BEATS

Work Package 1

Management of the BEATS project

List of published articles

D 1.13

June 2023

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PROJECT DETAILS

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SUMMARY

This deliverable lists the articles published during the course of the BEATS project. This list yields a snapshot taken at the moment of project closure (30/06/2023, project month 54).

[1] G. Iori, G. Crimi, E. Schileo, F. Taddei, G. Fraterrigo, and M. Pani, "Ciclope: micro Computed Tomography to Finite Elements," *Journal of Open Source Software*, vol. 8, no. 84, p. 4952, Apr. 2023, doi: 10.21105/joss.04952.

[2] J. Campmany *et al.*, "Design of Front End and a 3-Pole-Wiggler as a Photon Source for BEATS Beamline at SESAME," in *Proc. IPAC'21*, in International Particle Accelerator Conference. Campinas, Brazil: JACoW Publishing, Geneva, Switzerland, Aug. 2021, pp. 324–326. doi: 10.18429/JACoW-IPAC2021-MOPAB086.

[3] G. Iori *et al.*, "Design and Ray-Tracing of the BEATS Beamline of SESAME," presented at the 11th Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation (MEDSI'20), Chicago, IL, USA, 24-29 July 2021, JACOW Publishing, Geneva, Switzerland, Oct. 2021, pp. 246–248. doi: 10.18429/JACoW-MEDSI2020-WEPA10.

[4] G. Iori, S. Matalgah, C. Chrysostomou, A. Al-Dalleh, and M. Alzu'bi, "Data Acquisition and Analysis at the X-ray Computed Tomography Beamline of SESAME," in *2021 IEEE Jordan International Joint Conference on Electrical Engineering and Information Technology (JEEIT)*, Nov. 2021, pp. 134–139. doi: 10.1109/JEEIT53412.2021.9634151.

[5] A. Kaprolat, G. Iori, A. Lausi, "New beamline set to open up new research horizons", in *EU Research*, Autumn 2022.

Furthermore, in October 2022, Fortune Mokoena successfully presented his Master of Engineering Thesis "Design and Study of the Experimental Hutch Equipment for the BEATS Beamline at SESAME" based on results achieved during the design of the BEATS sample environment to the Faculty of Engineering and the Built Environment at the University of Johannisburg, South Africa.

A publication describing the beamline design and commissioning is currently (June 2023) being drafted for submission to the *Journal of Synchrotron Radiation*.

Ciclope: micro Computed Tomography to Finite Elements

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Summary

The Python package ciclope processes micro Computed Tomography images to generate Finite Element models. Ciclope is aimed to provide reproducible and fully open-source pipelines for simulating the mechanical behaviour of trabecular bone using the Finite Element method.

Statement of need

Micro Finite Element (microFE) models derived from micro Computed Tomography (microCT) volumetric data can provide non-destructive assessments of mechanical properties of trabecular bone. The technique is used to investigate the effect of pathologies, treatment and remodelling on the mechanical response of bone at the tissue level, and is applied both to human and animal samples. Linear elastic microFE simulations are implemented to back-calculate the tissue elastic modulus (Bayraktar et al., 2004), understand deformation mechanisms (Zauel et al., 2005), or predict failure (Pistoia et al., 2002) of trabecular bone, as well as to estimate the stiffness of whole bones from small animals (Oliviero et al., 2020).

Different pipelines for the generation of microFE models of trabecular bone were proposed (Cox et al., 2022; Fernández et al., 2022; Megías et al., 2022; Stauber et al., 2004; Verhulp et al., 2008). Nevertheless, the validation and comparison of results across studies is hindered by the use of proprietary or non-open-source software, and by the general absence of reproducible FE pipelines. We present the Python package ciclope: a fully open-source pipeline from microCT data preprocessing to microFE model generation, solution and postprocessing.

Design

Ciclope is composed of a core library of modules for FE model generation (ciclope.core), and a library of utilities for image and FE model pre- and postprocessing (ciclope.utils) that can be imported and used within Python. Additionally, the ciclope.py script generated during package installation allows to launch microCT-to-FE pipelines directly from the commandline.

