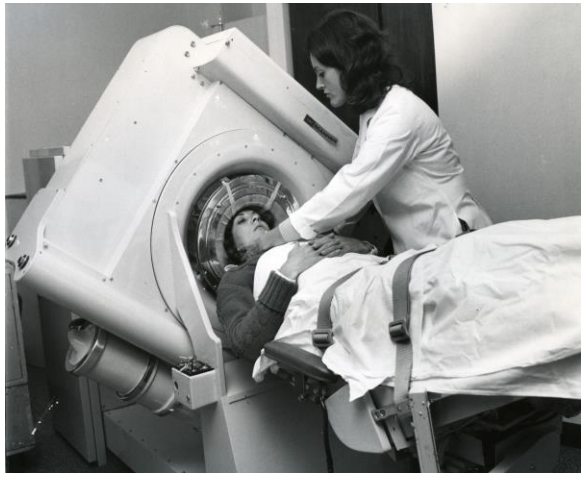
# **Part 1:** Advantages of Synchrotron X-ray Computed Tomography (SXCT)

# XCT experimental setups

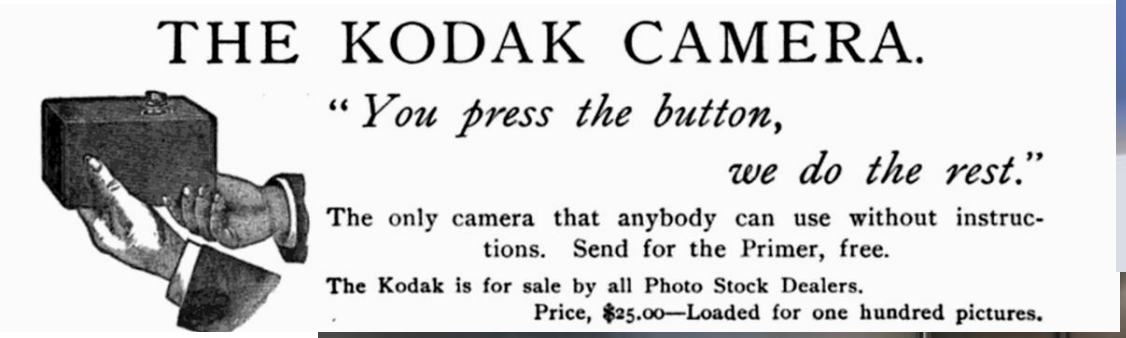
## Gantry setup – clinical XCT




First Computed Tomography scan
EMI Scanner (1971)
(Nobel prize for CT in 1979 Hounsfield & Cormack)



# XCT experimental setups


THE KODAK CAMERA.



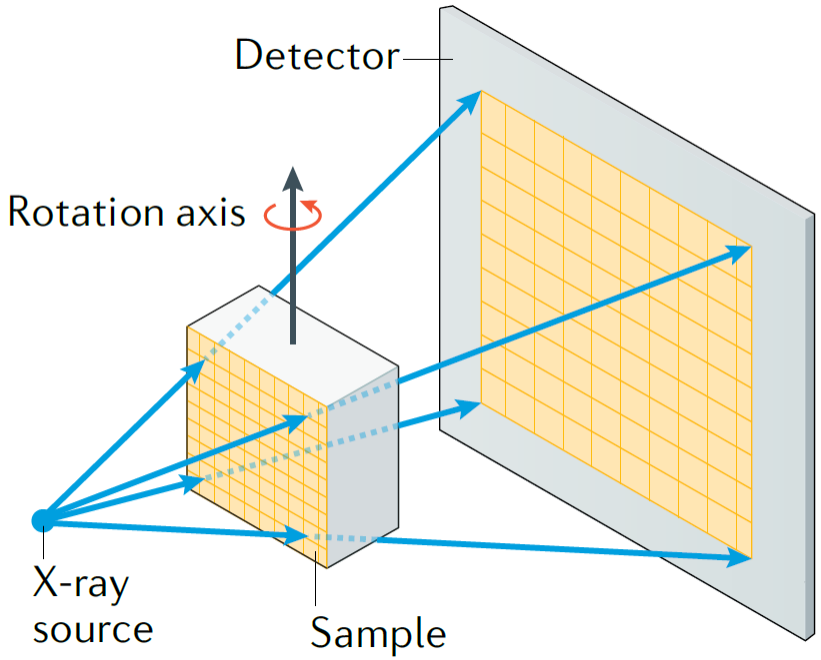
*"You press the button, we do the rest."*

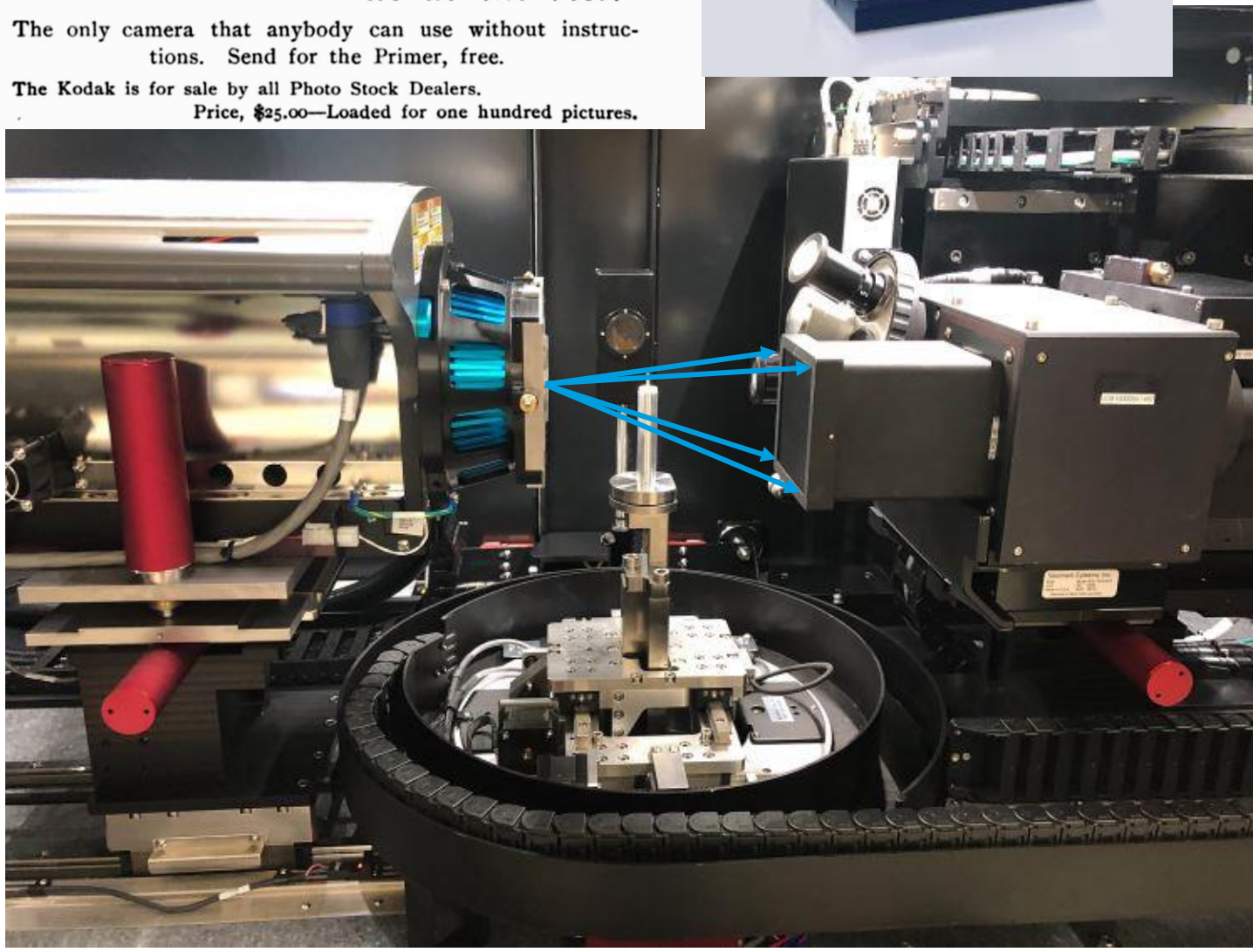
The only camera that anybody can use without instructions. Send for the Primer, free.

The Kodak is for sale by all Photo Stock Dealers.

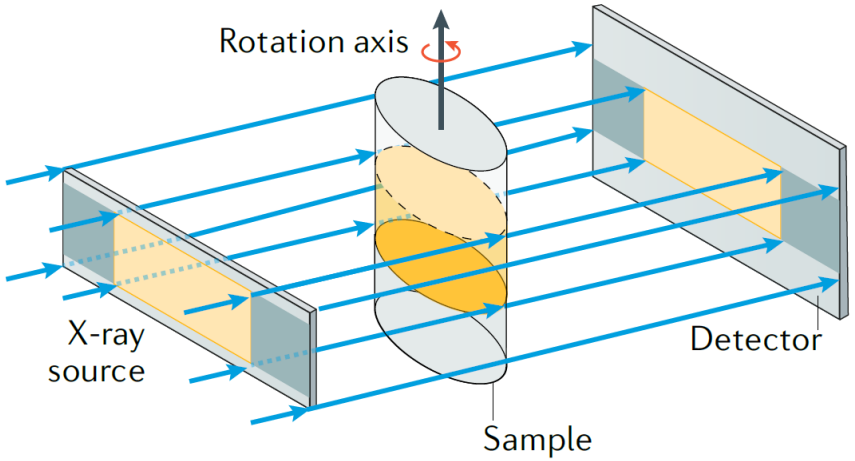
Price, $25.00—Loaded for one hundred pictures.

## Cone beam setup – lab XCT



# XCT experimental setups




10x, 5x detector (Optique Peter)

0.5x, 1x, 2x detector (ESRF)




TOMCAT endstation #1

**SESAME BEATS SXCT experimental station**

PAUL SCHERRER INSTITUT PSI

BEATS

BEAmline for Tomography at SESAME Project

NEWS & EVENTS THE PROJECT CONTACTS PARTNERS


# BEATS in motion - our new video has arrived

NEWS 05 JUL 2023

**BEATS, the BEAmline for Tomography at SESAME is an H2020 European project to build a beamline for tomography at the SESAME synchrotron in Jordan.**

More about the project → www.beats-sesame.eu

**BEATS_eu**
@BEATSeu1

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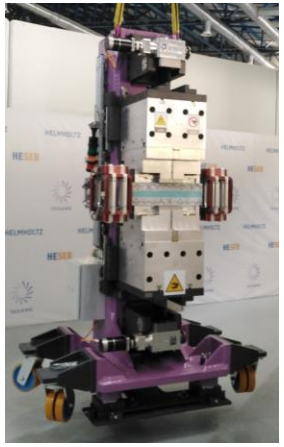
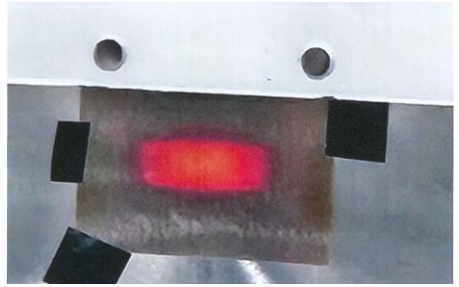
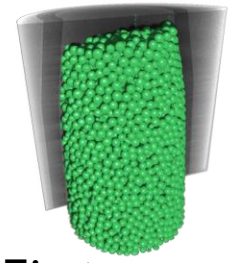
# Project timeline





Beamline technical design
2019 - 2020

X-ray source design
2019 - 2020

Infrastructure works
Floor preparation
New alignment survey
2021

Beamline installation
2022

Start of commissioning
2023

First 3D scan
May 11th, 2023

First user proposal
2024

2019 | 2020 | 2021 | 2022 | 2023 | 2024

BEATS science case
July 2020

BEATS TDR
August 2020

Delivery hutches
Dec 2021

First beam
Jan 2023

Beam @ exp. hutch
Feb 2023

Beamline inauguration
June 2023

Source: https://beats-sesame.eu/the-project/deliverables/

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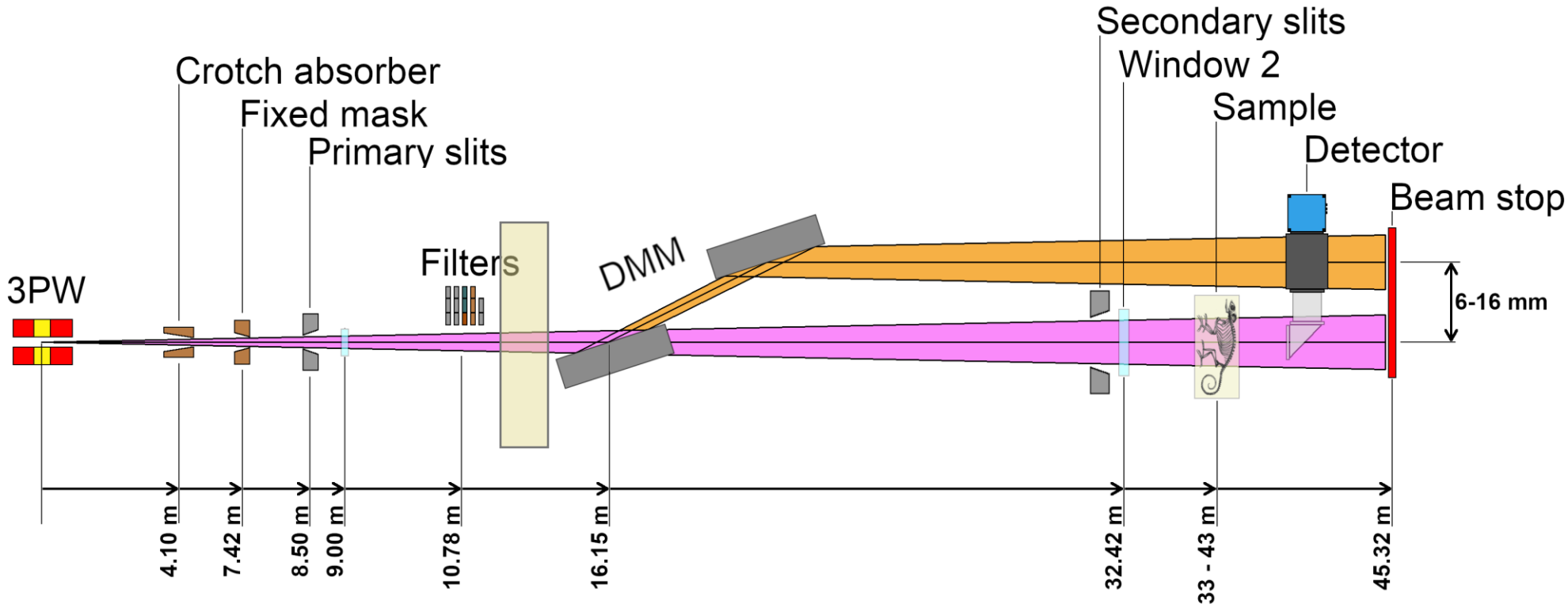
# BEATS beamline layout

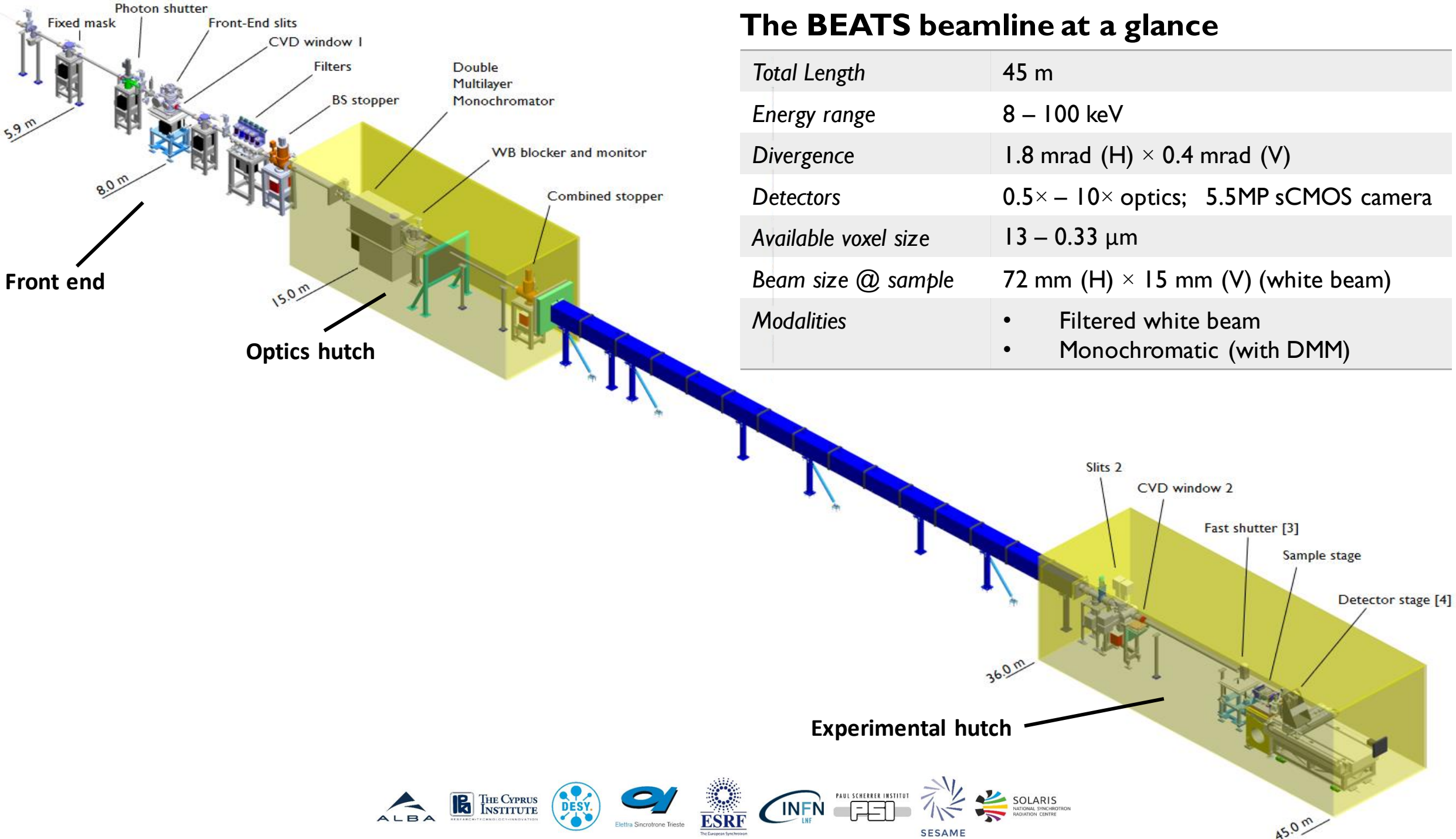
- Filtered **white beam**: high flux for dense samples or fast experiments
- **Monochromatic beam** (with DMM): highest resolution and sensitivity




Funded by the EU's H2020 framework programme under grant agreement n°822535

# The BEATS beamline at a glance

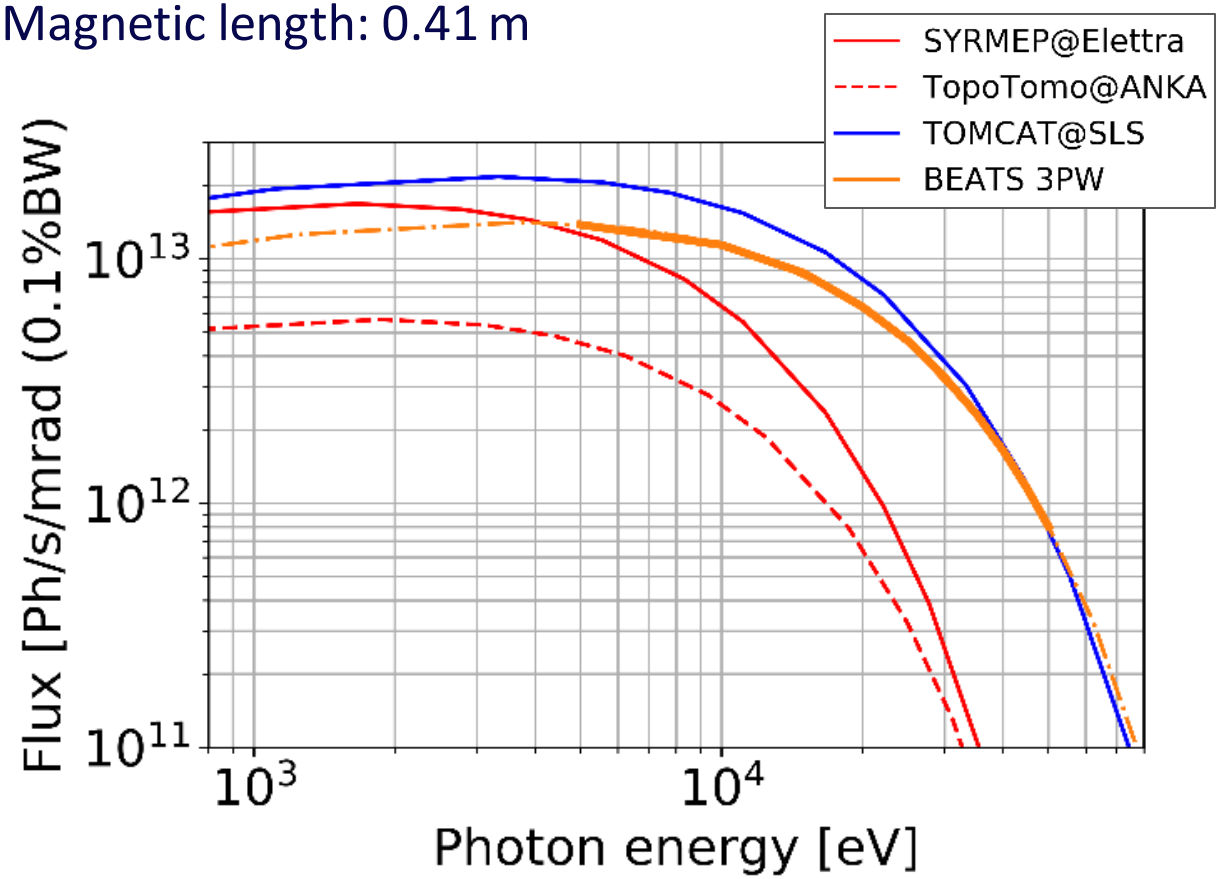
| | |
|---|---|
| *Total Length* | 45 m |
| *Energy range* | 8 – 100 keV |
| *Divergence* | 1.8 mrad (H) × 0.4 mrad (V) |
| *Detectors* | 0.5× – 10× optics; 5.5MP sCMOS camera |
| *Available voxel size* | 13 – 0.33 µm |
| *Beam size @ sample* | 72 mm (H) × 15 mm (V) (white beam) |
| *Modalities* | • Filtered white beam<br>• Monochromatic (with DMM) |