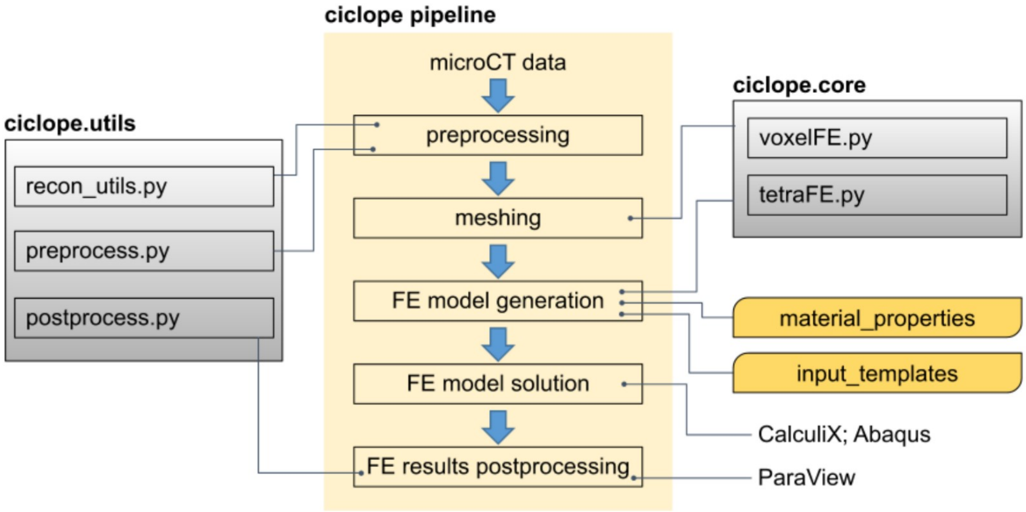

Figure 1: Design of ciclope, and application to a pipeline for FE model generation from microCT data.

A pipeline for the generation and solution of a FE model derived from 3D microCT data is shown in the central part of Figure 1. **Image preprocessing**: a microCT dataset is loaded as a `NumPy` `ndarray` within Python and segmented to isolate bone voxels and background using Otsu's method (Otsu, 1979) as provided by `scikit-image` (Walt et al., 2014). A connectivity check is performed to remove isolated clusters of voxels, that the segmentation might have disconnected from the main structure. According to the user's needs, additional image processing can be applied for smoothing, cropping, resampling and rotating the dataset using the `SciPy` (Virtanen et al., 2020) and `scikit-image` Python libraries. Furthermore, additional layers of material can be added at the top and bottom surfaces of the sample should the user need to replicate the effect of endcaps in the actual mechanical testing conditions. **Meshing**: `ciclope` allows to create two types of FE meshes. Image voxels can be directly converted to 8-node, hexahedral brick elements with the `voxelFE.py` module. Alternatively, meshes of 4-node tetrahedra can be generated calling `CGAL` (The CGAL Project, 2022) through the `tetraFE.py` module. **FE model generation**: the mesh is converted to an `.INP` input file for `Abaqus/CalculiX` FE solvers. Within model generation, it is possible to assign material properties, define the boundary conditions, analysis type and steps, and request specific simulation outputs using a separate analysis template `.TMP` file. Libraries of `material_properties` and `input_templates` are provided for this process. Additional `CalculiX` user examples and templates are available online (Kraska, 2022). For voxel-FE model generation, different material mapping strategies can be used: uniform tissue material properties (elastic modulus and poisson ratio) can be applied to all bone voxels. Alternatively, the local image intensity (voxel grey values) can be converted to heterogeneous material properties using a mapping law defined by the user. **FE model solution and postprocessing**: FE models can be solved using the external software `Abaqus` or `CalculiX`. Simulation ouptut files are read to compute, among other, total reaction forces on the model boundaries, or orthogonal cross-section plots of the model's displacement of stress fields.

The ciclope ecosystem

`Ciclope` relies on several other tools for 3D image and FE processing:

- Voxel and tetrahedra mesh exports performed with `meshio` (Schlömer, 2022a).
- Tetrahedra meshes generated with the Python `CGAL` frontend `pygalmesh` (Schlömer, 2022b).
- High-resolution surface meshes generated with `PyMCubes` (Márquez Neila, 2023).
- FE input files (`.INP`) generated by `ciclope` can be solved using the free software `CalculiX` (Dhondt, 2004) or `Abaqus`.

- 3D images and FE results can be visualized with `itkwidgets` (*Itkwidgets*, 2022), `ParaView` (Henderson, 2022), and `ccx2paraview` (Mirzov, 2022) as illustrated in the example Jupyter notebooks.

Examples

`Ciclope` contains a library of `Jupyter` notebooks of example applications in the field of computational biomechanics (Figure 2). The main use case is a pipeline for the generation of microFE models from microCT scans of trabecular bone (Figure 2A). The microCT bone dataset used in the examples is part of the public collection of the Living Human Digital Library (*LHDL*, 2006), funded by the European Commission under grant ID: FP6-IST 026932). Human tissues were collected according to the body donation program of Universitè Libre de Bruxelles (ULB), a partner of the LHDL project.

A linear elastic simulation of a mechanical compression test is used to calculate the apparent elastic modulus of trabecular bone. This procedure is demonstrated using hexahedra (voxel, Figure 2B), and tetrahedra (Figure 2C) finite elements. Two approaches for the local mapping of material inhomogeneities are illustrated using voxel and tetrahedra FE. Each example can be run within `Jupyter` or executed from the commandline with the `ciclope.py` script. `Ciclope` can be applied to microCT scans other than trabecular bone and in fields other than biomechanics. A simulation of a mechanical test of a whole human teeth, and a non-linear analysis of metal foam plasticity are illustrated in the software examples.

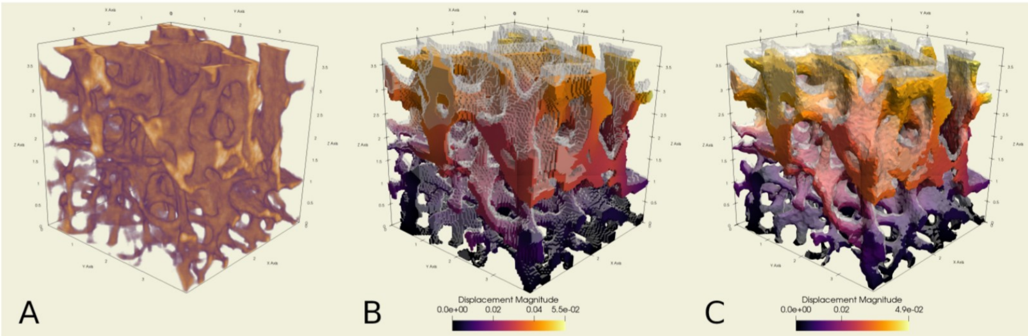

Figure 2: MicroFE models of trabecular bone generated from 3D microCT images with `ciclope`. (A) Input microCT volume data. (B) Hexahedra, and (C) tetrahedra finite element models generated with the `voxelFE.py` and `tetraFE.py` modules, respectively.

Acknowledgements

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DESIGN OF FRONT END AND A 3-POLE-WIGGLER AS A PHOTON SOURCE FOR BEATS BEAMLINE AT SESAME

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Abstract

BEATS is an international collaboration funded by EU under the Horizon 2020 program, aimed to design and construct a hard X-ray full-field tomography beamline to be installed at SESAME synchrotron in Jordan. In this paper we present the design of the photon source and of the front end that interfaces the beamline with the accelerator. The photon source will consist of an out-of-vacuum 3-pole wiggler with a peak field of 3 Tesla; the contract for its manufacturing has been awarded to Kyma.

INSERTION DEVICE REQUIREMENTS

BEATS is one of the new beamlines currently under construction at the 2.5 GeV synchrotron light facility SESAME in Jordan. The beamline will operate a hard X-ray micro tomography station allowing a wide range of applications, including high-resolution phase contrast tomography scans, rapid scans of dynamical phenomena at medium resolution, as well as low-dose applications (biomedical imaging and cultural heritage) [1].