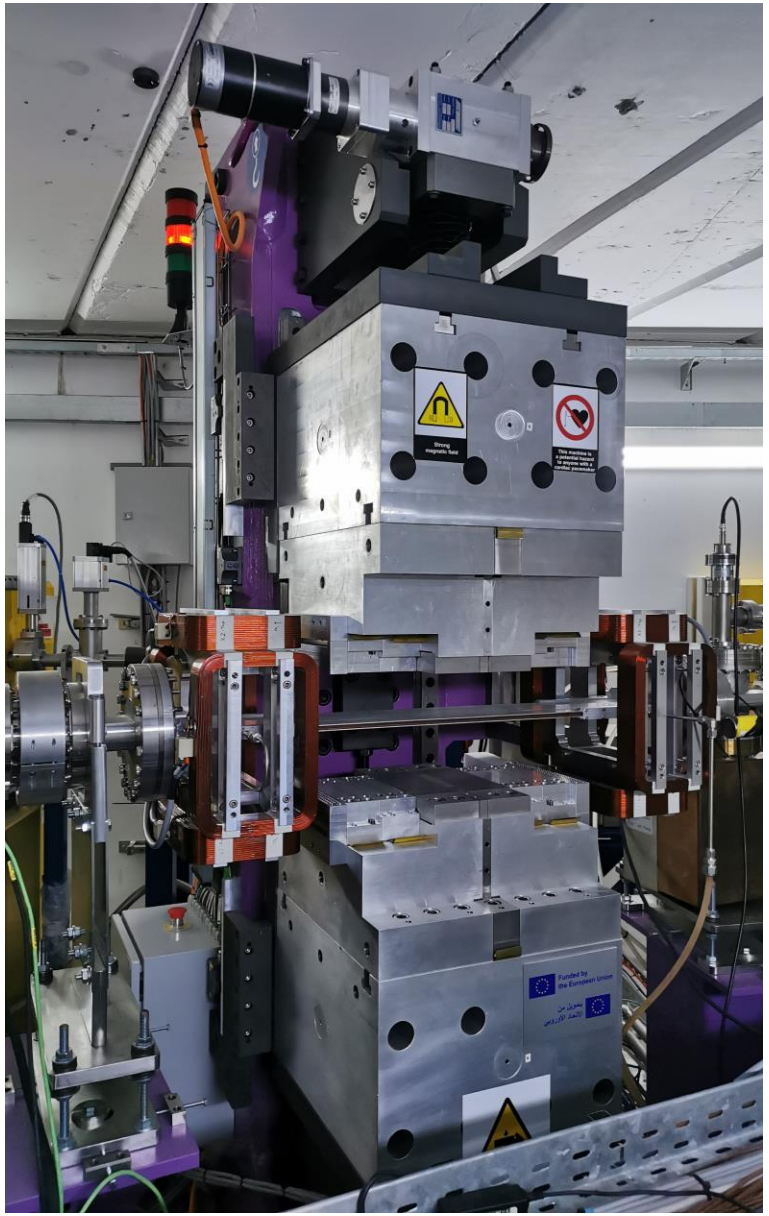


# BEATS X-Ray source

## 3-pole wiggler

- Minimum gap: 11.15 mm
- Maximum field: 2.92 T
- Magnetic length: 0.41 m



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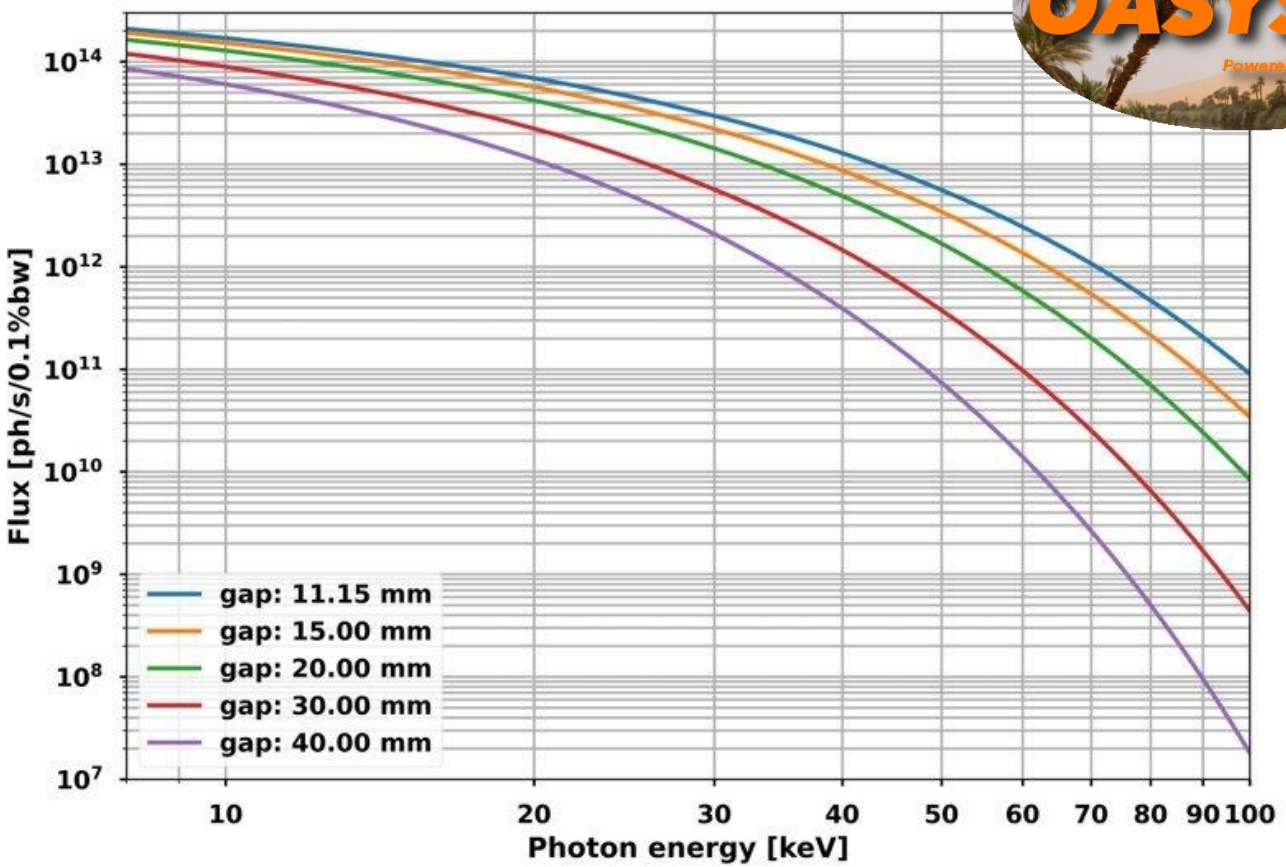


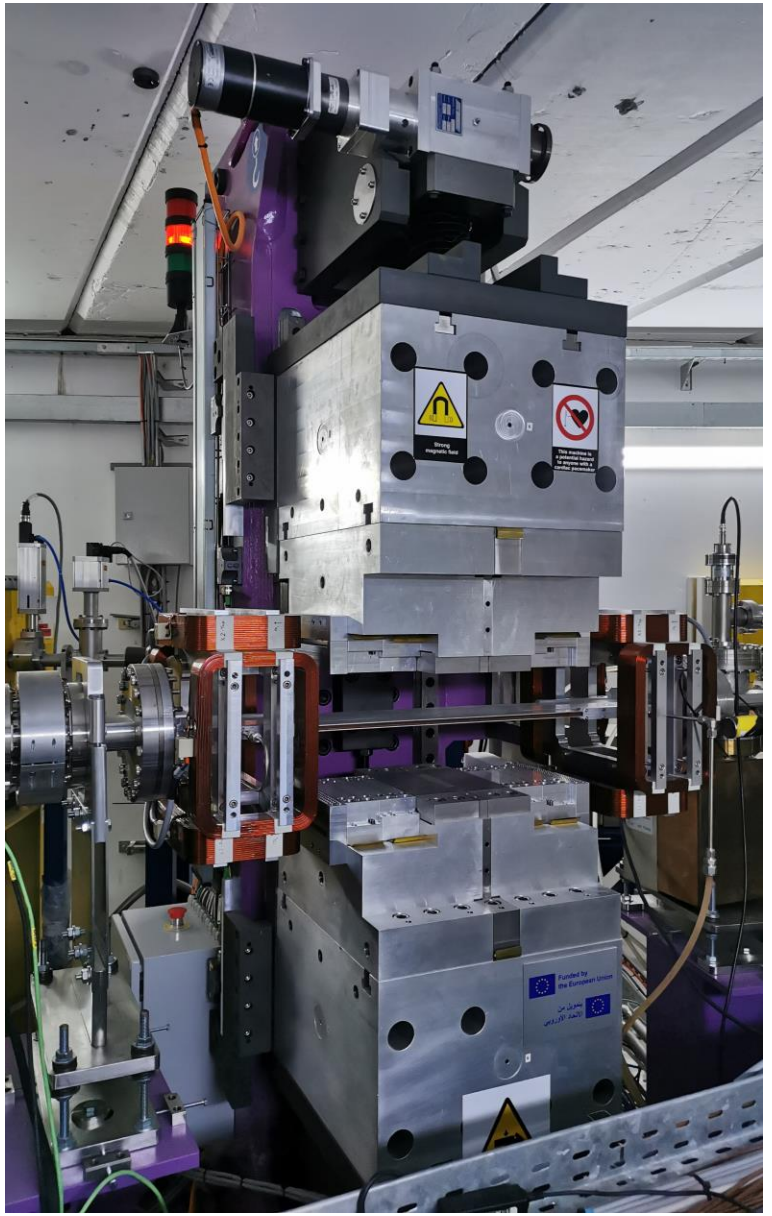

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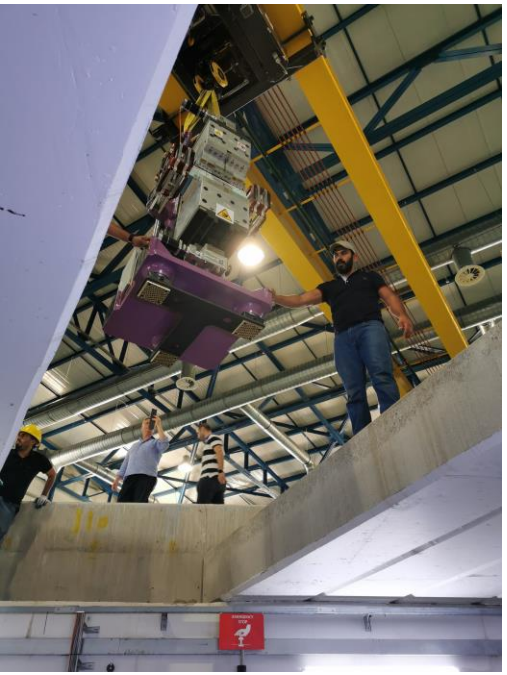
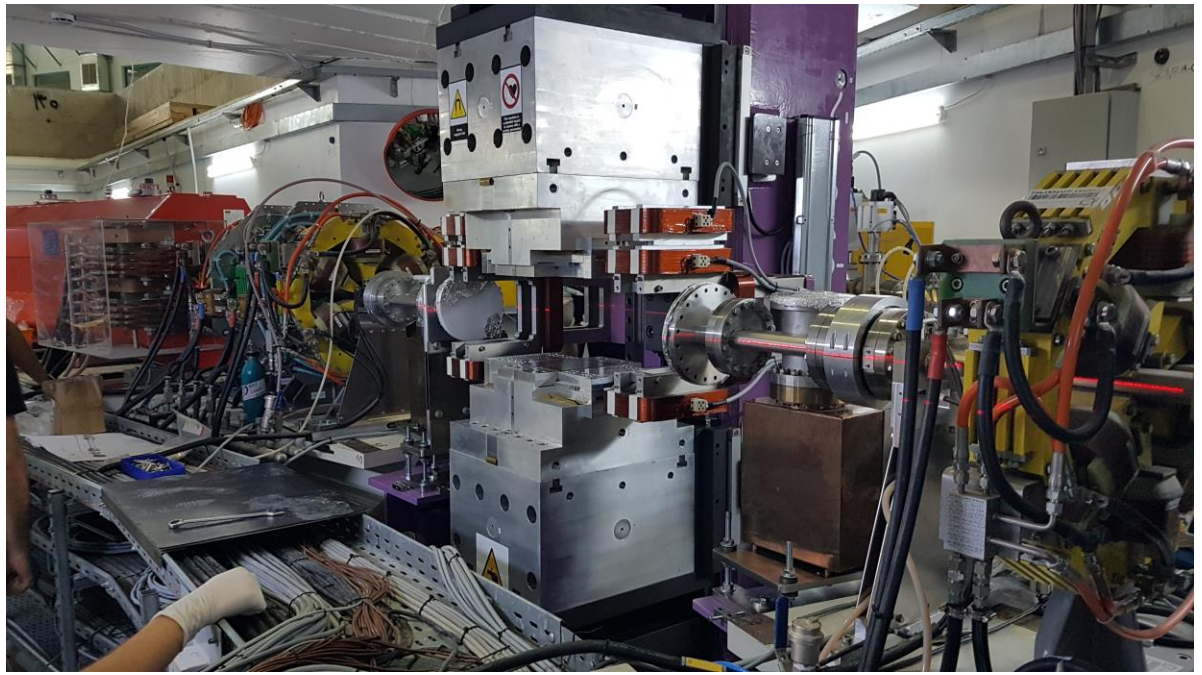
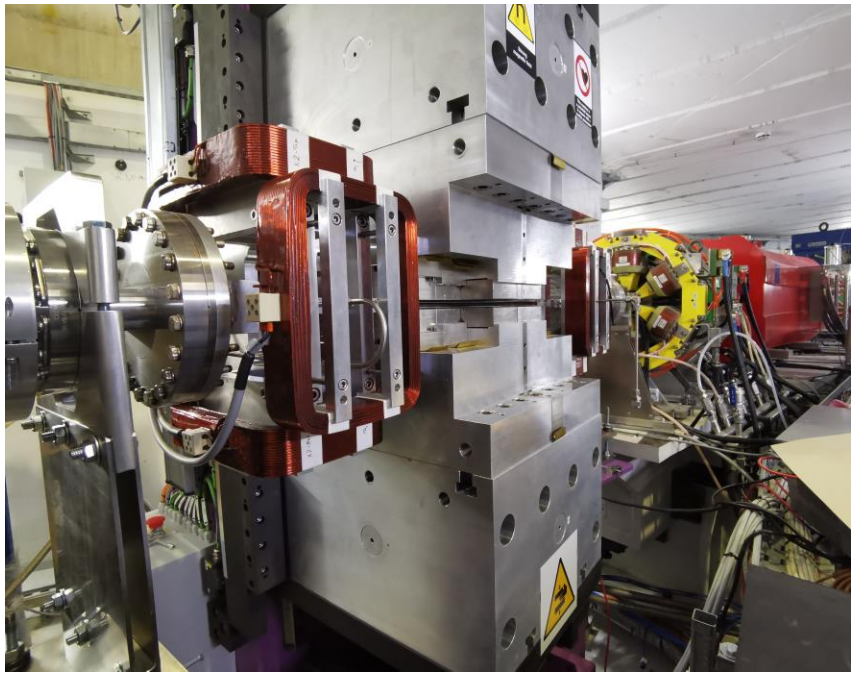
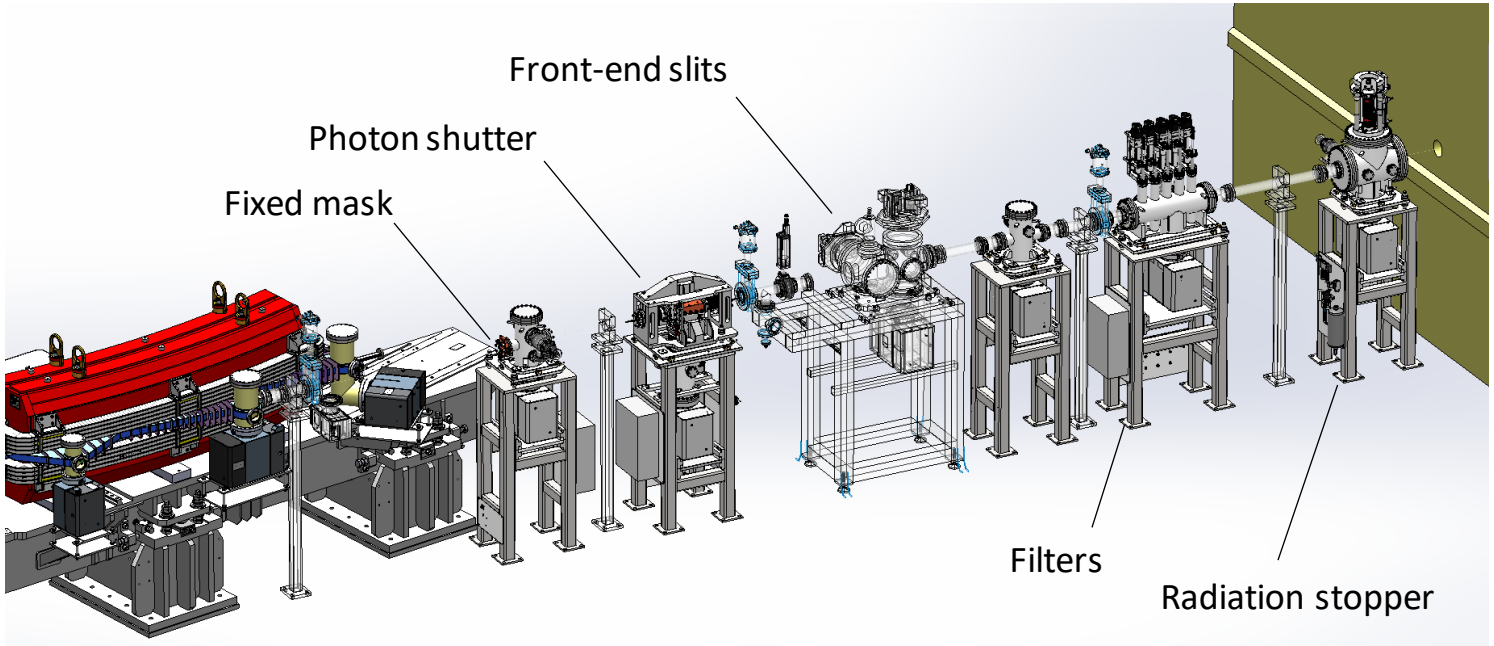
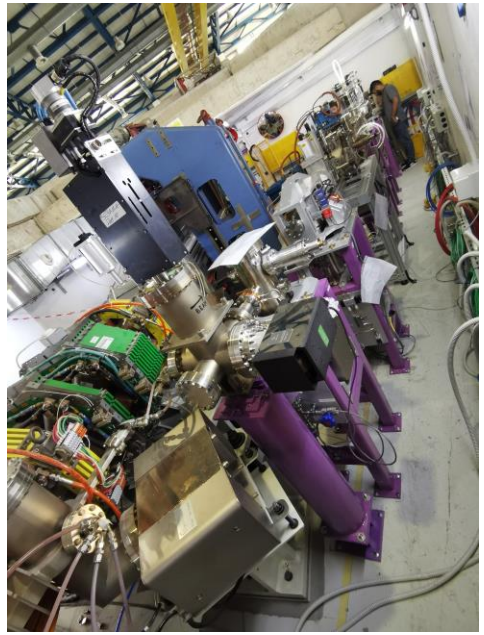
# August-September 2022 shutdown – ID and front-end installation



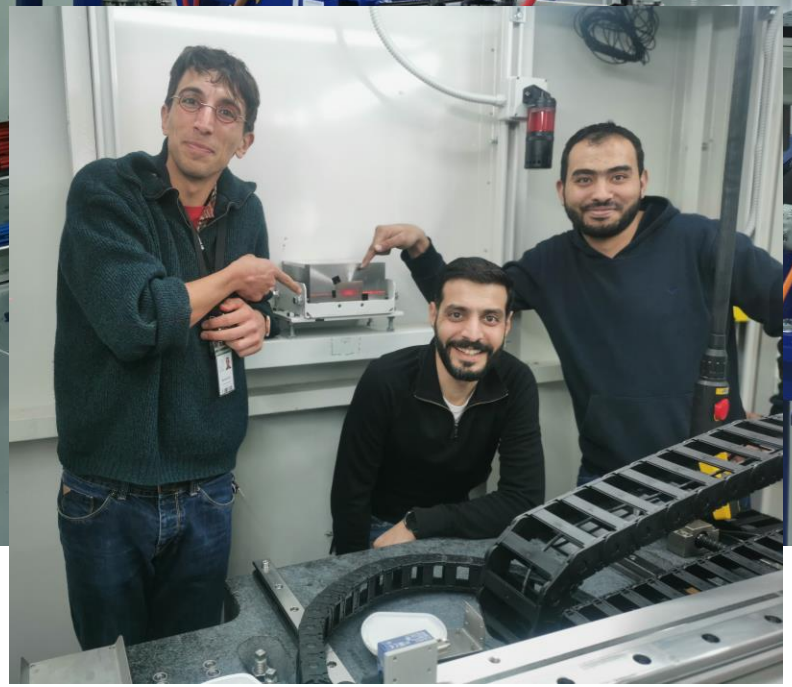


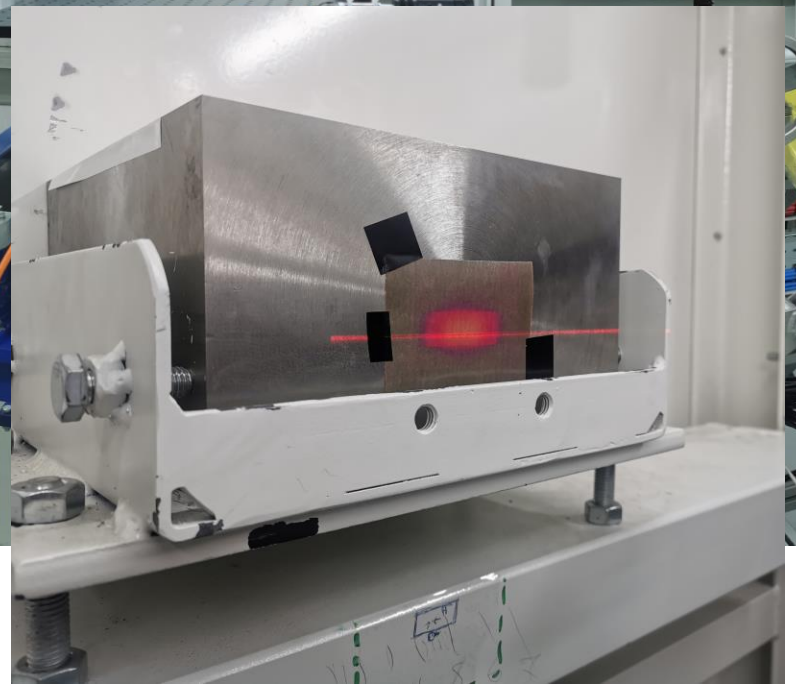


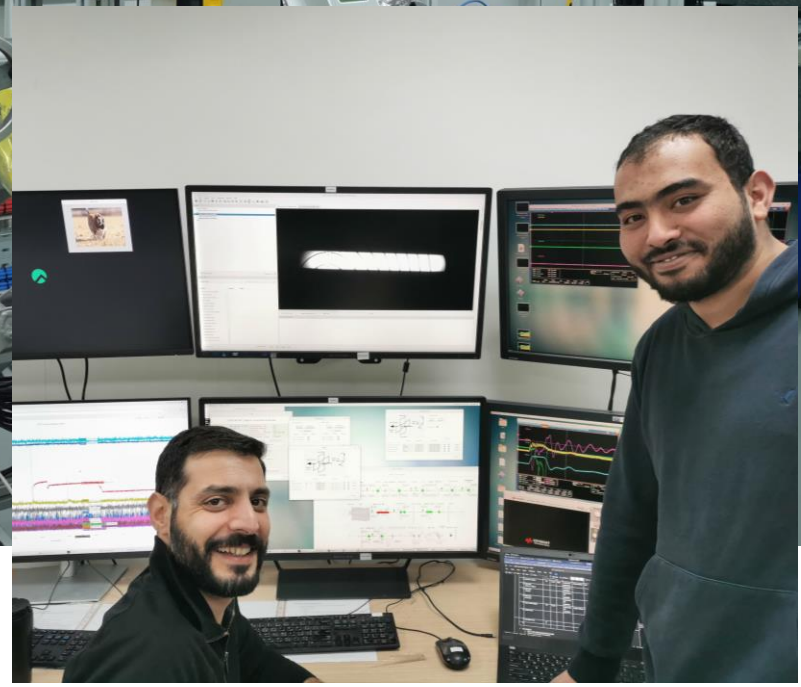


# Beamline commissioning (experimental station): February 2023

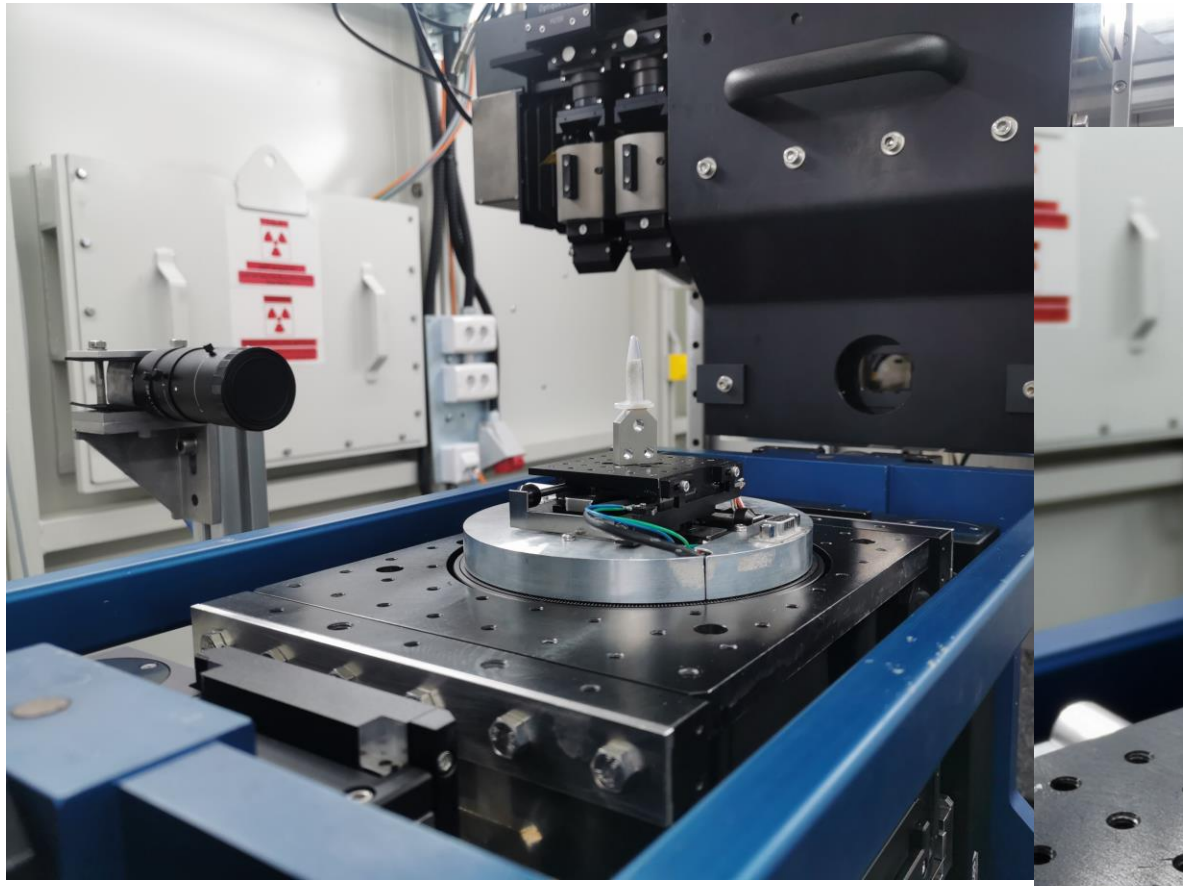



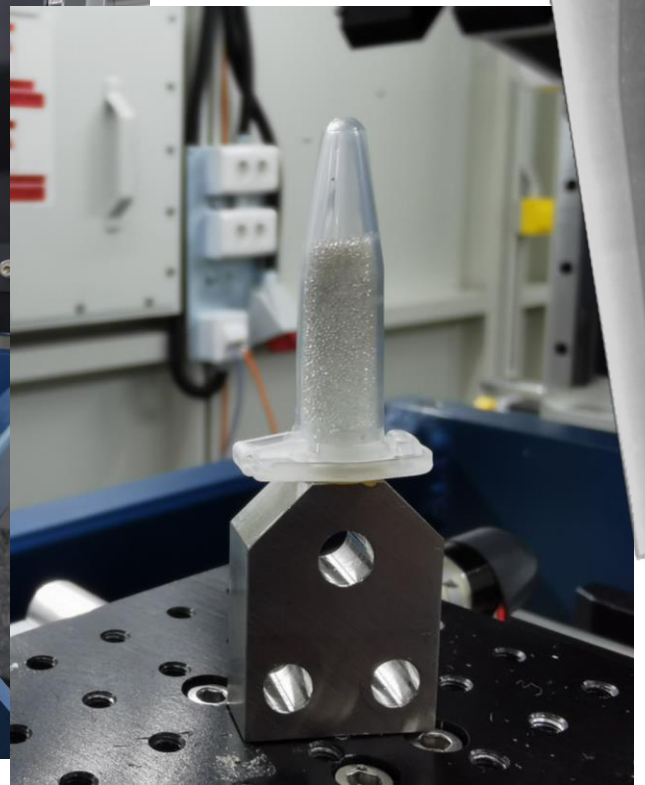


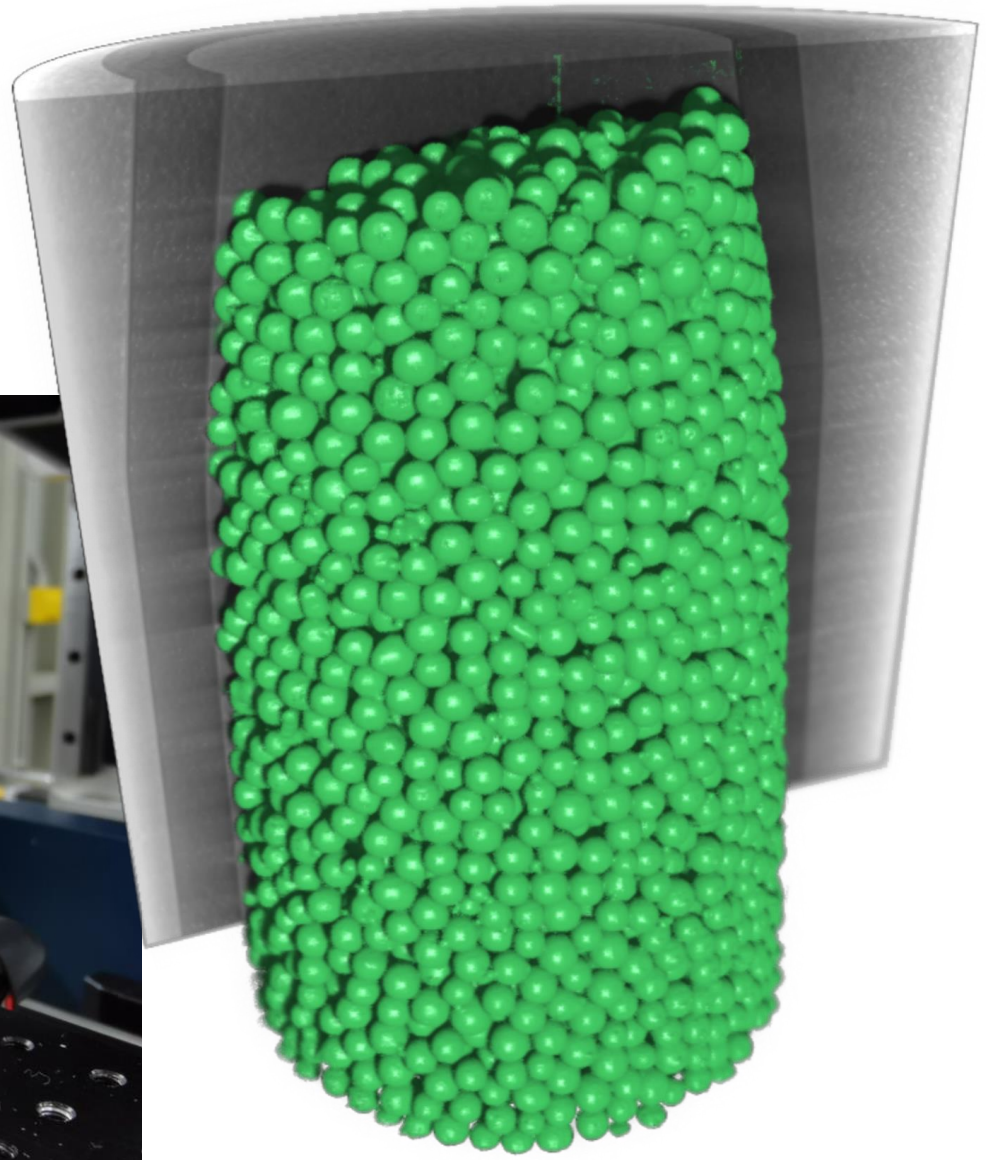


# 11 May 2023 – First BEATS scan

- 1000 radiographs; 180 degrees rotation
- Glass spheres (diameter ~300 micron)
- 4.5 micron voxel size
- Total scan time: 12 s



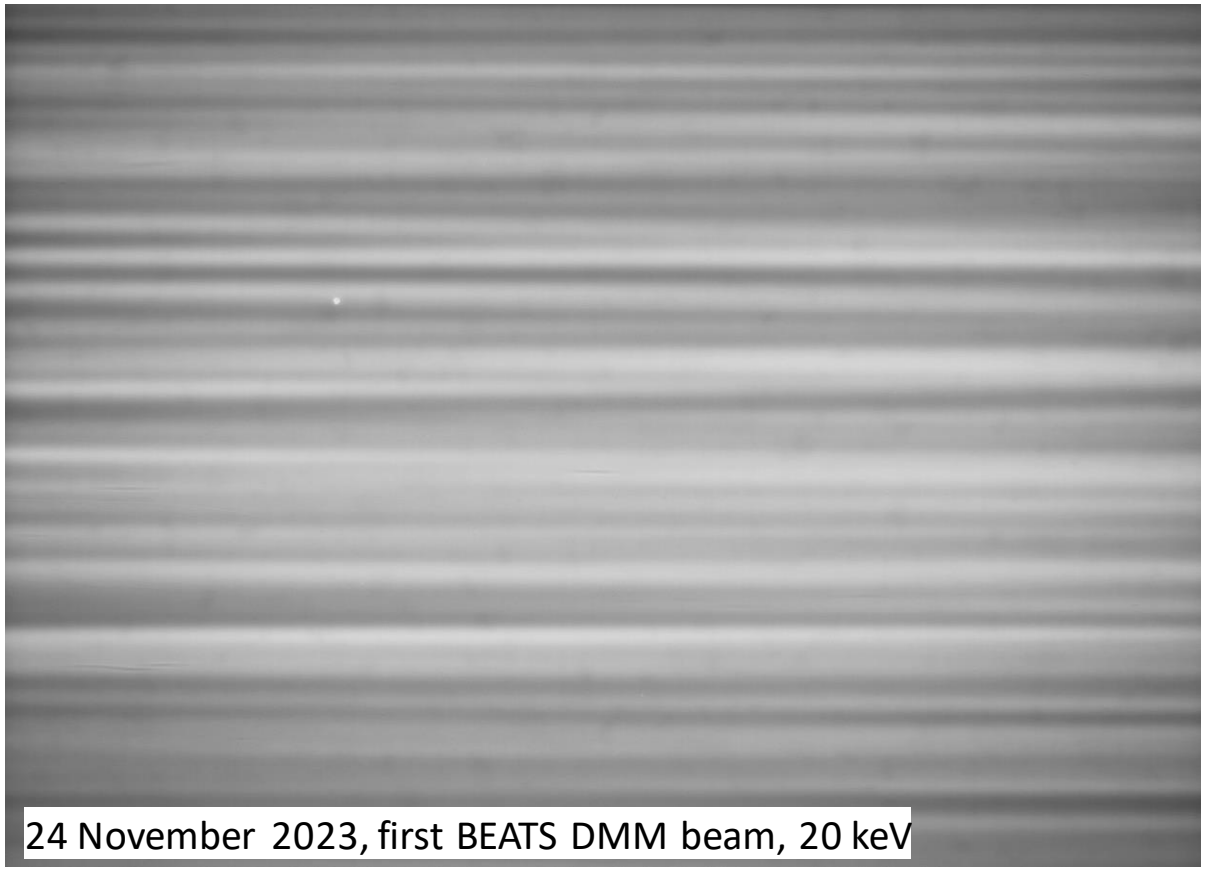




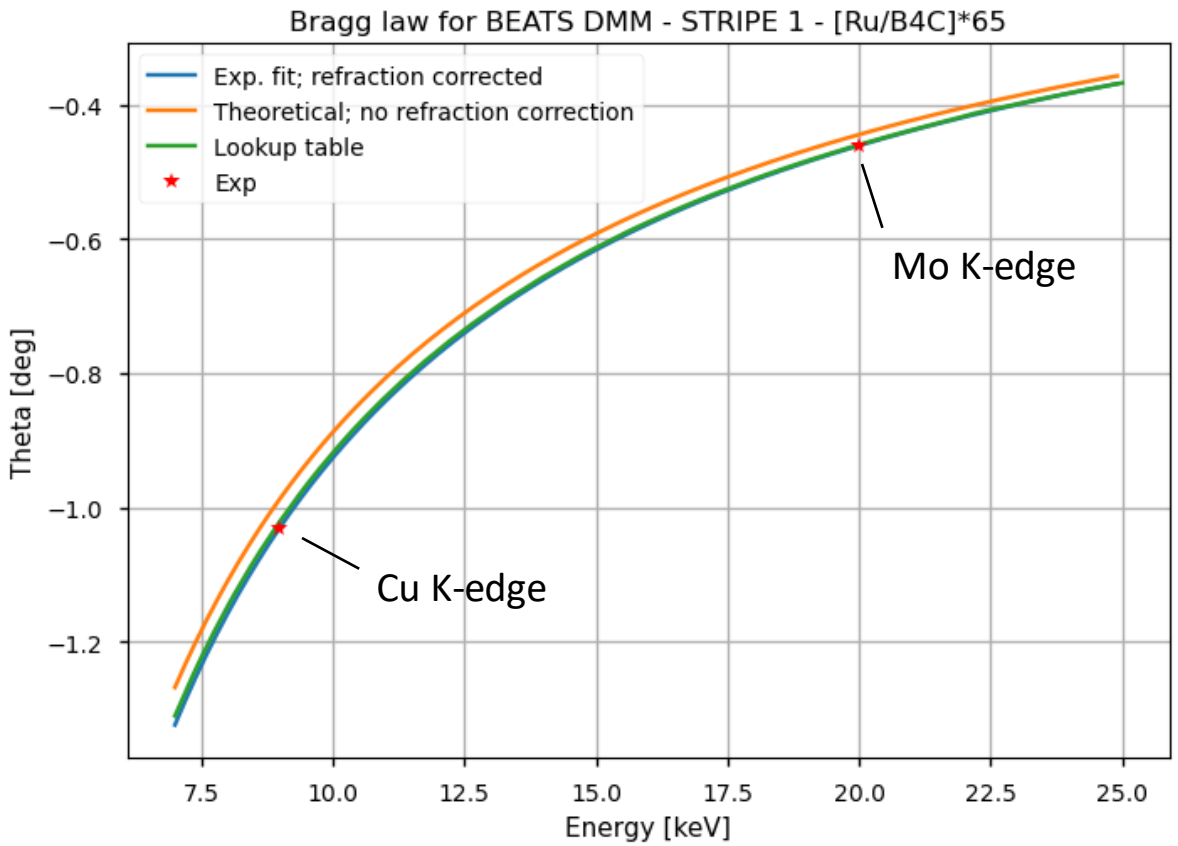
# Double Multilayer Monochromator

## First observation of BEATS monochromatic BEAM

- 24 November 2023: First observation of DMM beam
- November – December 2023: DMM calibration; prepare look-up table for user operation (C. Schlepütz, PSI)
- December 2023: Monochromatic beam performance tests (A. Rack, ESRF)



24 November 2023, first BEATS DMM beam, 20 keV



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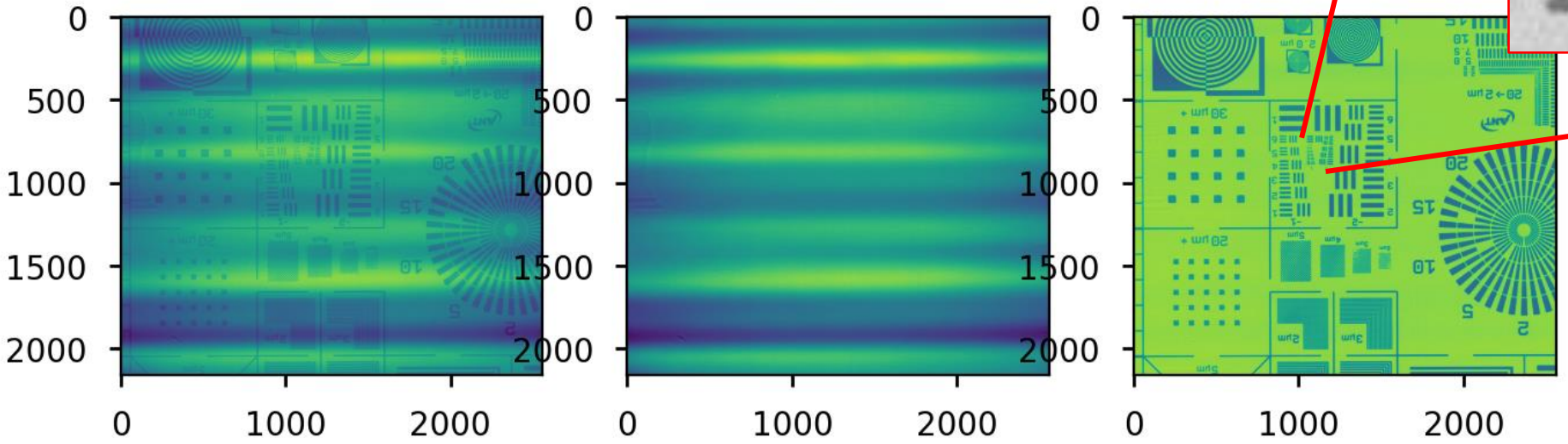
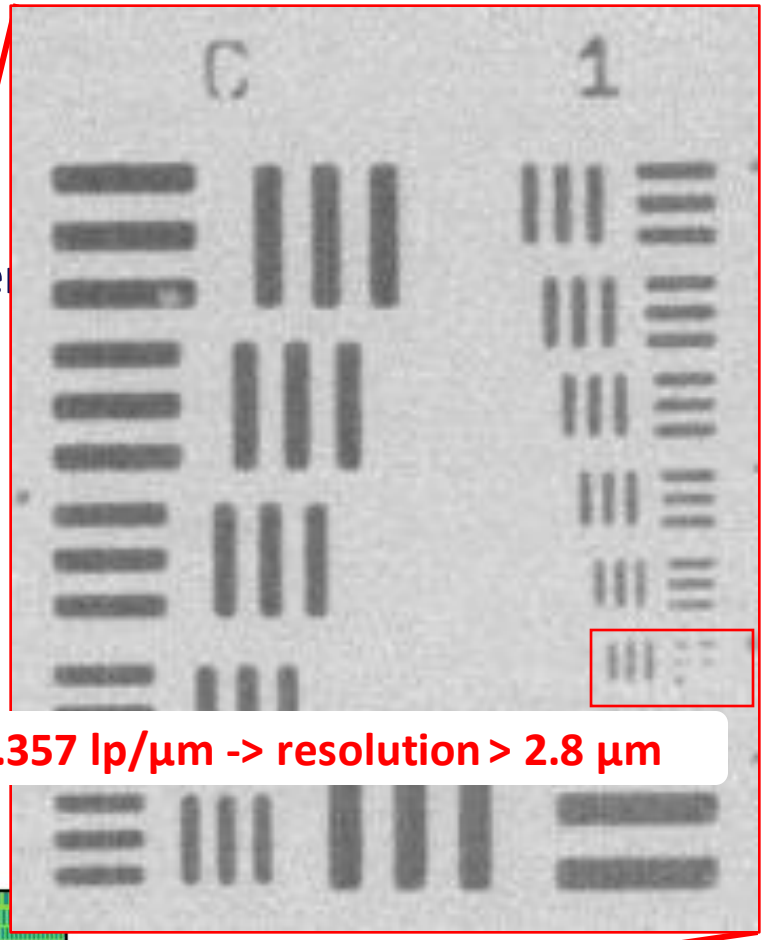


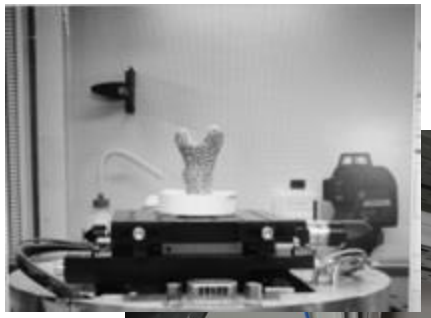




**0.357 lp/µm -> resolution > 2.8 µm**

# BEATS experimental endstation

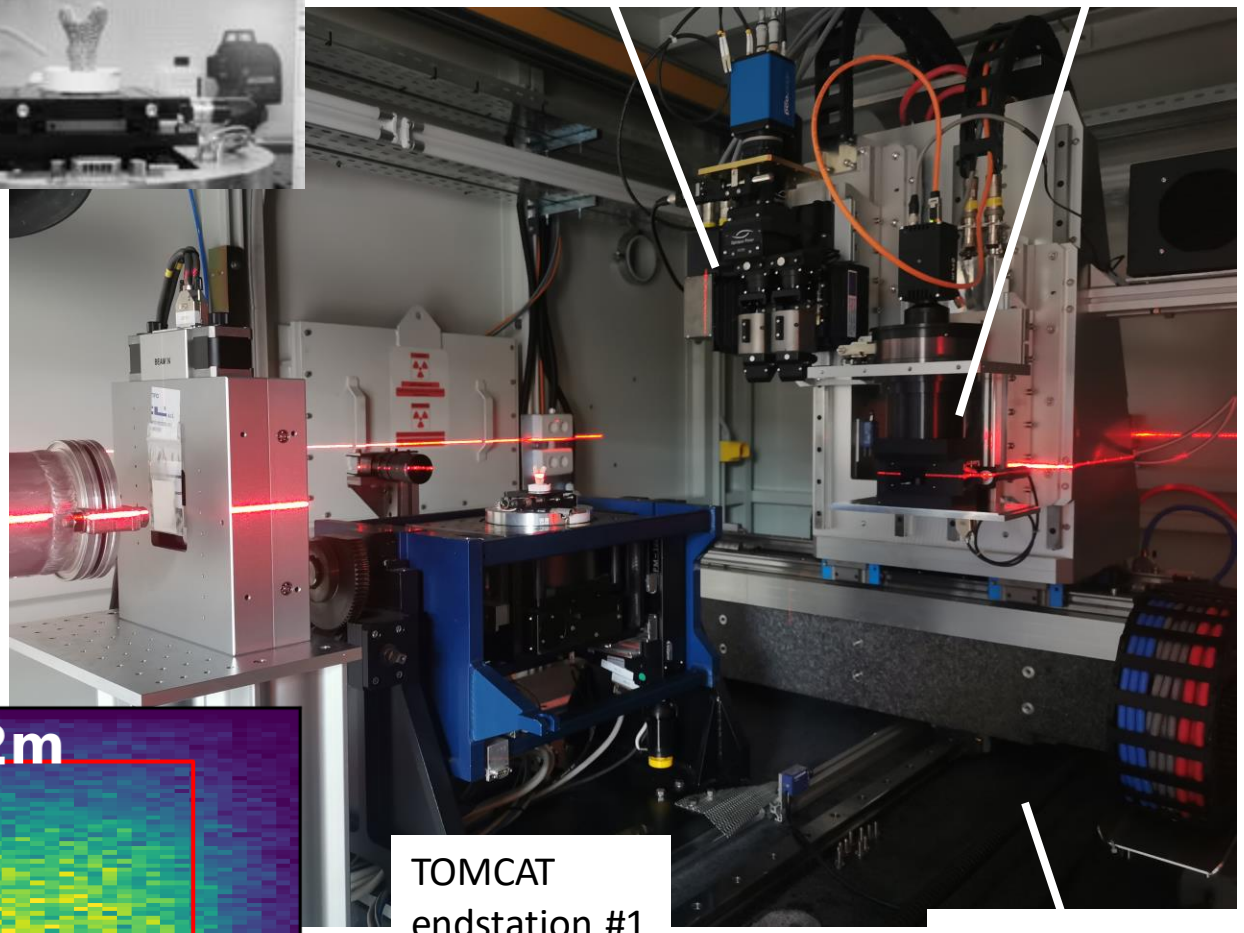
## Endstation #1

| Magnif. | Field of view | Pixel size |
|---|---|---|
| 0.5× | 33.2 × 28.0 mm$^2$ | 13.0 µm |
| 1× | 16.6 × 14.0 mm$^2$ | 6.5 µm |
| 2× | 8.3 × 7.0 mm$^2$ | 3.25 µm |
| 5× | 3.4 × 2.8 mm$^2$ | 1.3 µm |
| 10× | 1.7 × 1.4 mm$^2$ | 0.65 µm |
| 20× | 0.9 × 0.7 mm$^2$ | 0.33 µm |