From the point of view of the photon source, the main requirements were: (i) to shift the critical photon energy of the emitted X-ray spectrum considerably above the one for the existing storage ring (SR) dipoles (1.45 Tesla, E_c = 6 keV), (ii) to maximize the flux and brightness of the delivered photon beam, and (iii) to reduce as much as possible the SR modifications required in order to mitigate the impact of the source on the electron beam.

At an initial stage several options for the source were considered: a) a 3 Tesla superbend (E_c = 12.5 keV) replacing one of the SR dipoles, b) a 3 Tesla, λ_w = 50 mm period, 2.5 m-long multipole wiggler (MPW), c) a 3 Tesla 3-pole wiggler (3PW), with a strong central pole and two satellite poles to compensate the field integral.

All options were carefully analysed taking into account their impact on the accelerator at different levels: effect on the beam dynamics, required hardware modifications, associated services, etc. [2]. As a result of this investigation the 3PW option was finally selected. The superbend option was rejected due to the large accelerator adaptations that it would entail (modification of both the girder and the vacuum chamber together with the installation of two new quadrupoles), whilst the MPW option would most likely require a superconducting magnet, with the added complexity of the associated cryogenic system. Furthermore, a 3 Tesla 3PW can be realized using out-of-vacuum permanent magnet technology, and the resulting device can be easily fitted in one of SESAME's short straight sections, with a minimal impact on the technical systems of the facility.

ID DESIGN

Preliminary Design

A preliminary design of the 3PW based on a hybrid structure combining NdFeB permanent magnets and FeCo poles was developed using RADIA [3]. The main parameters of the magnetic structure are listed in Table 1, and the magnetic model is shown in Fig. 1.

Table 1: Main Parameters of BEATS Insertion Device

Device type	wavelength shifter
Magnetic configuration	Planar hybrid
Technology	Out vacuum
Number of poles	1 + 2
Magnetic minimum gap	11 mm
Gap range (magnetic)	11 mm to 30 mm
B_0 value at minimum gap	3T

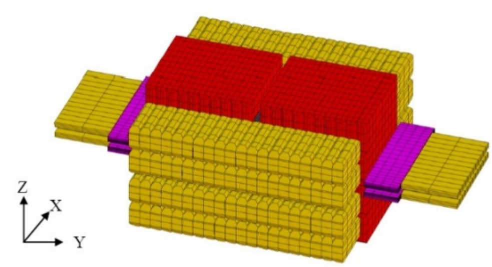

Figure 1: Preliminary magnetic model of BEATS 3PW generated by RADIA. Red and yellow parts are NdFeB magnets. The main iron poles are in the centre and edge poles to compensate the field integral are in pink. Side blocks have been introduced to compensate the large attractive force in the device.

The field profile generated by the device is shown in Fig. 2. A first version of the device with a main block/ central pole width of 90 mm/30 mm gave raise to very significant integrated multipoles (mainly sextupolar and decapolar terms). In order to reduce these components, the width of the main block and central pole was increased up to 180 and 150 mm, respectively, providing a reduction of the sextupolar term by a factor 100 and of the decapolar term by a factor 400.

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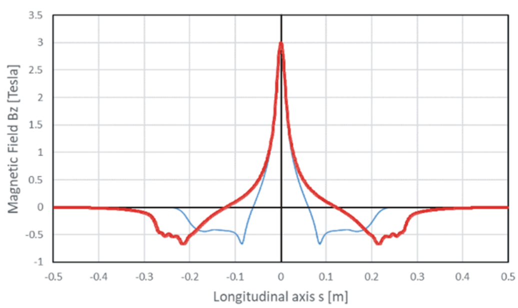

Figure 2: 3PW magnetic field along longitudinal axis, with the peak field of 3 T at the center of the device. Red line corresponds to the preliminary design, and blue line corresponds to the shortened design proposed by Kyma.