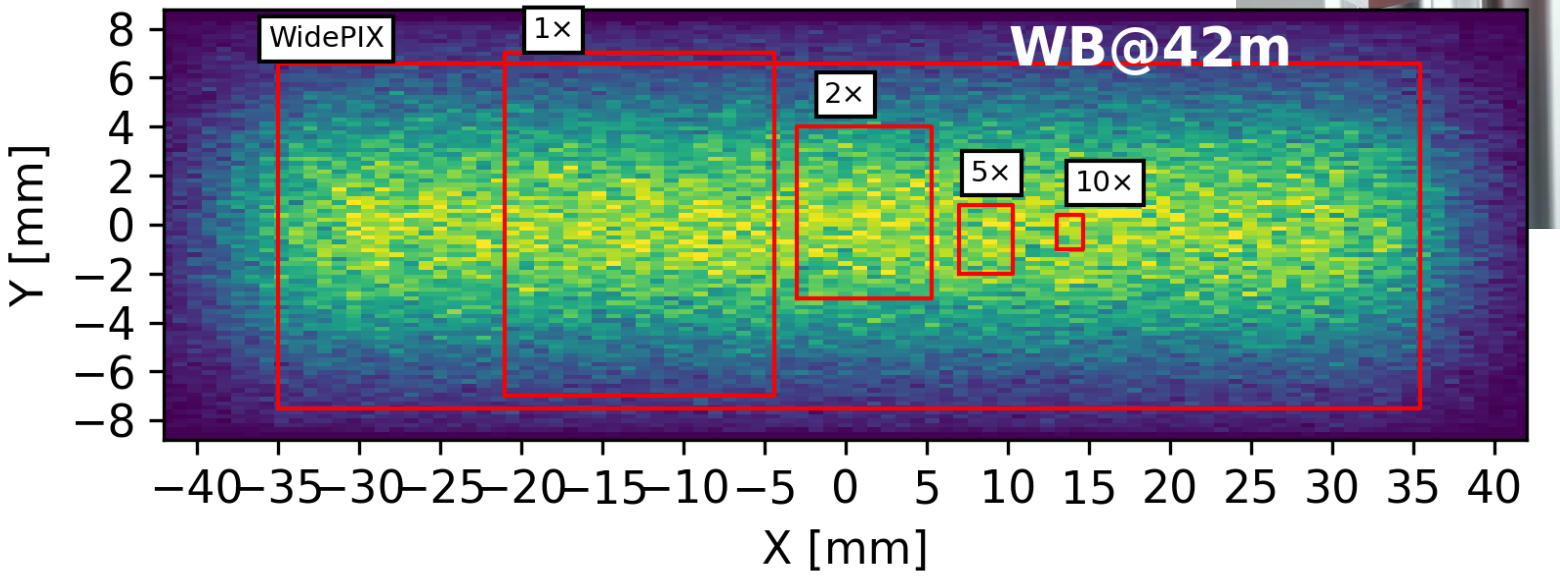
10x, 5x detector
(Optique Peter)

0.5x, 1x, 2x detector
(ESRF)



TOMCAT
endstation #1

Detector stage

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PSI

ESRF
The European Synchrotron

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[F. Mokoena et al., *R & D Journal of the South African Institution of Mechanical Engineering*, 2023]

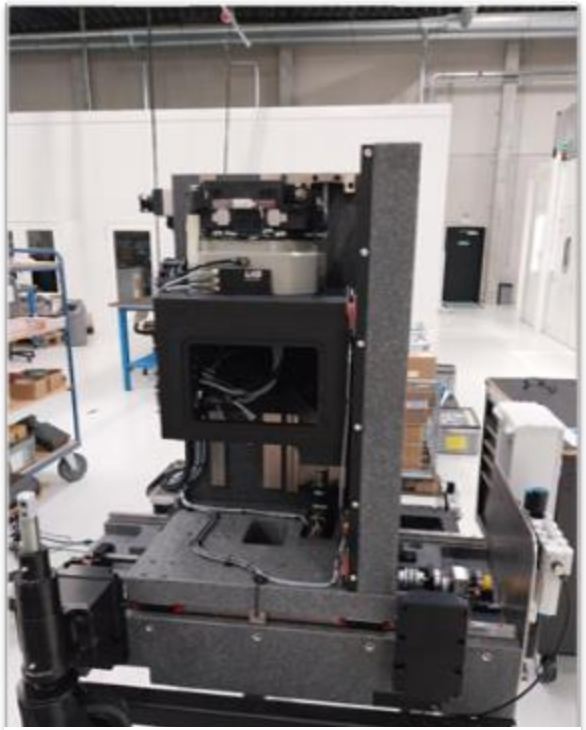
# BEATS experimental endstation

## Endstation #2 – LAB motion systems

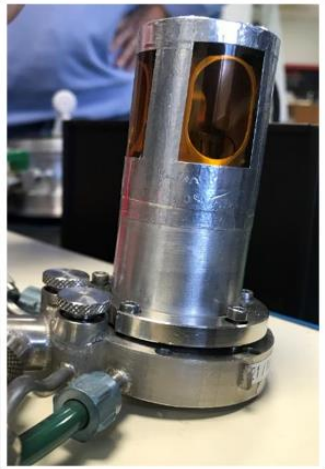
- Air-bearing stage for large samples: from 5 kg up to **25 kg**
- Include slip ring and ROT control systems

- Electrical slip ring for **sample environments:**
- 1000 N mechanical **compression/tensile stage**

- **Induction furnace** for sample heating up to 1100 C



November 2023, LAB Motion Systems
Installation: April 2024

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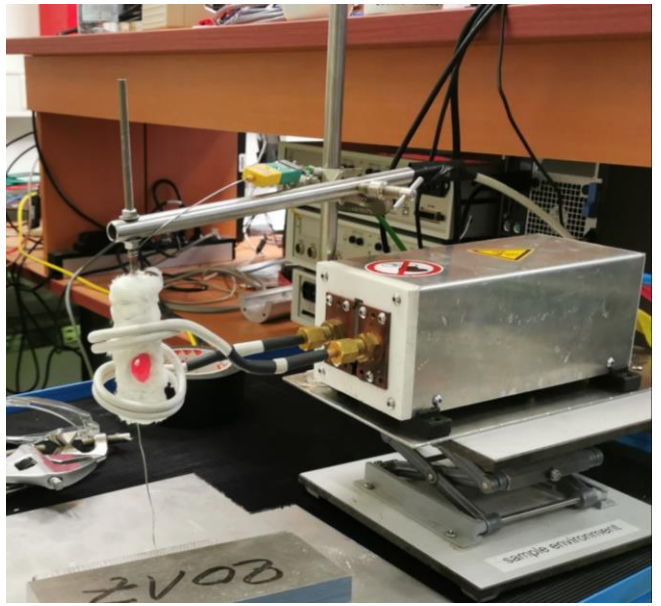
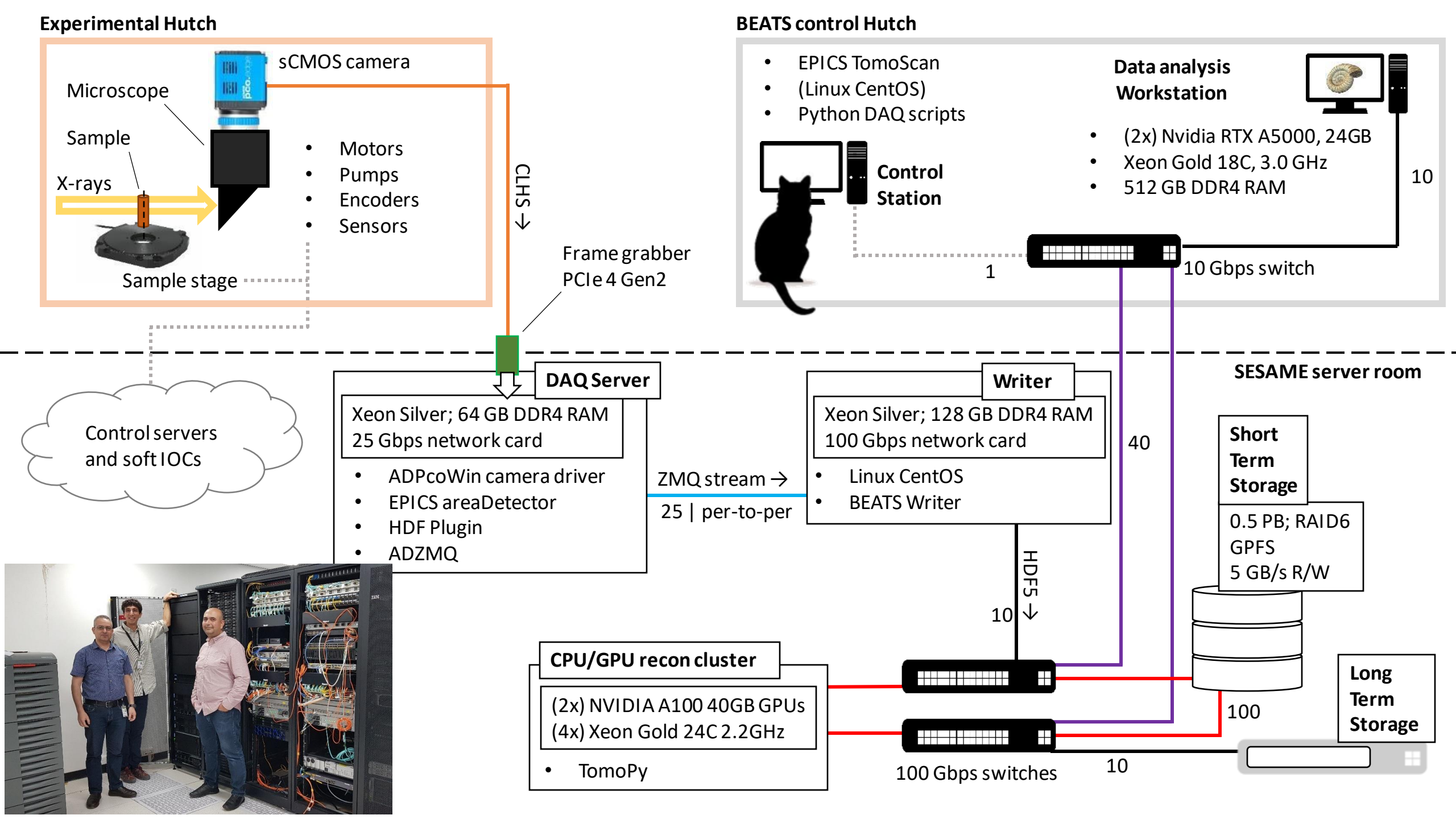


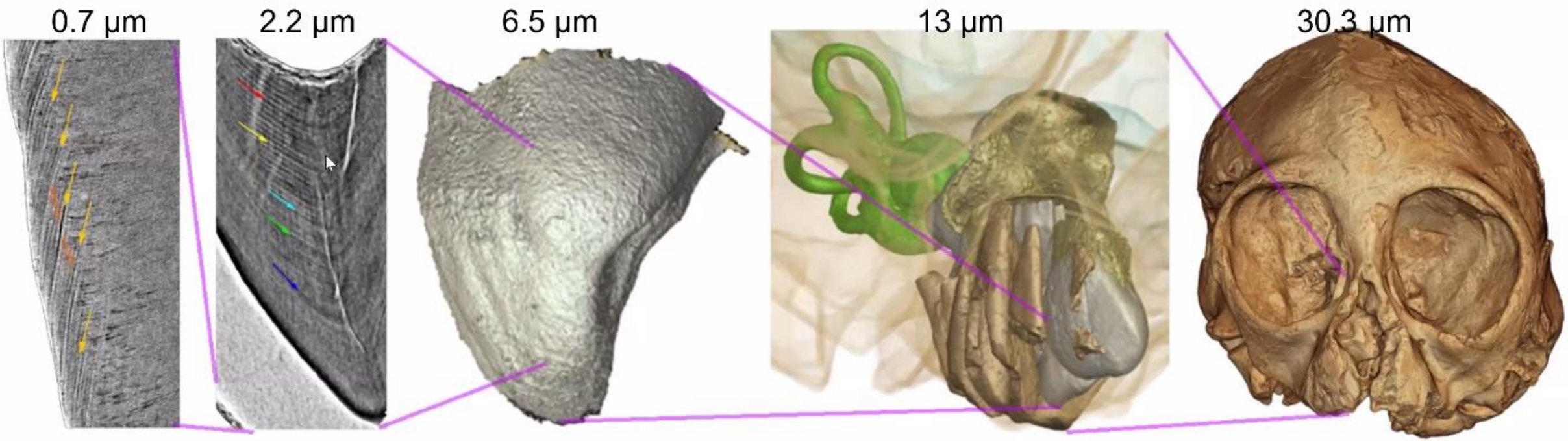
[F. Mokoena, M.Sc. thesis]


Experimental Hutch
sCMOS camera
Microscope
Sample
X-rays
Sample stage
Motors
Pumps
Encoders
Sensors
CLHS
Frame grabber
PCIe 4 Gen2
BEATS control Hutch
EPICS TomoScan
(Linux CentOS)
Python DAQ scripts
Control Station
Data analysis Workstation
(2x) Nvidia RTX A5000, 24GB
Xeon Gold 18C, 3.0 GHz
512 GB DDR4 RAM
10
1
10 Gbps switch
Control servers and soft IOCs
DAQ Server
Xeon Silver; 64 GB DDR4 RAM
25 Gbps network card
ADPcoWin camera driver
EPICS areaDetector
HDF Plugin
ADZMQ
ZMQ stream →
25 | per-to-per
Writer
Xeon Silver; 128 GB DDR4 RAM
100 Gbps network card
Linux CentOS
BEATS Writer
40
SESAME server room
Short Term Storage
0.5 PB; RAID6
GPFS
5 GB/s R/W
HDF5 ↓
10
CPU/GPU recon cluster
(2x) NVIDIA A100 40GB GPUs
(4x) Xeon Gold 24C 2.2GHz
TomoPy
100 Gbps switches
10
100
Long Term Storage

# MULTIRESOLUTION, ONE OF THE KEY FOR HERITAGE INVESTIGATIONS

## *Nyanzapithecus alesi*, fossil skull of an infant ape from Kenya aged of 13 My

Nengo I., Tafforeau P., Gilbert C. C., Fleagle J. G., Miller E. M., Feibel C., Fox D. L., Feinberg J., Pugh K. D., Berruyer C., Mana S., Engle Z. & Spoor F. (2017). New infant cranium from the African Miocene sheds light on ape evolution. **Nature**, 548:169-174.

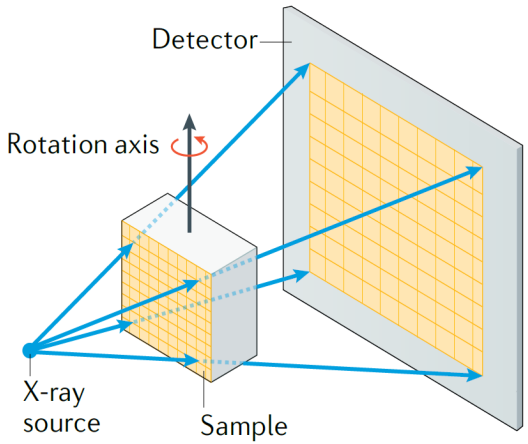



ESRF

[Courtesy P. Tafforeau, ESRF]

# Laboratory XCT

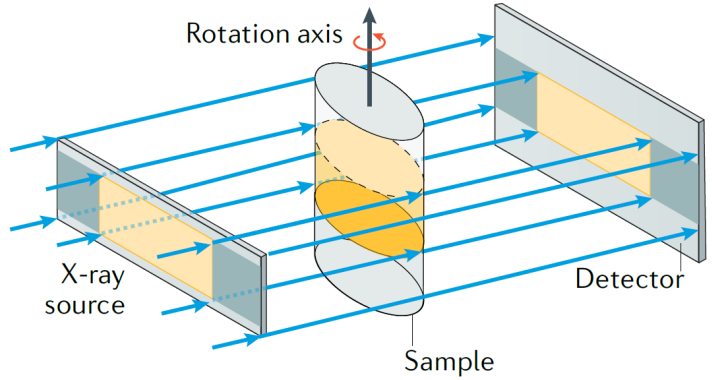
- Wide spectrum of (**polychromatic**) X-ray energies, with bright peaks characteristic of the source target material
- **Cone-beam** geometry




- Can illuminate **large objects** and exploit physical magnification
- **Typical scan times: hours to minutes**

# Synchrotron XCT

- **Higher flux** by several orders of magnitude
- **Monochromatic X-ray beam** possible: improved sensitivity and limited artefacts
- **Parallel-beam geometry**




- (Generally) **higher resolution**
- (But) smaller field of view
- **Typical scan times: minutes to <seconds**
- **Time-resolved (4D) CT**
- High spatial coherence enables **phase contrast**

[Withers et al. 2021]

10 MHz

100 kHz

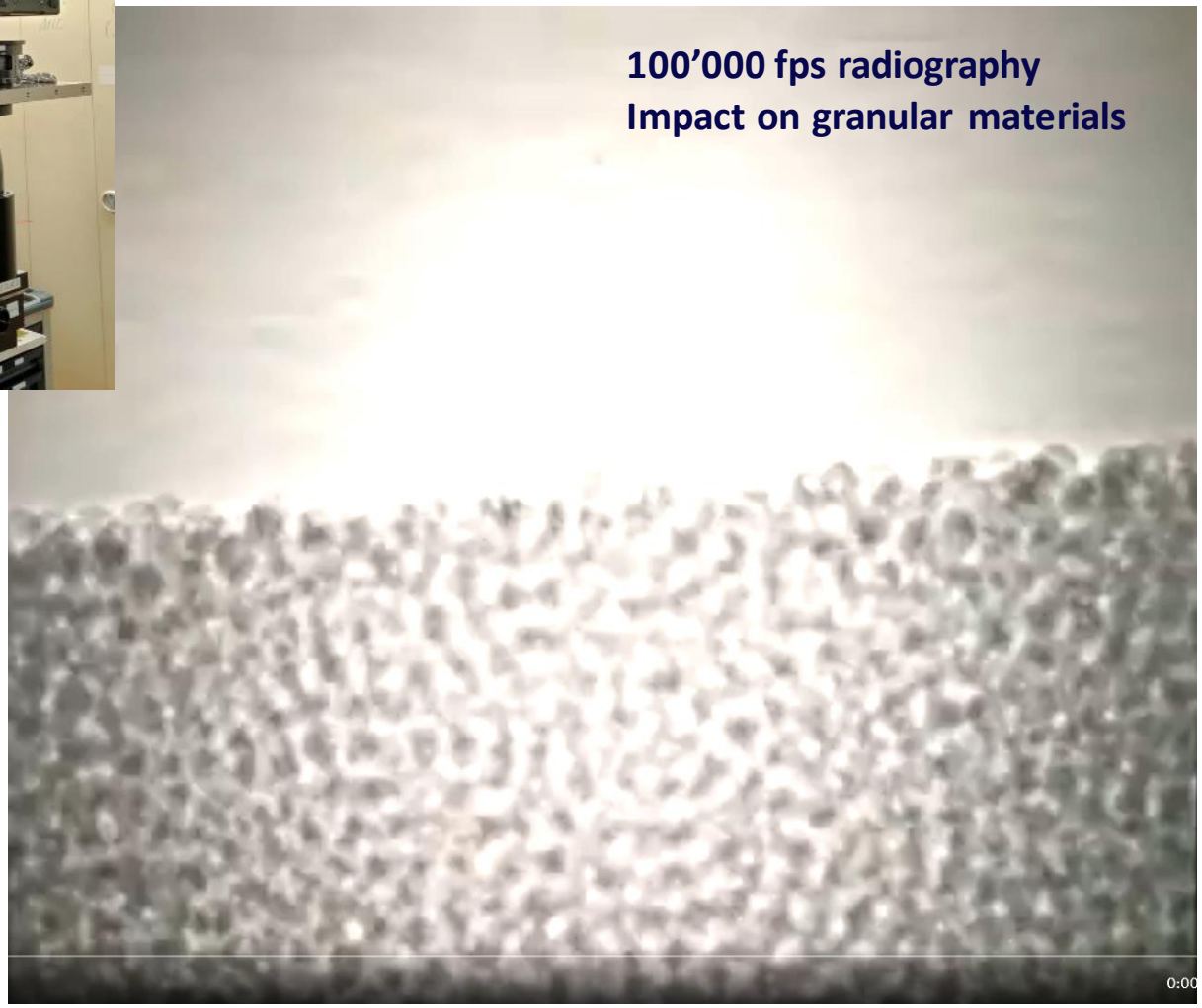
**StructureOfMaterials**

@SoM_esrf Follows you

The Structure of Materials Group @esrfsynchrotron provides world-class facilities for hard X-ray diffraction, scattering and microimaging experiments.