However, this widening of the device gave rise to a substantial increase of the magnetic forces, from ~7 kN up to 22.5 kN at the minimum gap of 11 mm. In order to alleviate these forces it was proposed to install a set of compensating magnets with opposite polarities at both sides of the device (yellows blocks in Fig. 1), which would allow to reduce the total force at 11 mm down to 1.2 kN.

The spectral flux delivered by the 3PW device through the user aperture of 1.8×0.4 mrad^2 obtained using the SPECTRA code [4] is shown in Fig. 3.

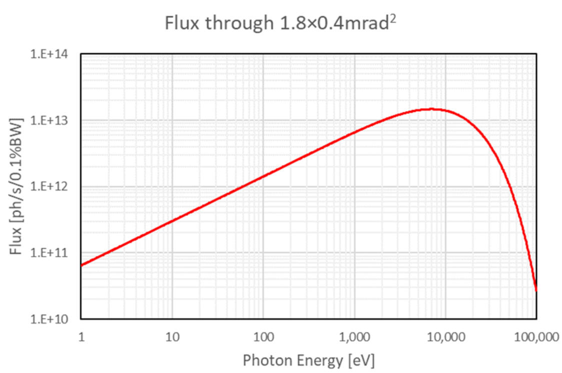

Figure 3: Emission spectrum of the 3-pole wiggler at minimum gap for an electron beam current of 200 mA.

Manufacturing

The manufacturing of the device was awarded to Kyma Srl (Trieste, Italy) on December 2020 and it is currently in its final design phase. The preliminary magnetic design has been modified in two main aspects: (i) the overall length of the device has been reduced from 755 mm down to 412 mm (see Fig. 2), leading to a reduction of magnetic material and associated forces; (ii) the compensation magnets have been removed from the design, due to the difficulty of integrating them into the assembly procedure. Despite this suppression, the shortening of the device by itself will result in a 30% reduction of the magnetic force at minimum gap, down to 15.5 kN, that will be handled by the mechanical support.

The magnetic structure proposed by Kyma is shown in Fig. 4. The final width of the main magnet has been increased by 5% (up to 190 mm) and the width of the central pole has been reduced by 25% (down to 110 mm) in order to leave space for the flux-concentrating lateral magnets (in orange in Fig. 4). The integrated multipoles, however, have been kept well within the requested limits.

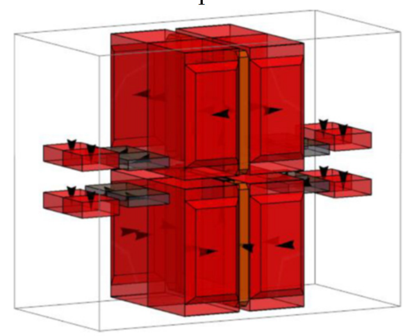

Figure 4: Final magnetic design of the 3PW developed by the manufacturing company. Red and orange pieces correspond to NdFeB magnets, and gray pieces to FeCo poles.

As for the materials, NdFeB 40UH grade ($B_r \geq 1.26$ T and $H_{cj} \geq 1900$ kA/m) has been selected for the magnet blocks and the pole pieces a FeCo alloy with properties comparable to Vacoflux50 will be used.

Figure 5 shows a view of the mechanical design developed by Kyma. It can be seen that two sets of correction coils at each end of the device for the active compensation of residual field integrals have been foreseen.

The 3PW device is expected to be delivered to SESAME on December 2021.

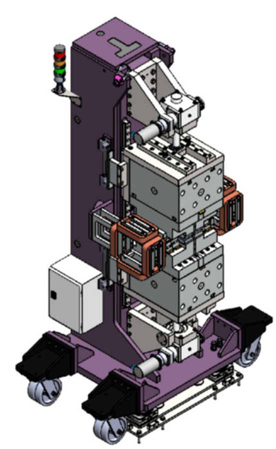

Figure 5: View of the complete design for the 3PW proposed by Kyma.

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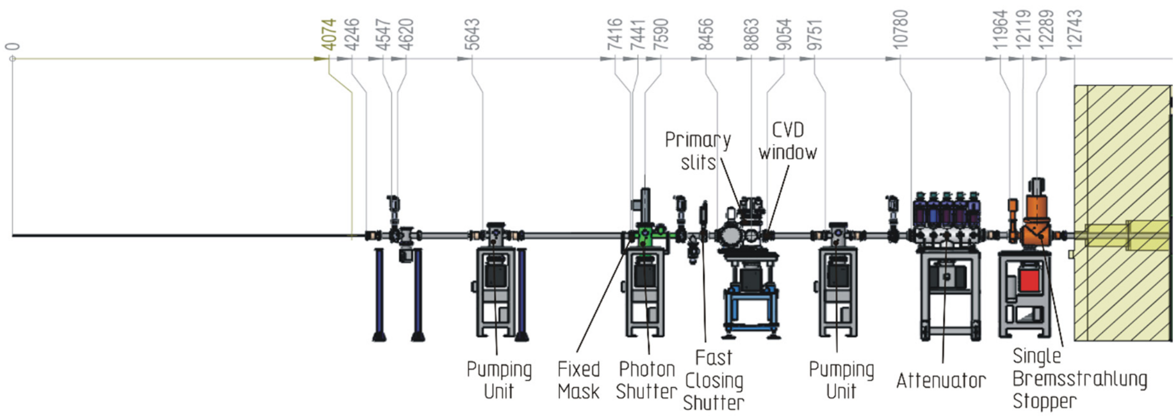

Figure 6: Layout of the FE for BEATS, with the distances from the 3PW source point indicated.

BEATS FRONT END

The total power (~1 kW @400 mA) and the peak power density (250 W/mrad^2 @400 mA) associated with the 3PW source are relatively small, similar to the values corresponding to SR dipoles of medium energy (2-3 GeV) 3rd generation light sources. Taking this into account, together with the requested user aperture of 1.8×0.4 mrad^2, the front end (FE) has been designed accordingly.

As a reference for the design we have taken the standard configuration for bending magnet FEs at ALBA [5], adapting it to the particularities of SESAME. The design includes: (i) a fixed mask to protect the downstream elements and to define the user aperture, (ii) a photon shutter, (iii) a fast closing valve triggered by gauges installed on the beamline side for protection of the accelerator's vacuum, (iv) a system of primary slits (refurbished from ID19 beamline at ESRF), (v) a set of beam attenuators with 5 independent axes, and (vi) a single-block Bremsstrahlung stopper. The layout of the FE is shown in Fig. 6. All power absorbing elements have been dimensioned to withstand the power delivered by a stored electron beam of up to 400 mA.

Most of the FE units are being manufactured by JJ X-ray A/S (Denmark), and will be delivered on April 2022.

CONCLUSION

A photon source for the new tomography beamline BEATS at SESAME has been designed and is currently under construction. The developed 3PW device will deliver the requested flux at high energies (above 20 keV) while at the same time enabling a smooth integration into SESAME's accelerator. BEATS beamline is expected to enter into operation by the end of 2022.

ACKNOWLEDGMENTS

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DESIGN AND RAY-TRACING OF THE BEATS BEAMLINE OF SESAME*

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Abstract

The European Horizon 2020 project BEAmline for Tomography at SESAME (BEATS) has the objective to design, procure, construct and commission a beamline for hard X-ray full-field tomography at the SESAME synchrotron in Jordan. In this paper we present the raytracing simulations performed to quantify the performance and verify the optical design of the beamline. The specifications of a vertically-deflecting double multilayer monochromator are investigated comparing multilayer mirrors with different meridional slope error. The use of a pinhole in the beamline Front-End (FE) acting as a secondary source with enhanced spatial coherence is discussed for phase-contrast applications. We anticipate that the BEATS beamline will fulfill the needs of a heterogeneous community of users of X-ray tomography at SESAME.