Grenoble, France esrf.eu/UsersAndScienc... Joined February 2016

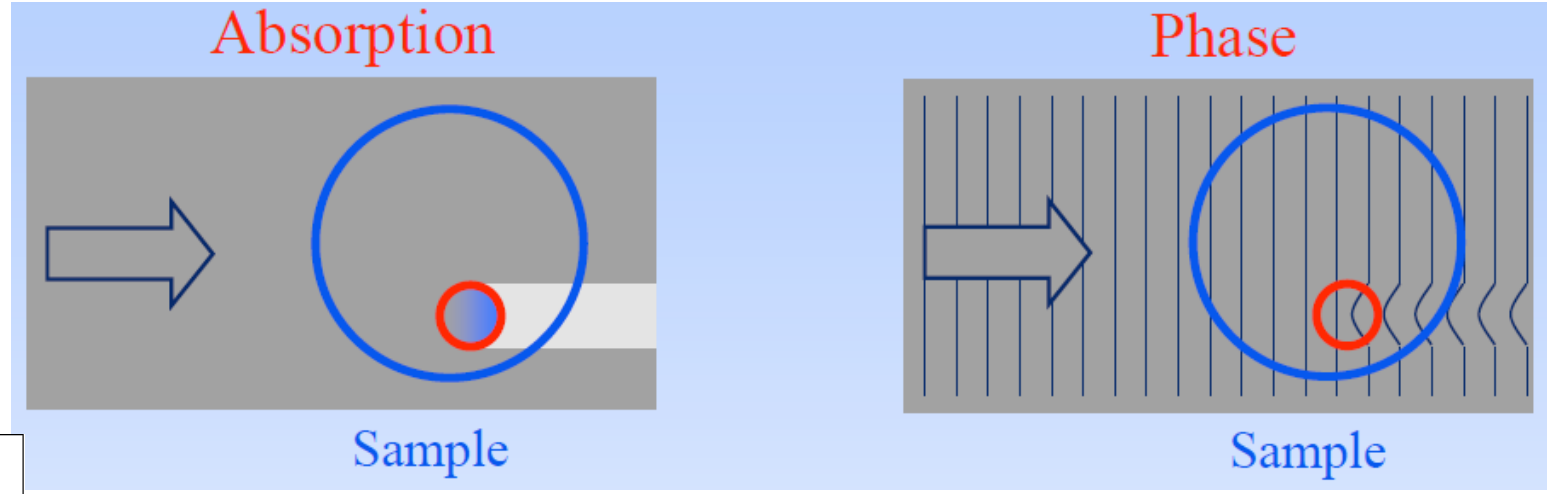
ESRF

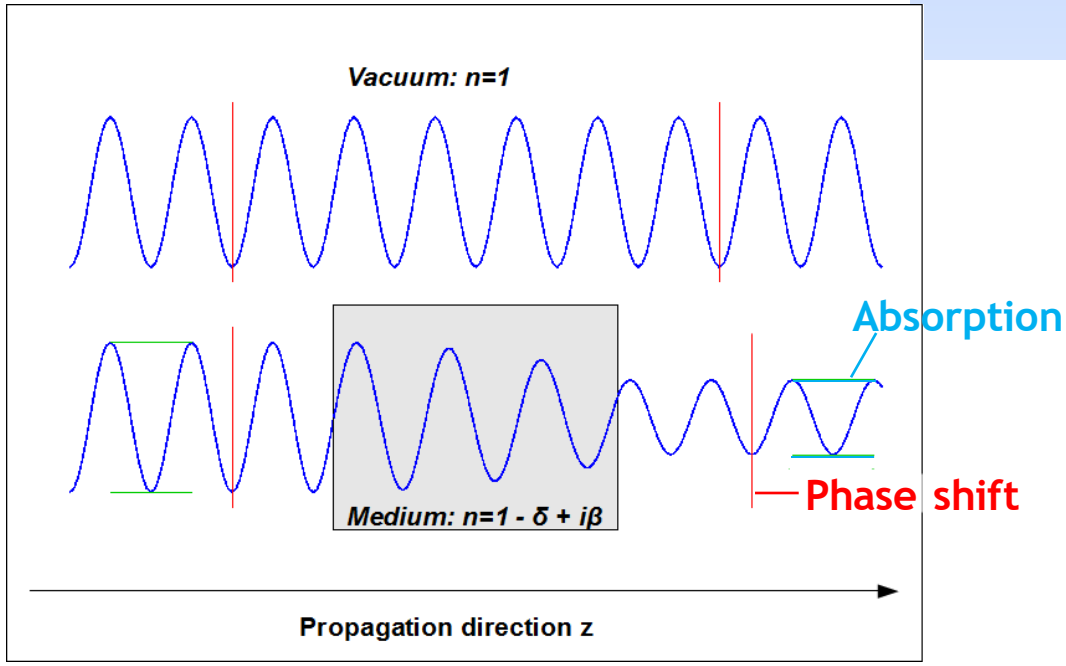



**In-situ mechanical testing**

# Weak interaction with matter - Phase contrast imaging

- Many specimens contain materials that attenuate X-rays similarly (e.g. soft tissue)
- Better contrast can be obtained by exploiting the materials' X-ray phase contrast



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X-ray refractive index

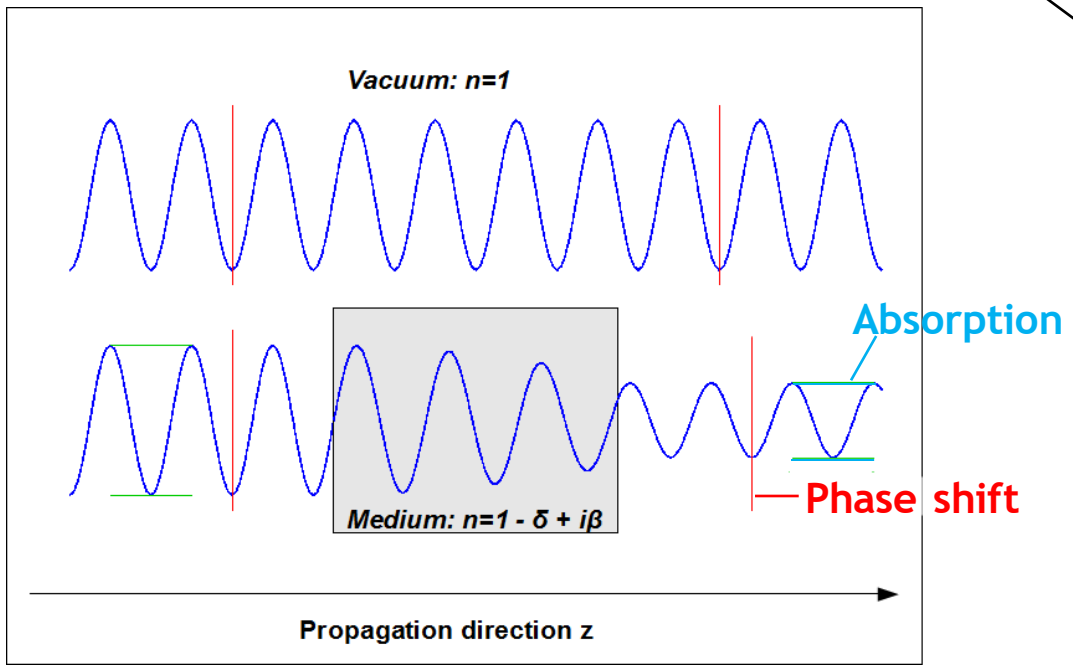
$$n = 1 - \delta + i\beta$$

**Absorption index:**

- Photoelectric effect
- Compton scattering
- Strong energy dependence

**Refractive index decrement:**

- Proportional to electron density
- Inversely proportional to energy$^2$




[Peter Cloetens – ESRF Phase contrast imaging school, 2007]

# Weak interaction with matter - Phase contrast imaging

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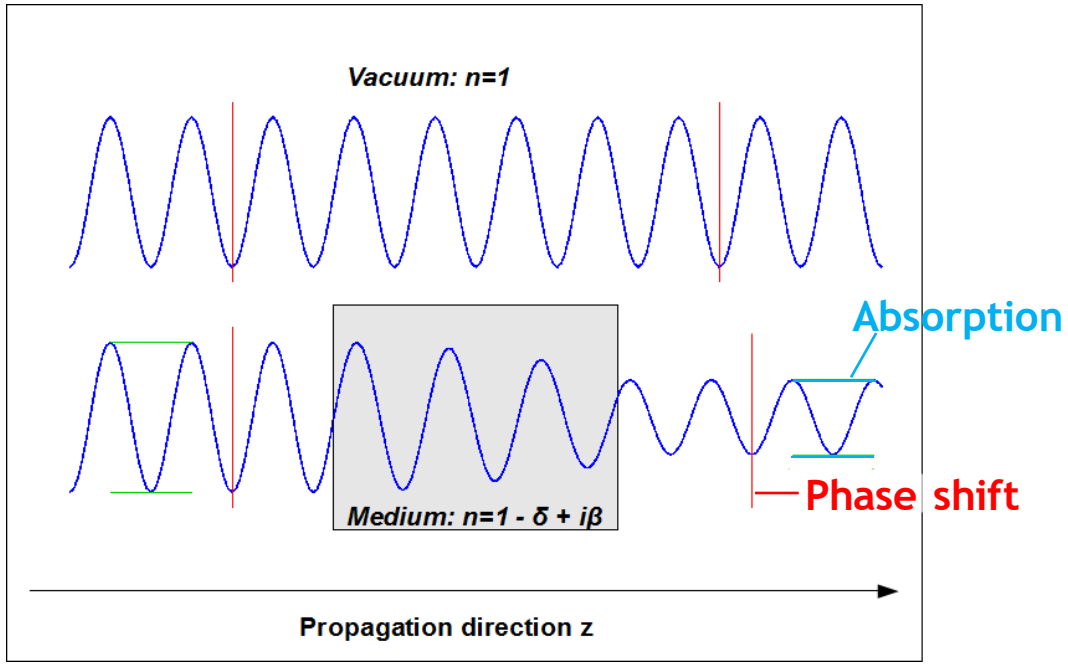
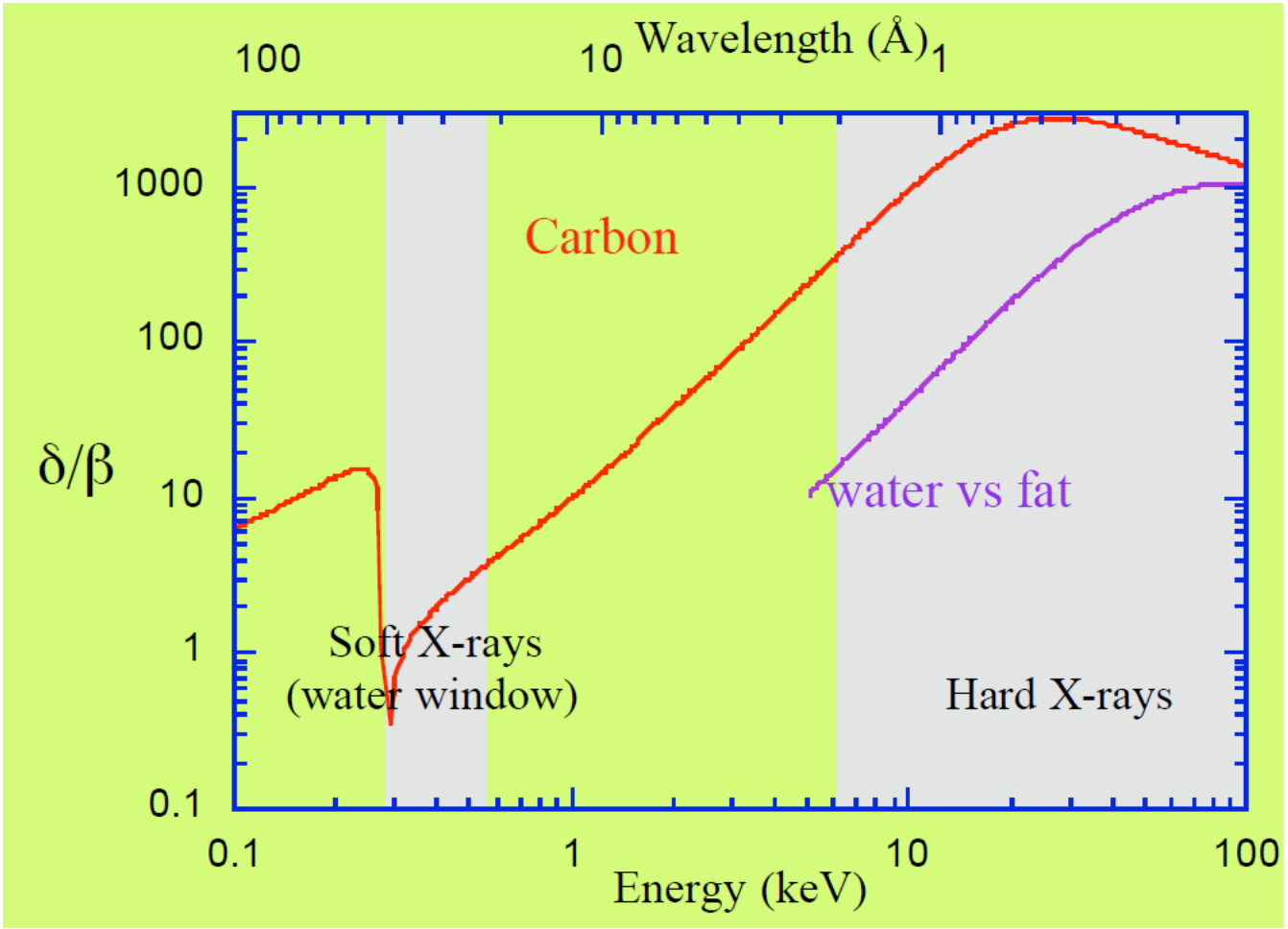
$$\delta \gg \beta \quad \rightarrow \text{Gain of 100 to 1000}$$

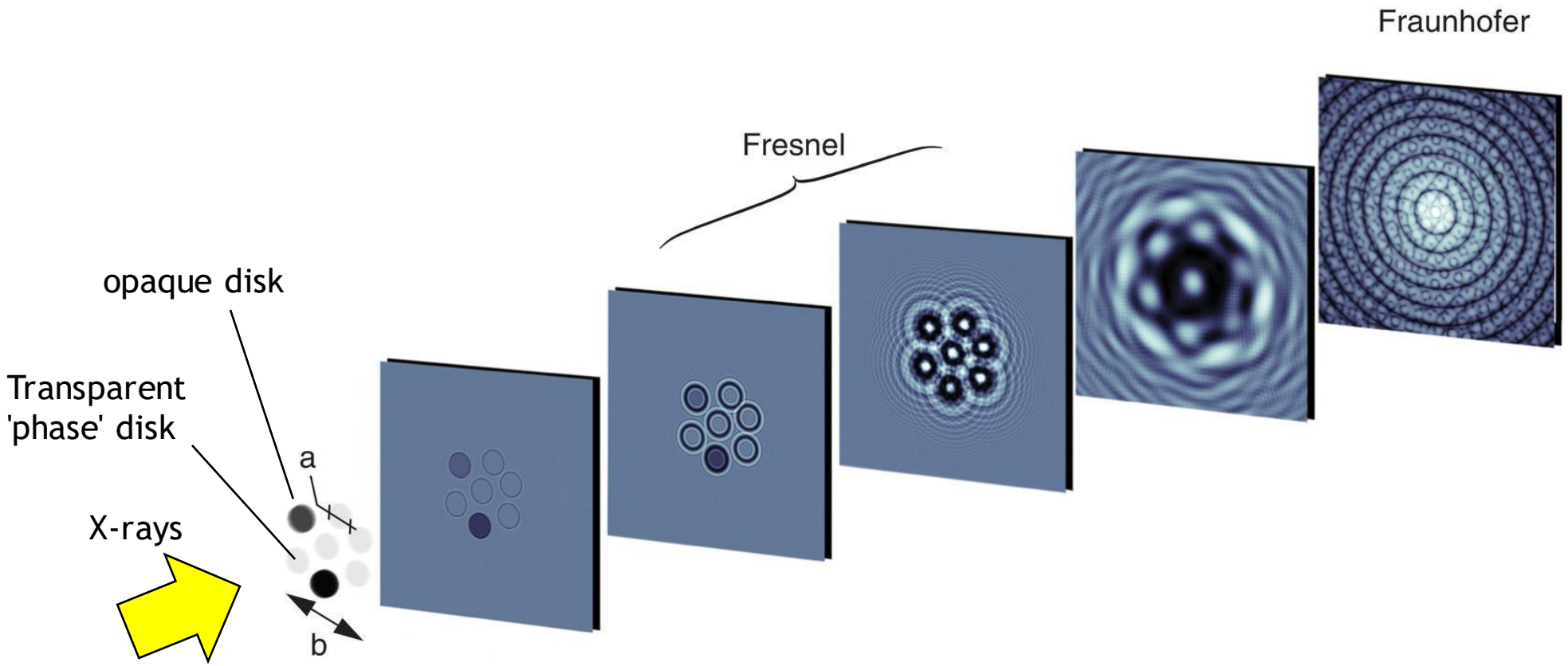



[Peter Cloetens – ESRF Phase contrast imaging school, 2007]

# Propagation-based phase contrast XCT

- The transmission function of an object varies with **propagation distance**
- **Edge enhancement:** the projected image of the object develops **fringes** at the boundaries between discs and background, where the refractive-index decrement makes a step-like change




[Withers et al. 2021]
[An Introduction to Synchrotron Radiation: Techniques and Applications 2nd edition - Philip Willmott, 2018]

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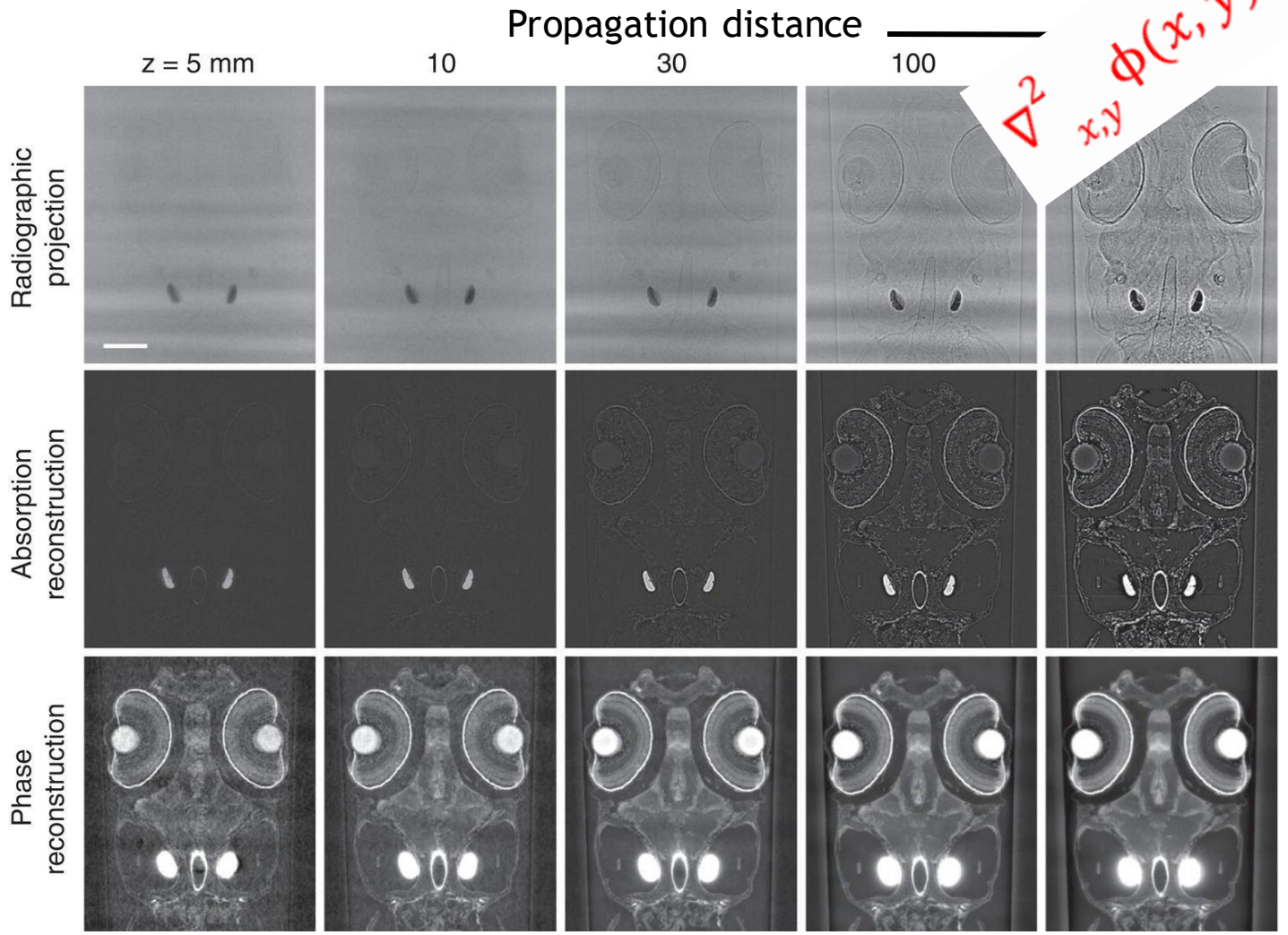
- Propagation-based tomography of a zebrafish embryo
- **Phase retrieval:** tomograms based on phase maps are retrieved from edge-enhanced projections
- The phase-contrast signal can be approximated as the Laplacian of the wavefront phase profile




[An Introduction to Synchrotron Radiation: Techniques and Applications 2nd edition - Philip Willmott, 2018]

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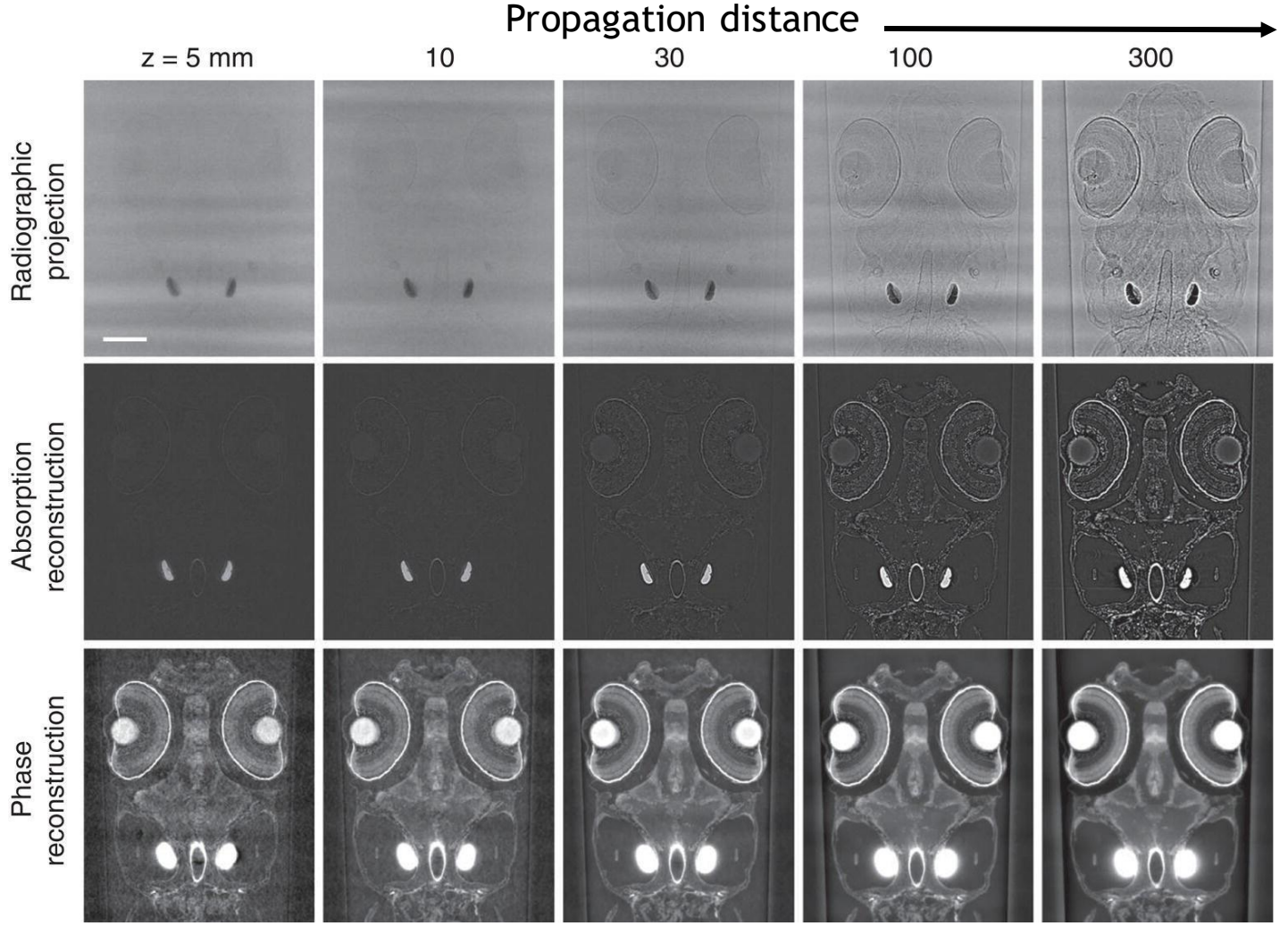
- **Phase retrieval**: tomograms based on phase maps are retrieved from edge-enhanced projections
- Requires **coherent illumination**:
  - **Small** X-ray source
  - **Distant** X-ray source