INTRODUCTION

The BEATS beamline will operate an X-ray micro tomography station serving a broad user community. The scientific case of the BEATS beamline is the result of close interactions with the scientific communities of current and potential synchrotron users in the SESAME region. Special emphasis is given to the regional aspect, taking stock of existing research contributions from the region. Four key areas for the scientific case for BEATS in the SESAME landscape are identified:

- Archaeology and Cultural Heritage – This includes the study of archaeological materials such as human, plant or animal remains and artefacts of animal bone, antler and teeth.
- Health, Biology and Food – Research in bone and dentistry; in vitro imaging of the brain vascular and neuronal network and of other organs such as the eye, heart, lung and liver; musculoskeletal and soft tissue imaging; bio mineralisation; entomology; food science.
- Material science and Engineering – Study and development of light and composite materials for construction and transport engineering; energy materials research
- Geology and Environment – Research in soil and rock characterization.

Applications within other domains as well as the possibility to provide services to industrial and private sector users are also envisaged.

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BEAMLINE DESIGN

The design of the beamline allows for a variety of operation modes and ensures sufficient photon flux density in filtered white beam or monochromatic beam from 8 keV and up to 50 keV. The broad energy range and required high photon flux is achieved by a 3 T wavelength shifter insertion device (ID) installed on one of SESAME's short straight sections. The beamline can work with either monochromatic or filtered white beam, with minimum energy tunable by absorbers in the FE. The beam size at the sample position and the propagation distance between sample and detector can be varied displacing the rotation and detector stages along the beam path. For measurements requiring high sensitivity and spatial coherence of the beam (e.g., for phase-contrast tomography), the beamline FE slits are partly closed to define a smaller, secondary source with higher spatial coherence.

Layout

The beamline FE comprises photon absorbers and stoppers, a mask defining a useful beamline aperture of 1.8 $mrad$ (h) by 0.36 $mrad$ (v), a CVD diamond window separating the machine and the beamline vacuum, filters and primary slits. The main optical component is a Double Multilayer Monochromator (DMM) placed outside of the SESAME storage ring tunnel in a dedicated optics hutch. The experimental station is located approximately 45 m from the photon source and comprises secondary slits, a linear fast shutter allowing to reduce exposure of delicate samples [1], a high precision sample positioning and rotation stage, and two full-field detectors based on scintillating screens and sCMOS sensor cameras mounted on a common granite stage [2].

Raytracing

The BEATS optical design is verified with simulation tools included in the OASYS suite [3]. Raytracing calculations are performed in ShadowOui, while power profiles are computed using XOPPY. Software and notebooks for the reproduction of this work are available on Zenodo [4].

Heat Load

The beam power density is calculated for each beamline component sustaining the white beam during operation or possibly in direct sight of the white beam with the OASYS *Wiggler Radiation* widget [5]. The power density profile of the incoming or absorbed beam is used as input for thermal verification with commercial Finite-Element software. Due to the position of absorbers and apertures in the storage ring

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and beamline FE, a portion of dipole emission can enter the beamline. Therefore, for the calculation of the power density profiles on the first two beamline apertures (crotch absorber and fixed mask) the contribution from the upstream and downstream bending magnets is considered in addition to the emission of the BEATS wavelength shifter. For simulations in XOPPY, the magnetic field profile of the BEATS ID is modified to include part of the dipole field as shown in Fig. 1. For all components after the fixed mask, only the ID contribution is considered. The heat load expected on the main beamline components is reported in Table 1.

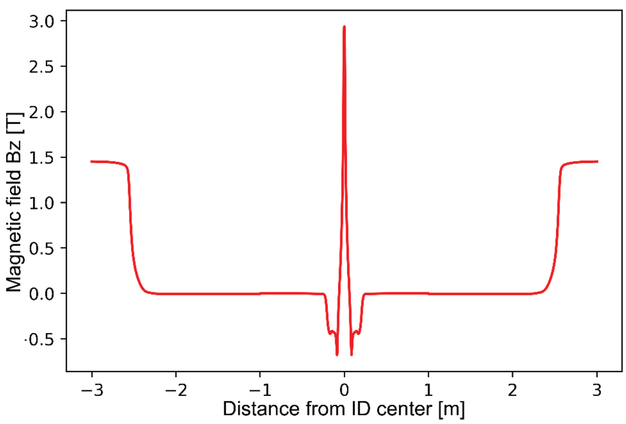

Figure 1: Magnetic field profile modified for simulation in XOPPY considering the BEATS wavelength shifter and the upstream and downstream dipoles.