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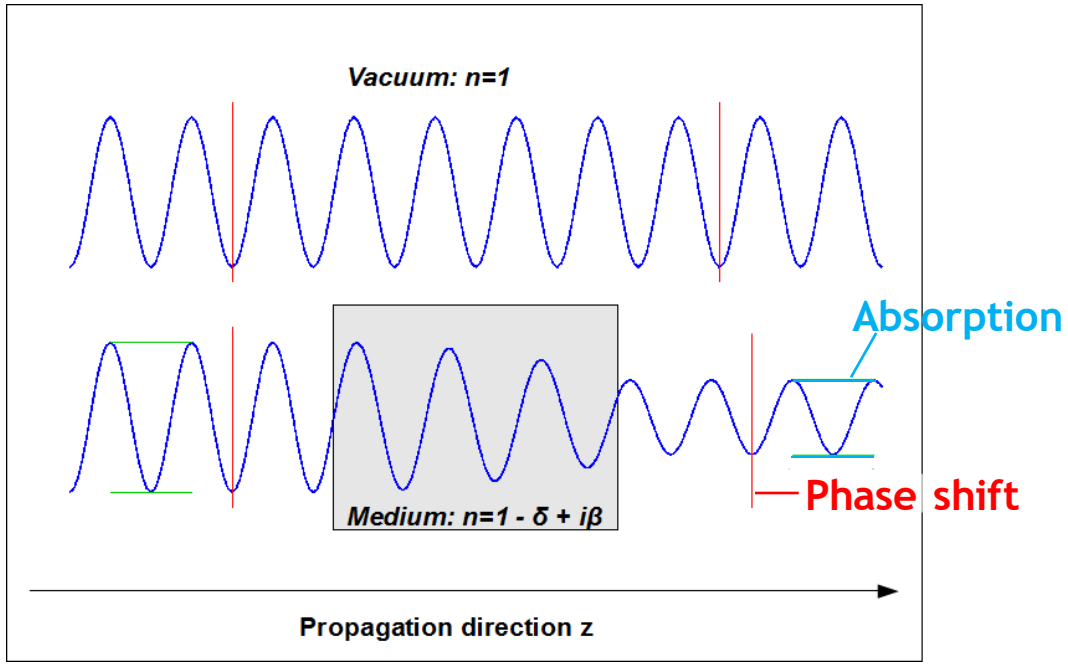
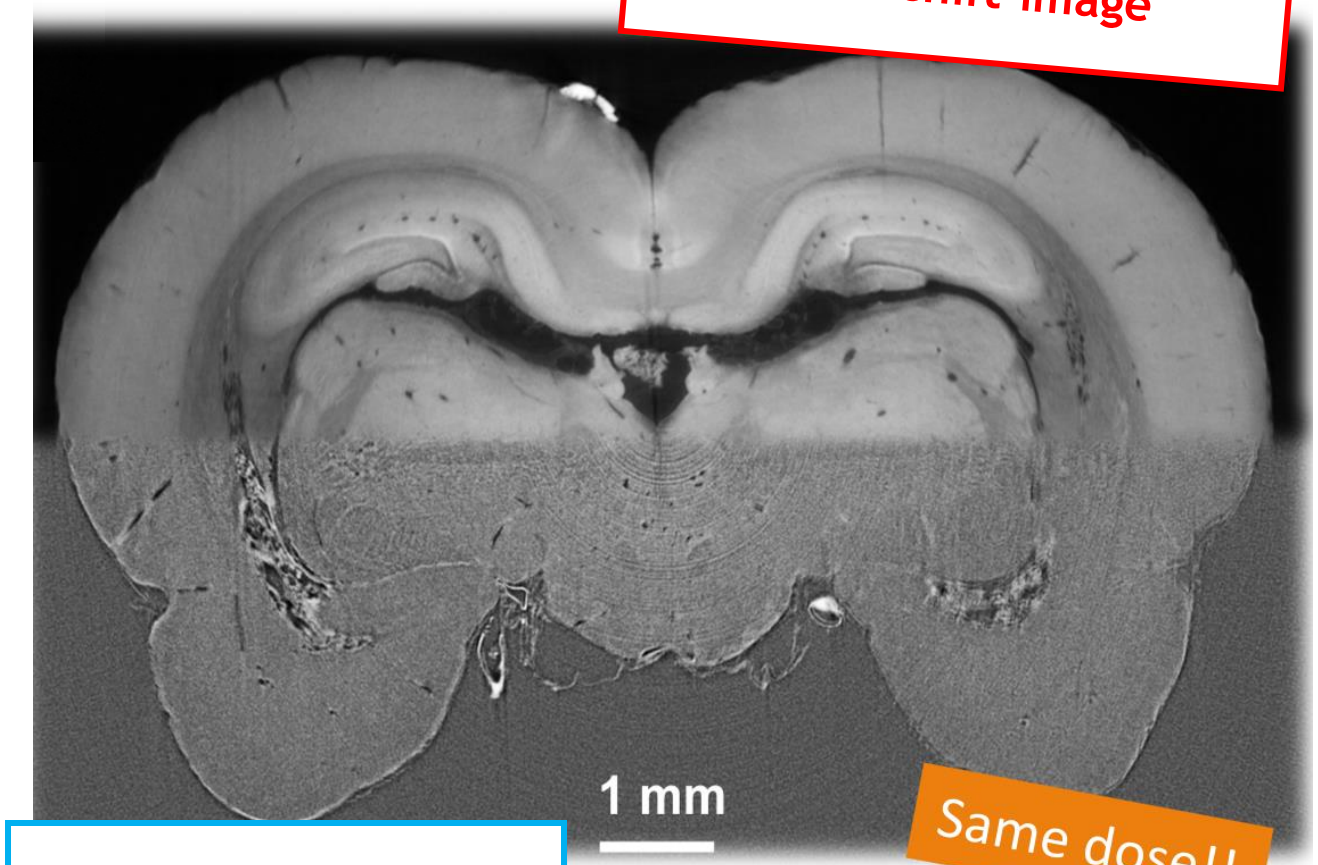


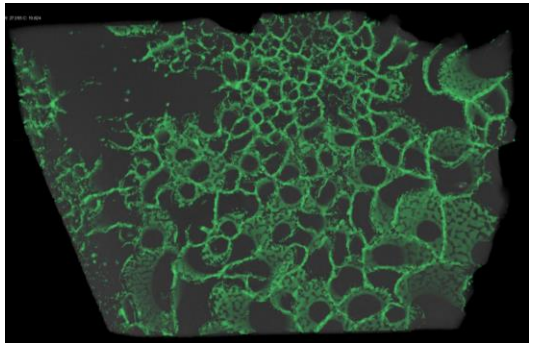

[Marco Stampanoni – BEATS inauguration school, 2023]

# **Part 2:** Applications of SXCT & First scans at the BEATS beamline

# BEATS scientific case

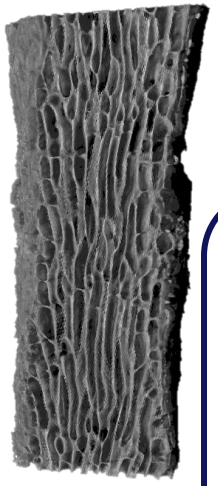
Synchrotron Tomography @ BEATS

**Archaeology and Cultural Heritage**
- Archaeological Materials
- Human bioarchaeology
- Plant and animal remains
- Artefacts



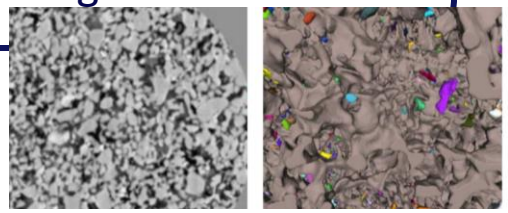
Roman glass

Mineralized algae (red sea)

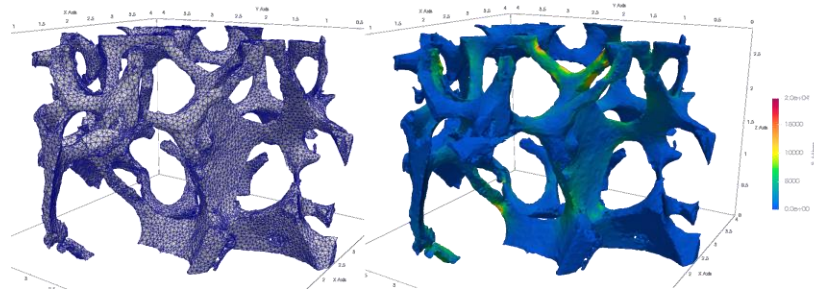



**Health, Biology and Food**
- Musculoskeletal research
- Bone and dental implants
- Soft tissue imaging
- Animal and plant characterization
- Food science

**Agriculture and Environment**
- Simulation of rock properties
- Soil characterization
- Sustainable agriculture



Sandstone core



**Material science and Engineering**
- Light materials and alloys
- Materials under mechanical stress
- Energy materials research

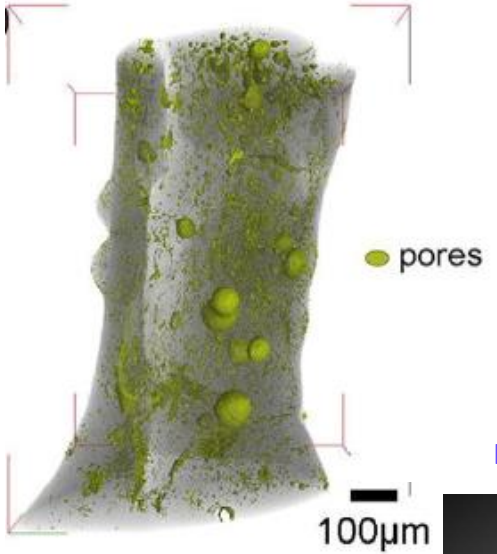
**Services to Industry and Private sector**

Funded by the EU's H2020 framew ork programme under grant agreement n°822535

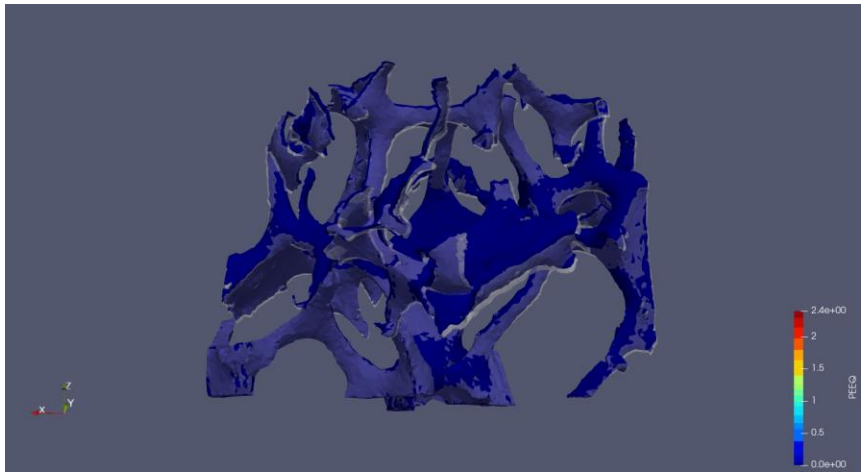
# Scientific Opportunities at BEATS

**Material science and Engineering:**

- Energy materials research
- Concrete, fiber-composites, 3D printed materials
- Light materials and alloys
- Materials under mechanical stress
- From CT images to FE simulations



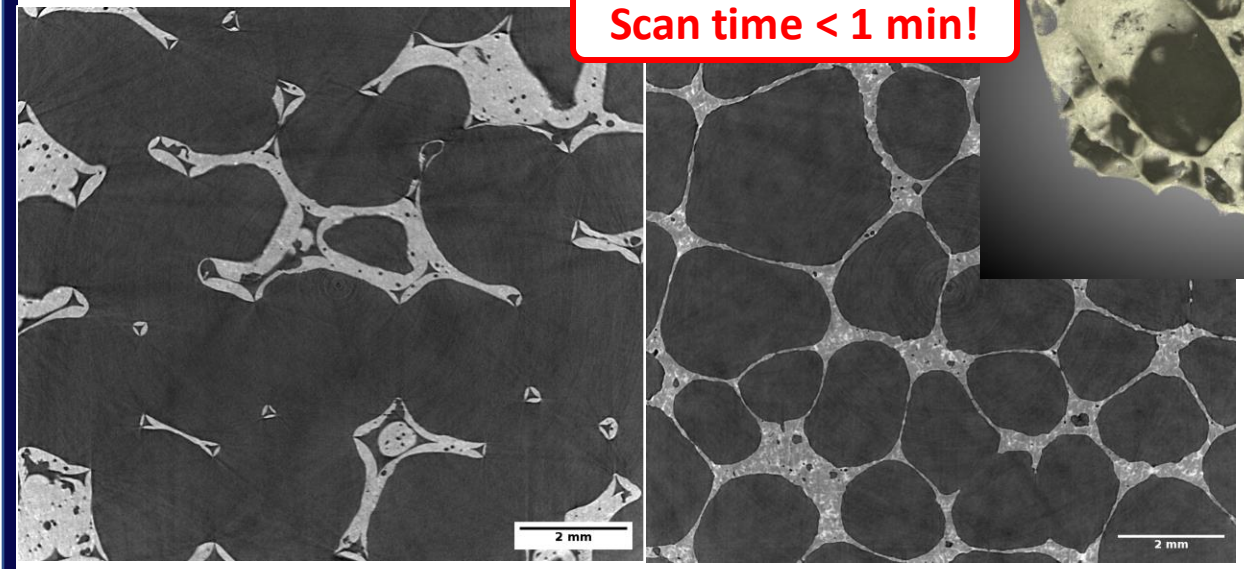

From CT images of cast iron foams to sample-specific FE



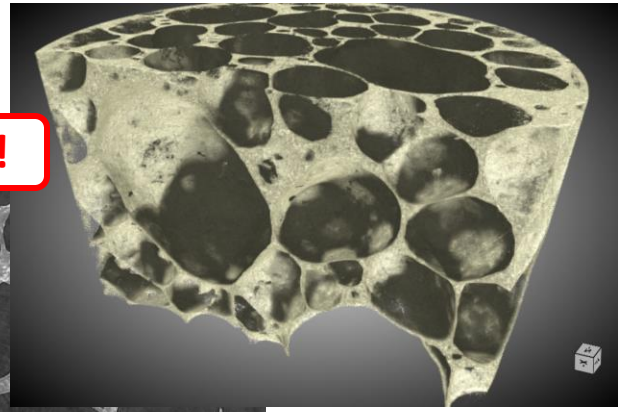
Kaya, A. et al. Advanced Engineering Materials 21, 1900080 (2019).

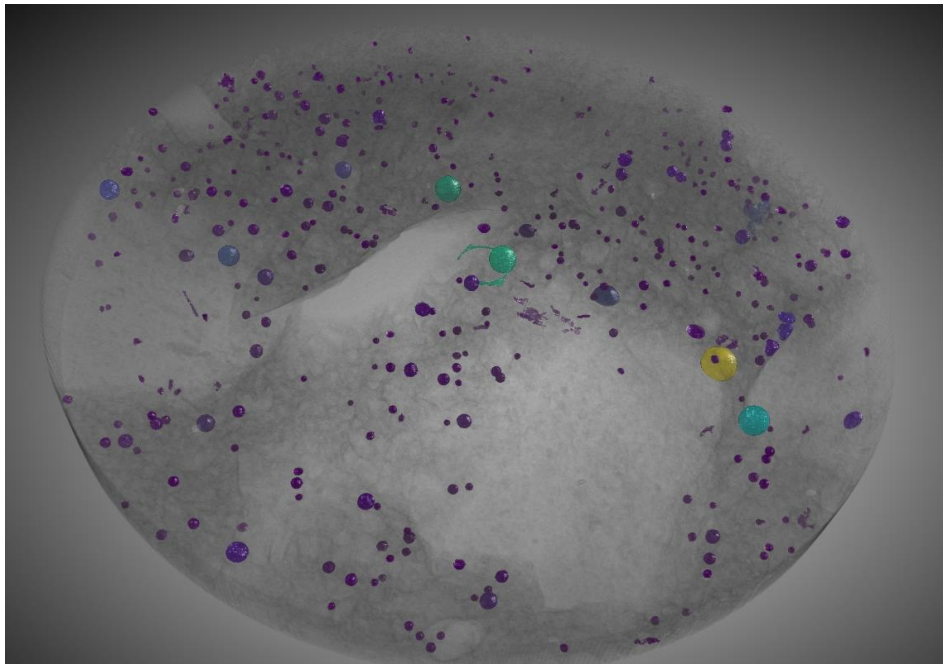
Courtesy A. Rack (ESRF) (BEATS, 2023)

**Scan time < 1 min!**




Hard X-ray phase-contrast CT of foams (plastic, ceramic, aluminum)





Courtesy A. Saadaldin (BEATS, 2023)

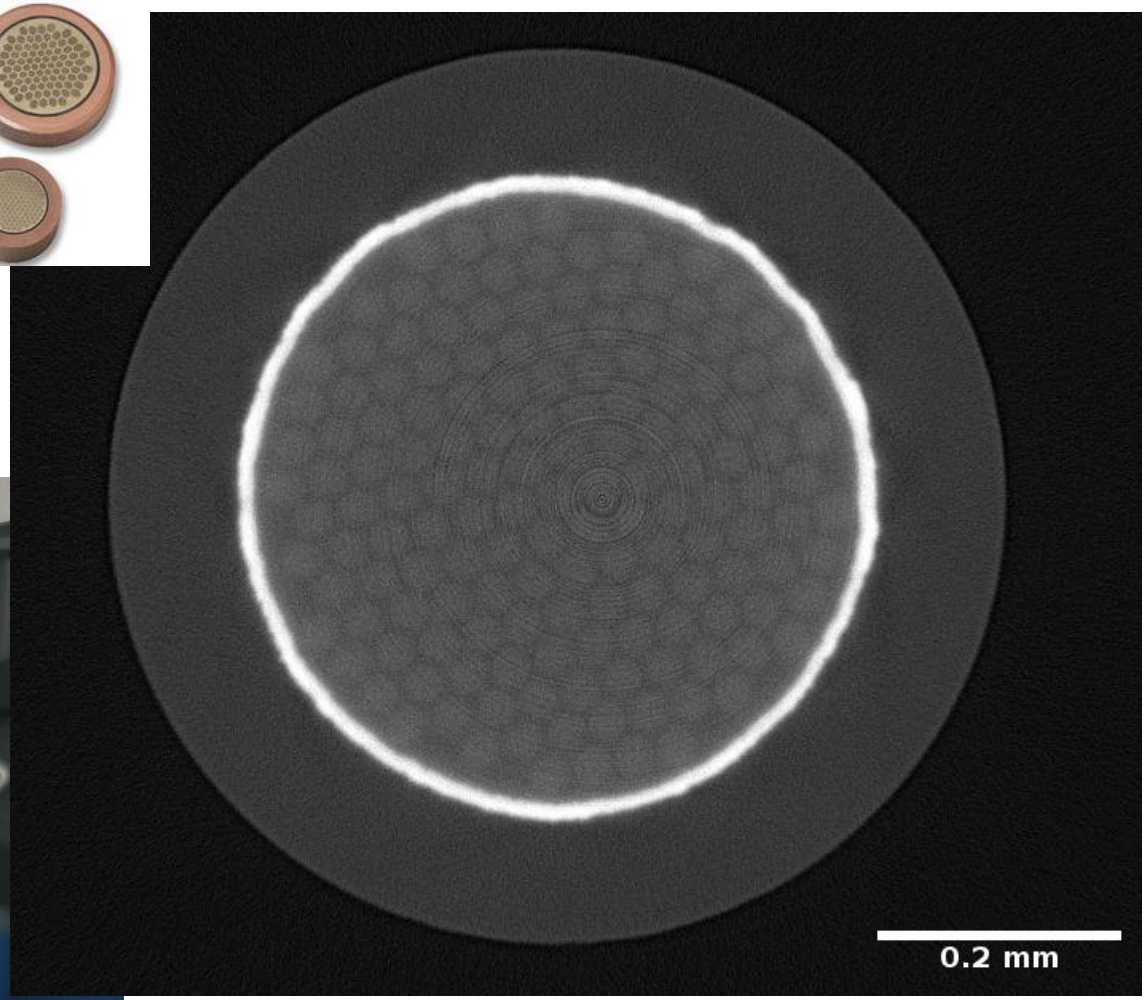
Micro-porosities of self-compacting concrete segmented with CNN

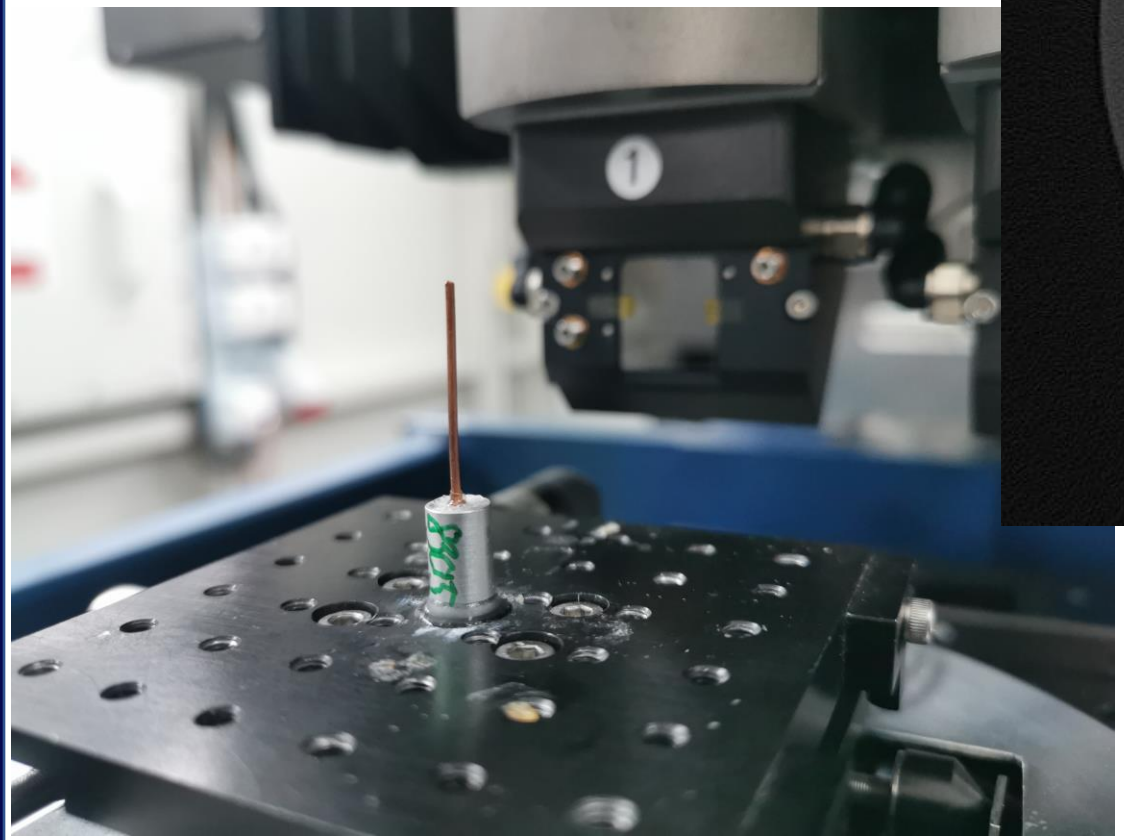
# Scientific Opportunities at BEATS

**Material science and Engineering:**

- Energy materials research
- Concrete, fiber-composites, 3D printed materials
- Light materials and alloys
- Materials under mechanical stress
- From CT images to FE simulations

80 keV high-resolution scan of $Nb_3Sn$ superconducting wire
NMR, fusion, high-energy physics applications



Courtesy A. Rack (ESRF) (BEATS, 2023)

- Sample diameter: 0.82 mm
- Detector: Twin Microscope (5x magnification)
- PCO edge camera
- Voxel size: 1.3 micron

Funded by the EU's H2020 framew ork programme under grant agreement n°822535

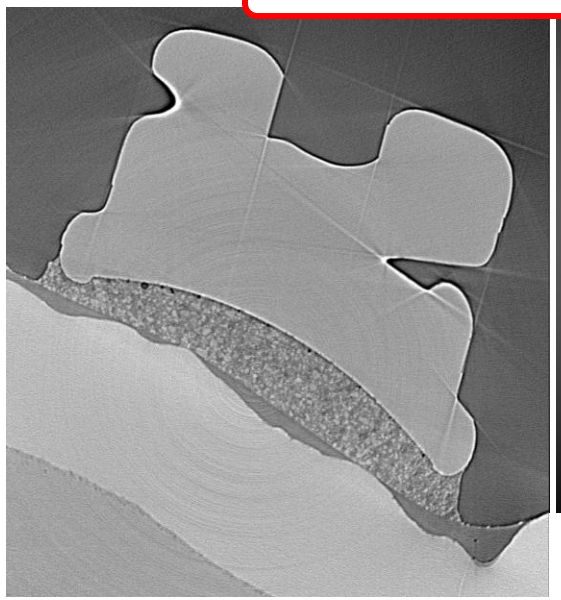
# Scientific Opportunities at BEATS

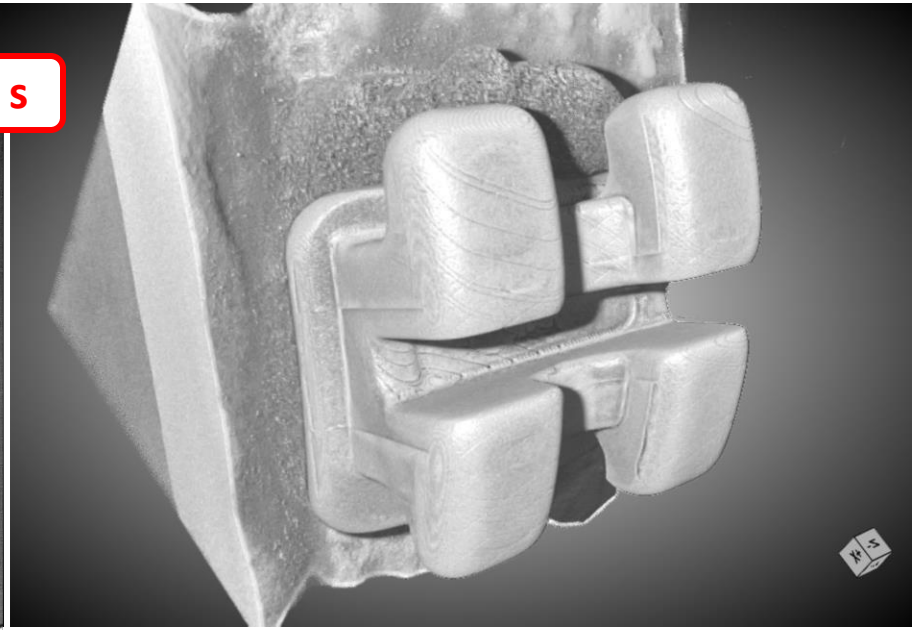
**Bone and dentistry research:**

- Implant design and optimization
- Functional biomaterials research
- Interfaces and interphases
- Biomineralized materials

White beam scan of dental bracket.

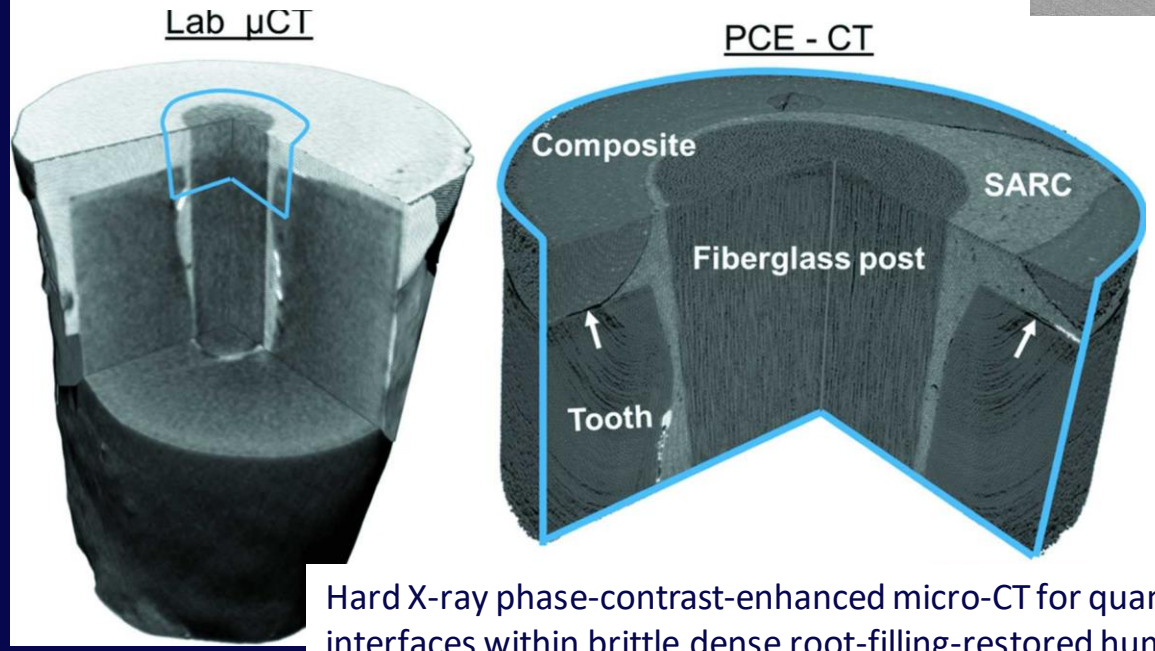
**Scan time: 40 s**



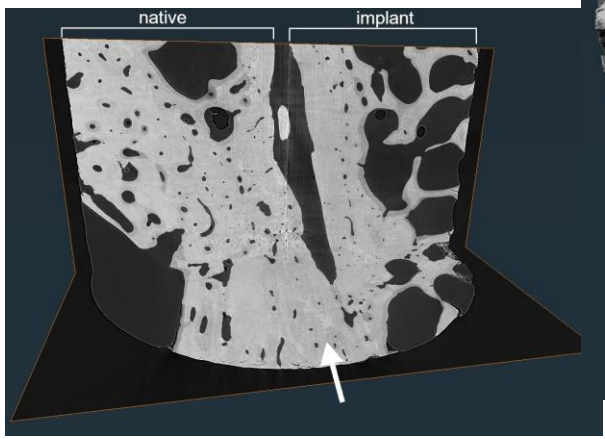


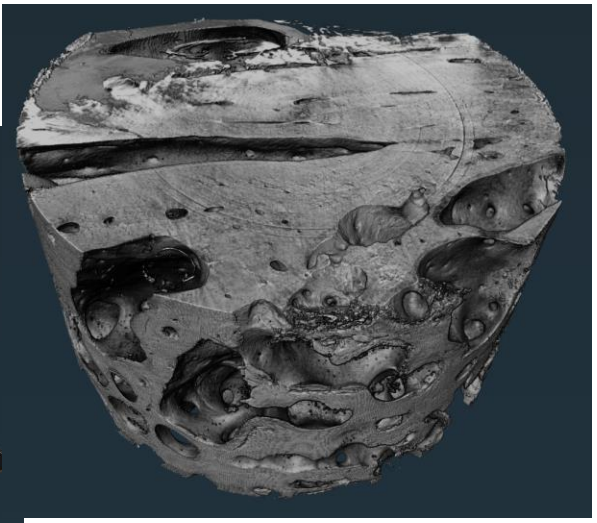
Courtesy P. Koch, P. Zaslansky (Charite Berlin) (BEATS, 2023)

Prates Soares et al. J. of Synchrotron Rad. (2020).




Hard X-ray phase-contrast-enhanced micro-CT for quantifying interfaces within brittle dense root-filling-restored human teeth.



Courtesy M. Manfrini (BEATS, 2023).

Bone vascularized implant

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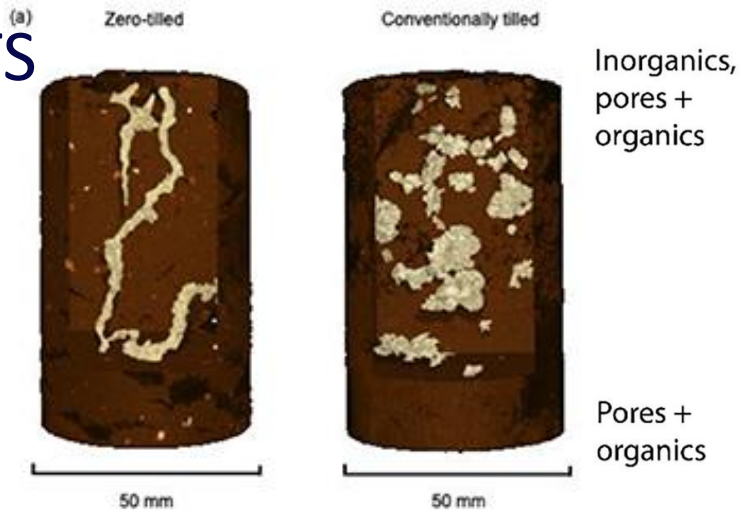
BEAmline for Tomography at SESAME

# Scientific Opportunities at BEATS

**Agriculture and Environment**

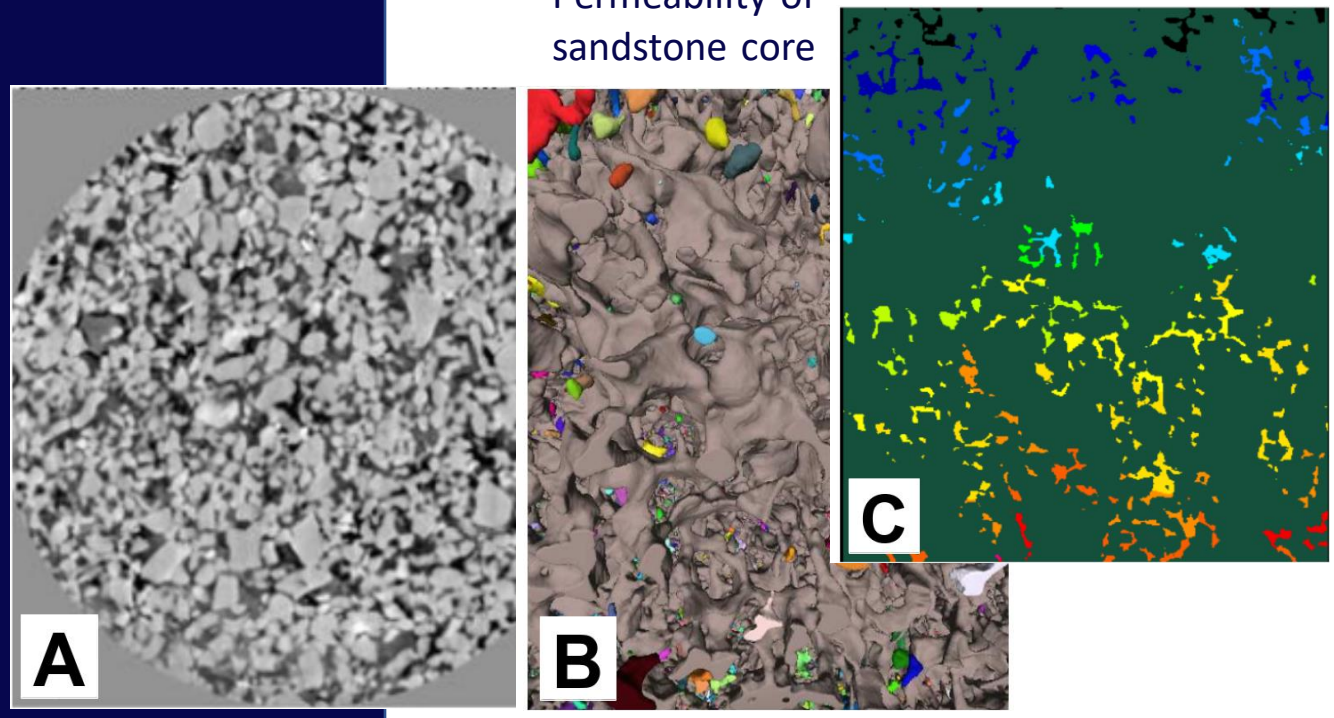
- Quantification of rock properties
- Soil characterization
- Sustainable agriculture



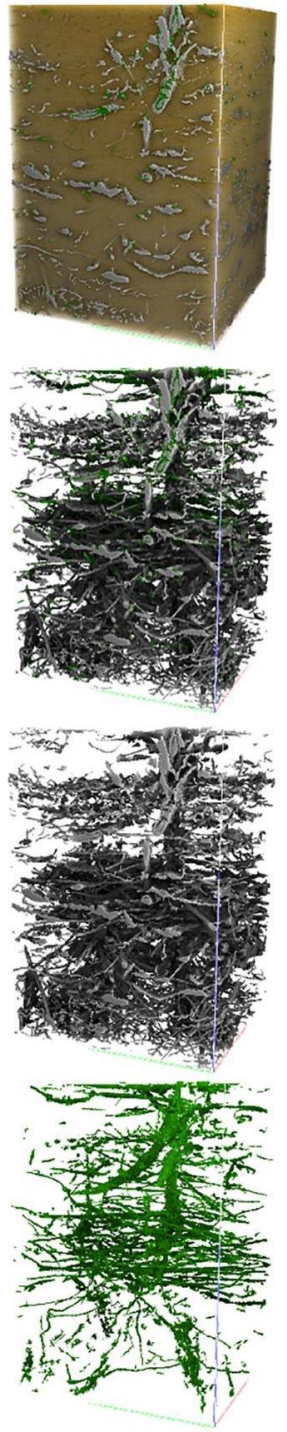

Cooper, H V. et al. Environ. Res. Letters (2021).

Excessive soil tillage associated with soil degradation processes: compaction, decrease in soil stability, increased soil erosion.

Permeability of sandstone core



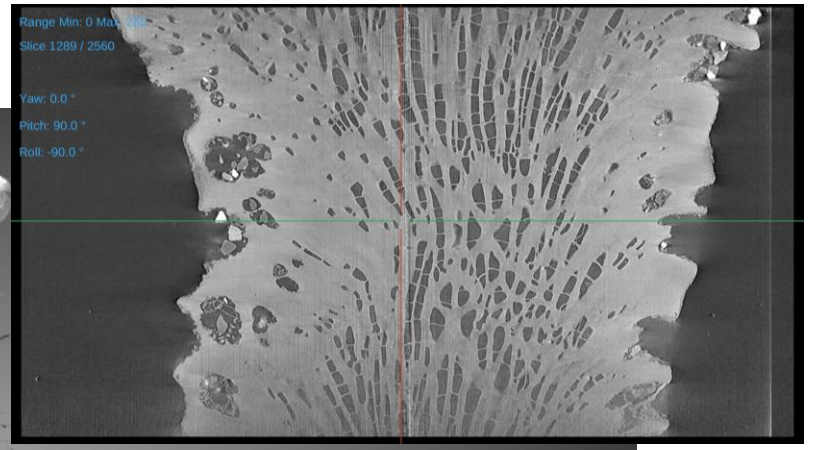

Kakouie, A. et al. Unpublished. Courtesy Shiva Shirani.




Chirol, C. et al. Geoderma (2021).

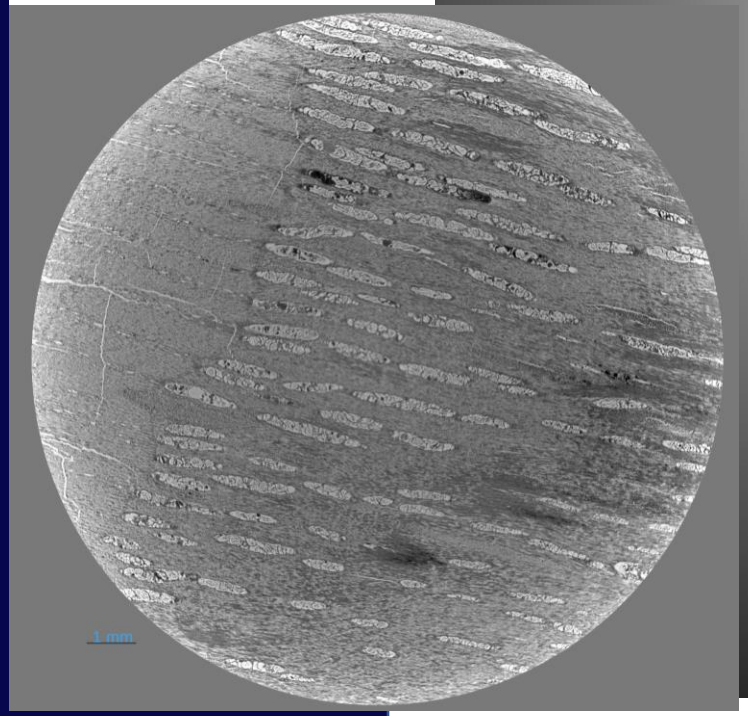
Pore, live root and inorganic quantification in complex heterogeneous wetland soils using XCT

# Animal and plant characterization




Play

Ancient wood (Turkey)

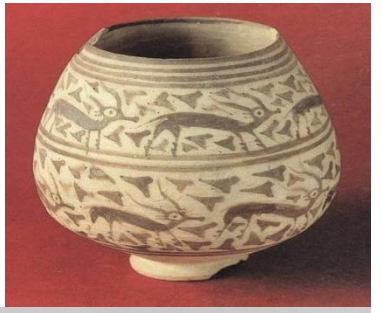


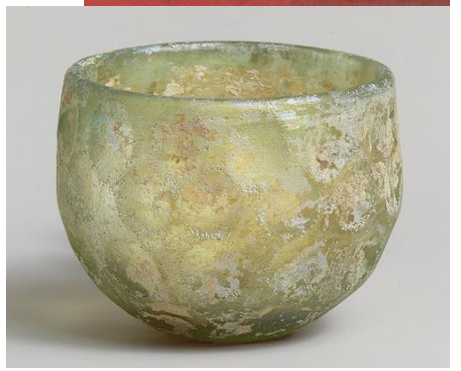
# Scientific Opportunities at BEATS

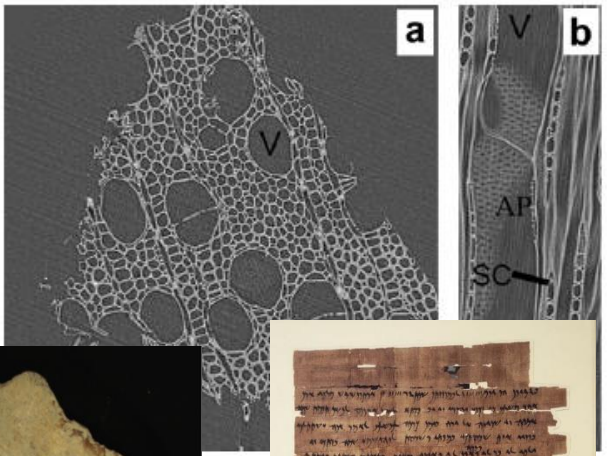
BEAmline for Tomography at SESAME

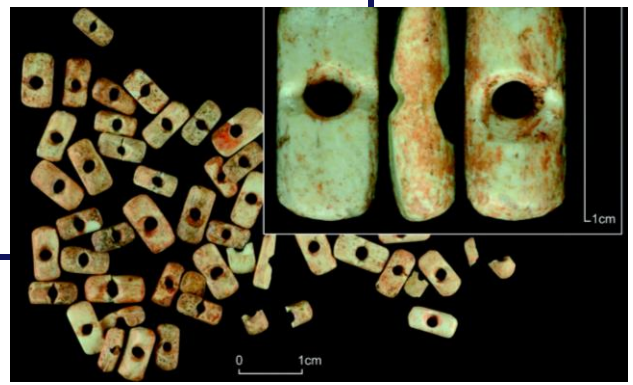
**Archaeology and Cultural Heritage:**

- Archaeological Materials
  - Pottery and Ceramics
  - Glass
  - Textile
  - Wood
  - Manuscripts
- Plant remains
- Animal remains
  - Bone
  - Antler
  - Ivory
  - Teeth
- Statues
- Ornaments






Funded by the EU's H2020 framew ork programme under grant agreement n°822535

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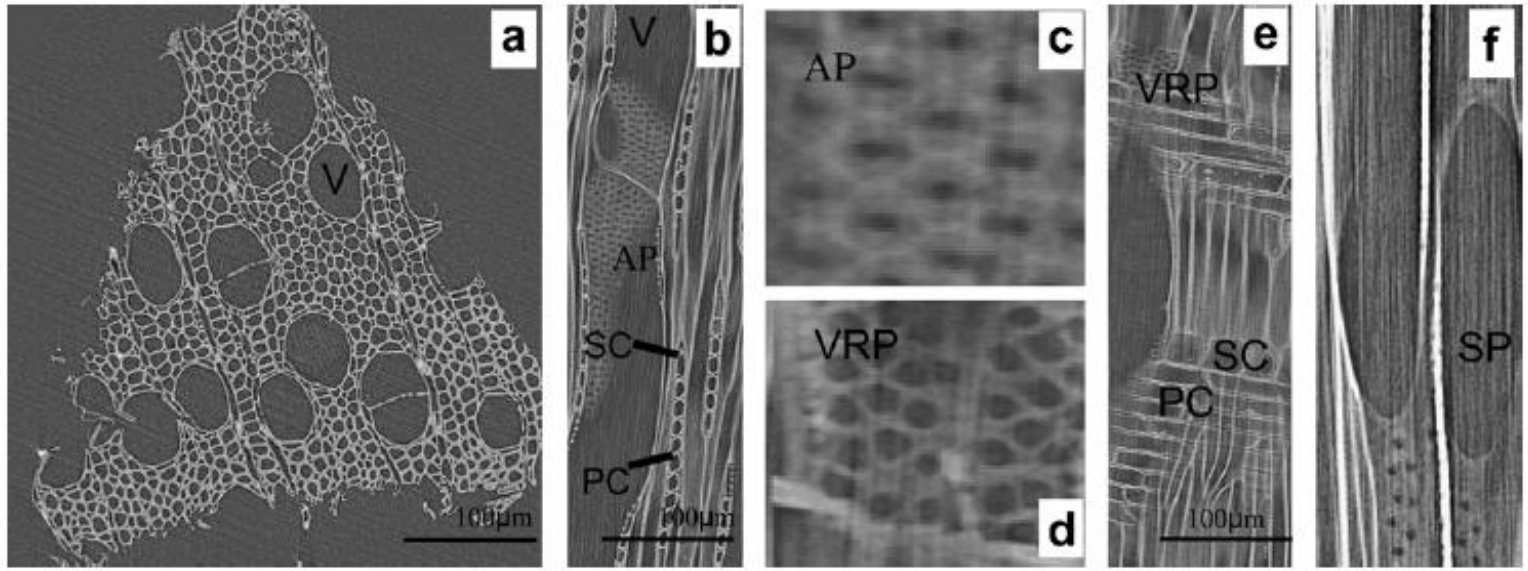
BEAmline for Tomography at SESAME

# Applications in Archaeology and Cultural Heritage

## 16th century wooden mask brought from Korea to Japan Raw Material Identification and Archaeological Implications

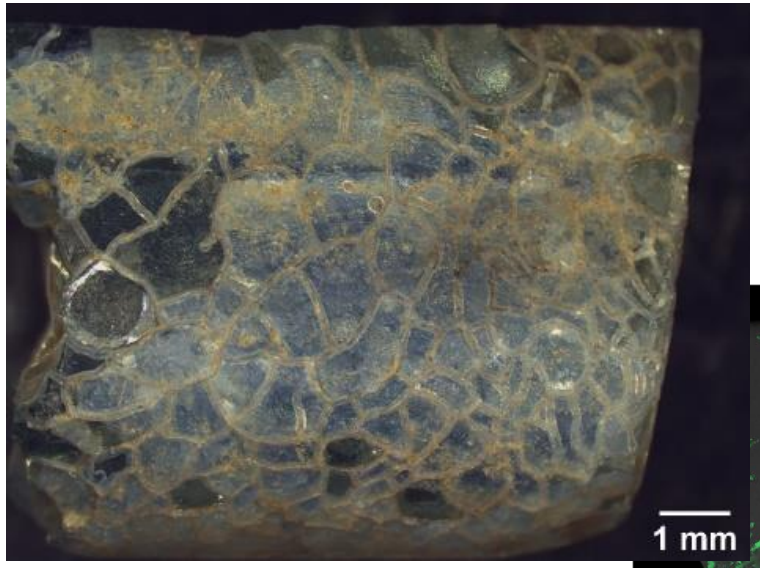



Mizuno et al. 2010. Journal of Archaeological Science Vol. 37

- Wood identification requires microscopic observation from three directions: transverse, radial and tangential
- The conventional method is to make thin sections from all three directions
- Material identified without damaging the sample (Salix sp.)
- Works of art, ancient icons and other artefacts painted on wooden substrates; understanding of architectural elements

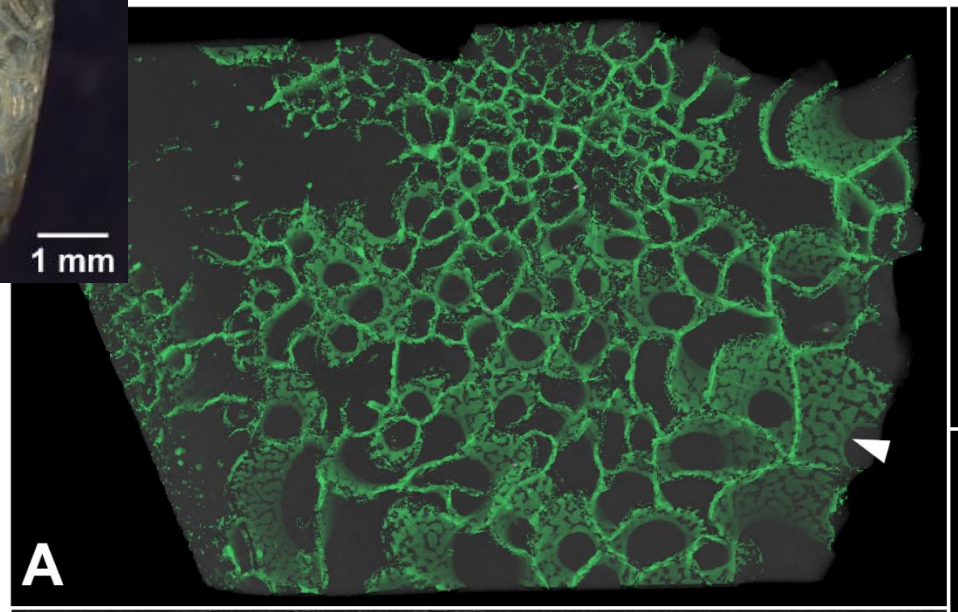
Funded by the EU's H2020 framework programme under grant agreement n°822535

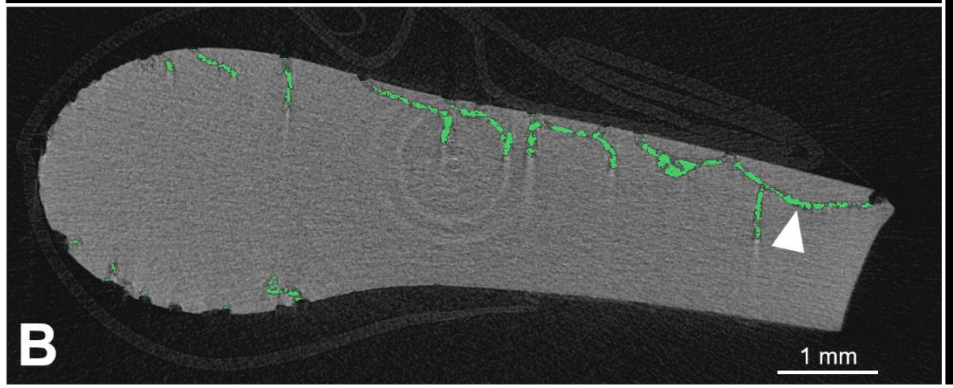
# Micro-CT scanning to non-destructively study Roman and early medieval glass

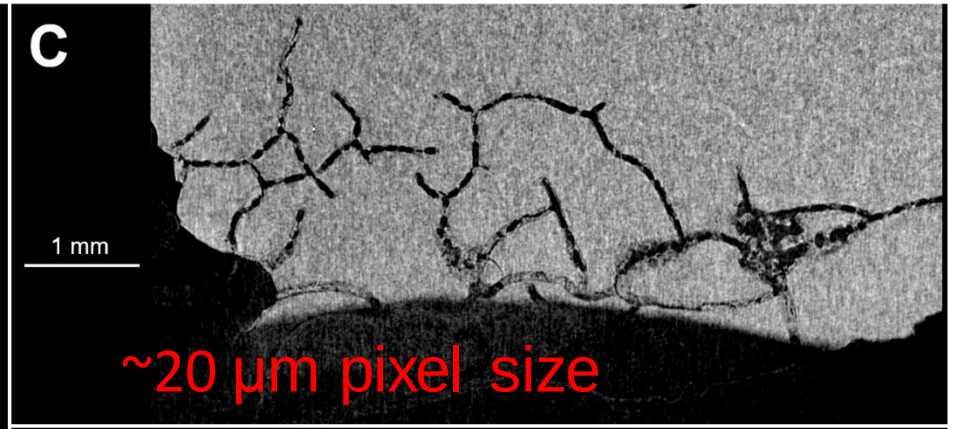


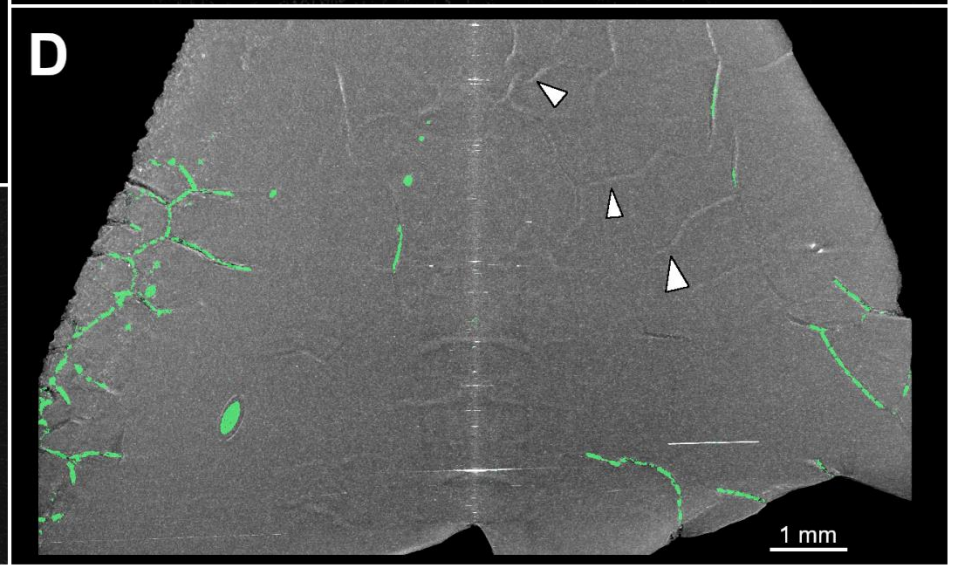

- Understand corrosion mechanisms
- Define novel **conservative strategies for glass**

Courtesy of CCHT- Italian Institute of Technology




Elettra Sincrotrone Trieste

ISTITUTO ITALIANO DI TECNOLOGIA

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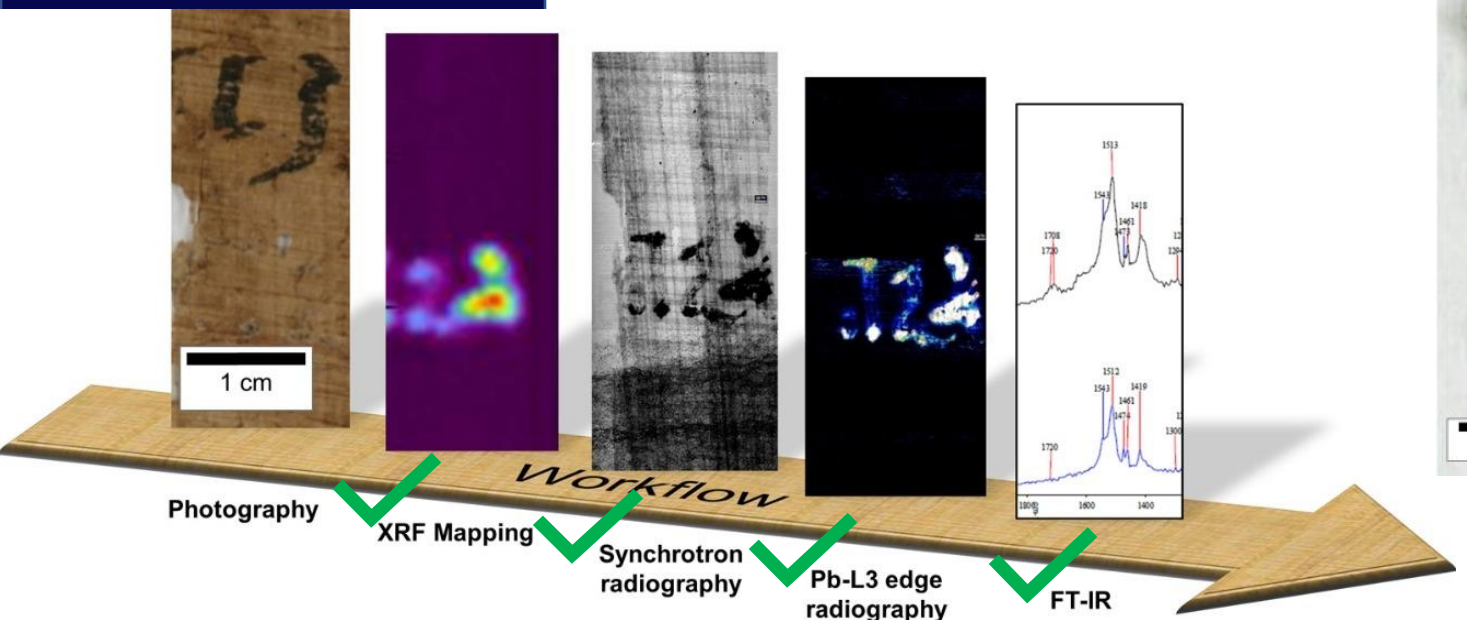
BEAmline for Tomography at SESAME

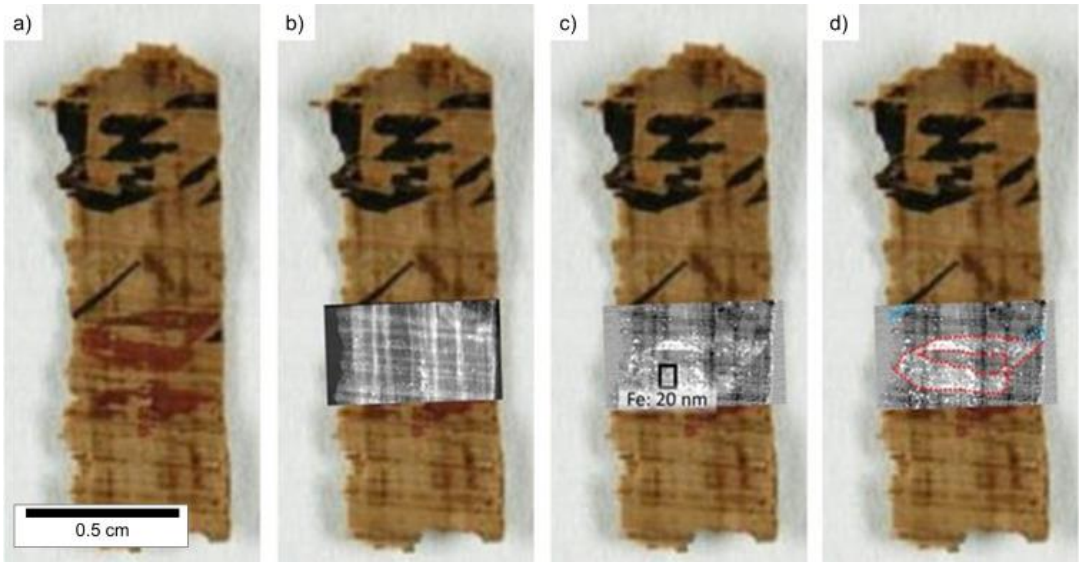
# Multi-technique studies require multiple beamlines

## Non-invasive digitization and analysis of historical objects (Papyri)

- XRF for information about Fe/Pb distribution
- BAMline@BESSY-II; 0.44 µm pixel size; 7, 13 and 19 keV
- Absorption edge radiography revealed element-sensitive distribution
- Invisible lead-carboxylate-based pigment identified by FT-IR

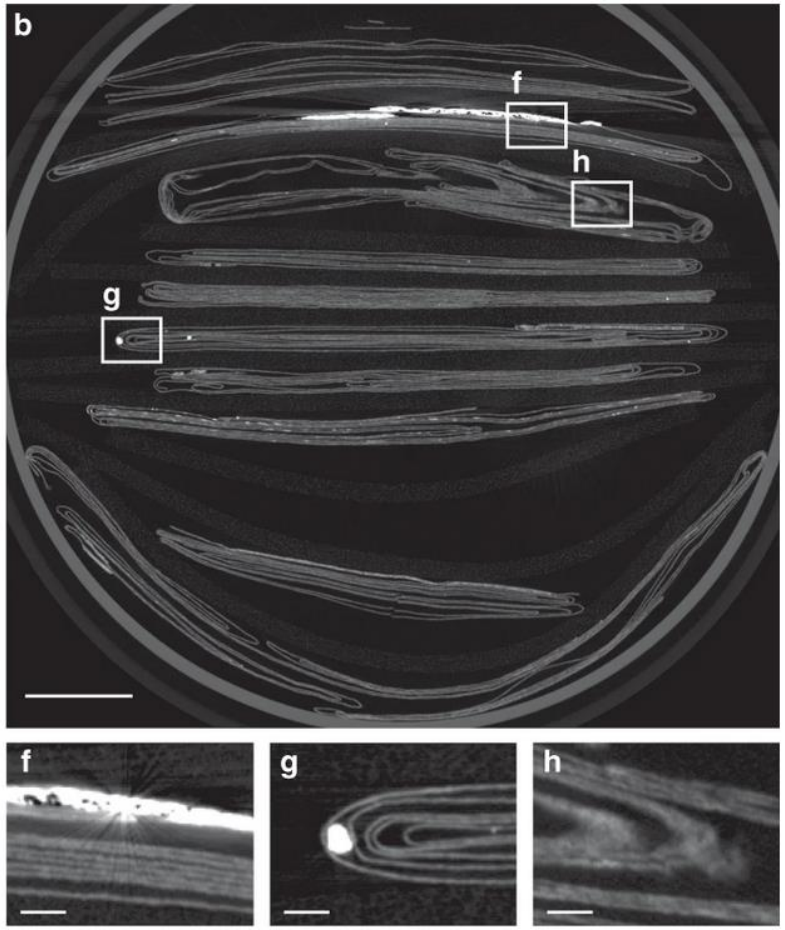


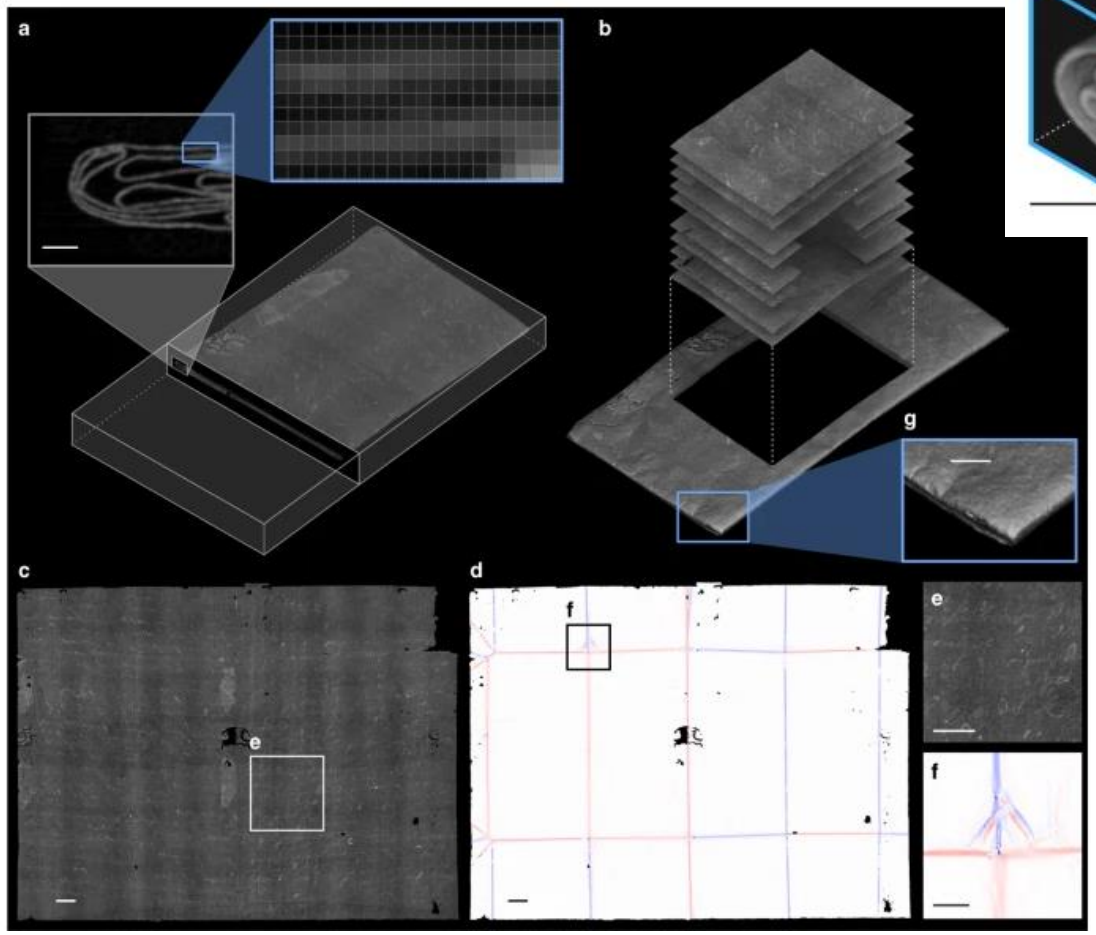

Arlt et al. 2019. Journal of Cultural Heritage 39 (September): 13–20

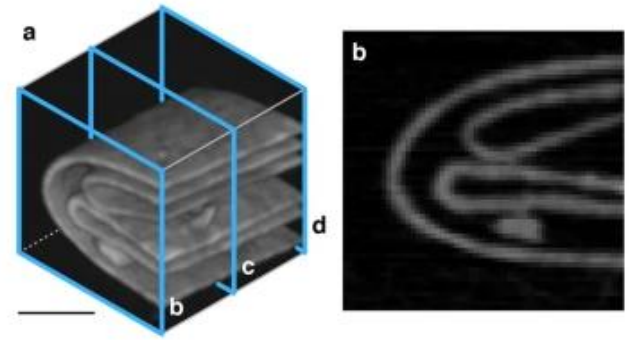


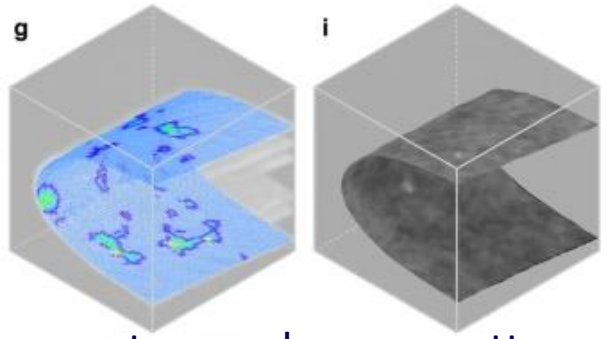
Unlocking History through Automated Virtual Unfolding of Sealed Documents Imaged by XCT. Dambrogio et al. 2021. Nature Communications 12 (1): 1–10. https://doi.org/10.1038/s41467-021-21326-w

- Fully automatic computational approach for reconstructing and virtually unfolding volumetric scans of a locked letter with complex internal folding

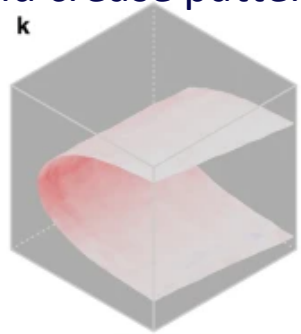


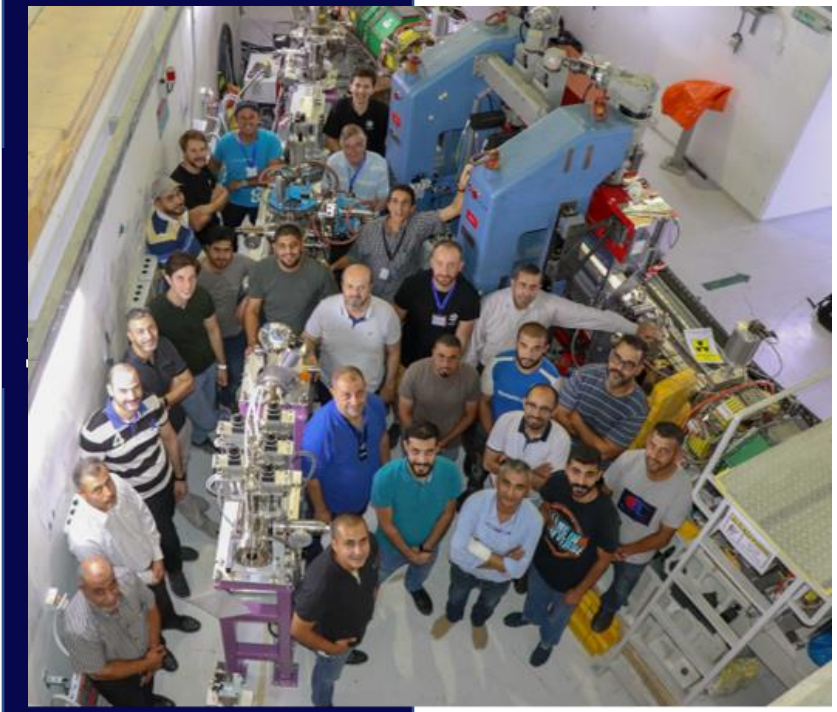




curvature and crease pattern





# Thank you for your attention

**Contact us to plan your experiment!**

**BEATS_eu**
@BEATSeu1

BEATS beamline webpage:
https://www.sesame.org.jo/beamlines/beats

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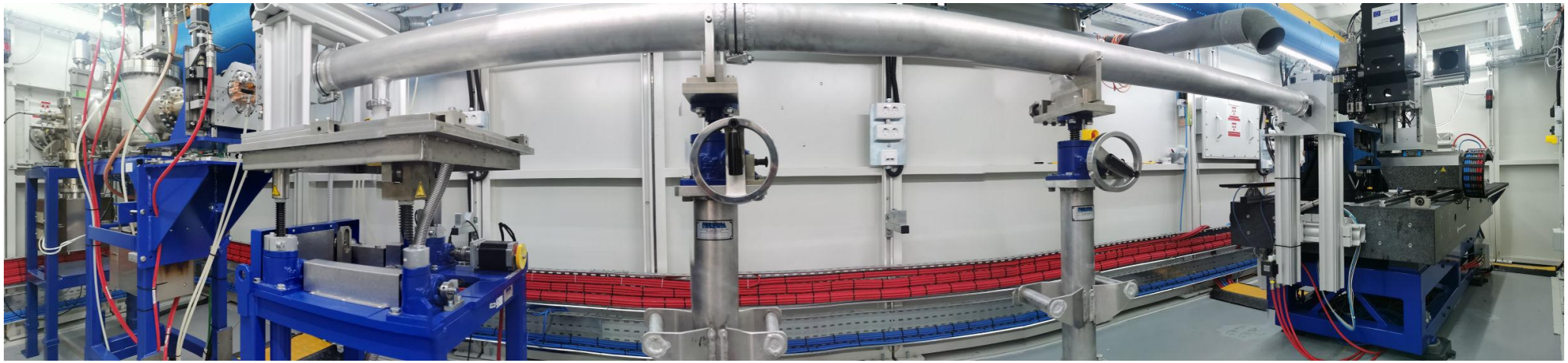
*gianluca.iori@sesame.org.jo*



SESAME

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