Table 1: Maximum Power and Power Density on Beamline Components Illuminated by the White Beam

Component	Position $[m]$	P $[W]$	P density $[W/mm^2]$
ID	0.0	857	
Absorber	4.1	4300	20.4
Fixed mask	5.9	271	9.7
Photon shutter	7.6	134	5.2
Window 1	9.0	134	3.7
Filters	11.0	94	1.9
DMM M1	15.1	94	1.0
Combined stopper	94.0	271	0.6
Window 2	37.9	94	0.2

Double Multilayer Monochromator Design

A double-bounce, vertically-deflecting DMM is modelled as a series of two Shadow *Plane Mirror* widgets. The surface and reflectivity of each multilayer is modelled with the Shadow *PreMLayer* PreProcessor. Discrete multilayer surface errors are simulated by external splines with slope error along the beam axis varying between 0.1 and 0.5 μrad (RMS). Modified surfaces are generated with the Shadow PreProcessor - *Height Profile Simulator* widget. The slope error perpendicular to the beam axis is kept constant at 20 μrad RMS, and fractal profiles are chosen (Fig. 2). Plots of the positions of both multilayer mirrors at different working energies are generated for varying bilayer composition and d-spacing. DMM configurations with independent pitch cradles or a common, pseudo-channel-cut layout are investigated.

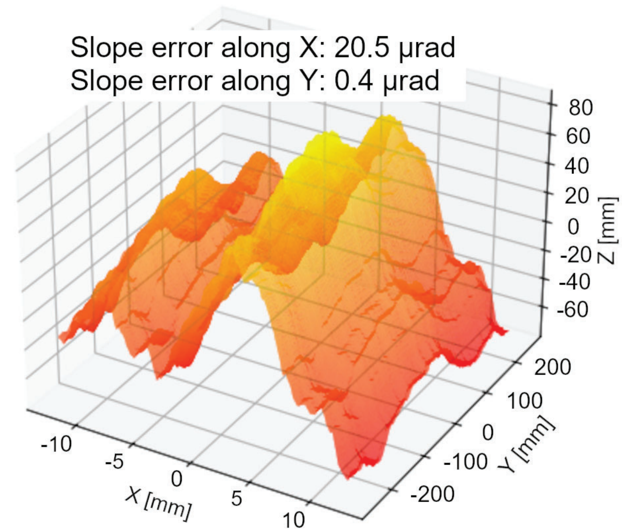

Figure 2: Example of modified multilayer surface: the Y-axis corresponds to the beam path and the X-axis is perpendicular to the beam.

Secondary Source and Coherence Length

Owing to the electron optics of the SESAME storage ring, the BEATS ID generates an X-ray source almost 2 mm in width. Consequently, the beam spatial coherence is limited. To allow for propagation-based phase contrast tomography requiring a certain degree of spatial coherence, the FE slits can be closed to generate a horizontal aperture acting as a smaller and coherent secondary photon source. A comparison of the transverse coherence length at 20 keV with that of other tomography beamlines is shown in Table 2. The transverse coherence length is calculated as:

$$l_{coherence} = \frac{2\lambda d}{\sigma_x} \quad (1)$$

where d is the distance between source and sample, λ is the wavelength (0.62 $\mathring{A}$) and σ_x is the FWHM horizontal photon source size [6].

The reduced beam size available with FE slits closed can be calculated as $2\eta_x d$ where η_x is the effective beam half-divergence behind an aperture of size a:

$$\eta_x = \frac{\sqrt{(\frac{\sigma_x}{2})^2 + (\frac{a}{2})^2}}{d} \quad (2)$$

The effect of closing the FE slits on both the available white beam size and flux for experiments is investigated through raytracing simulations.

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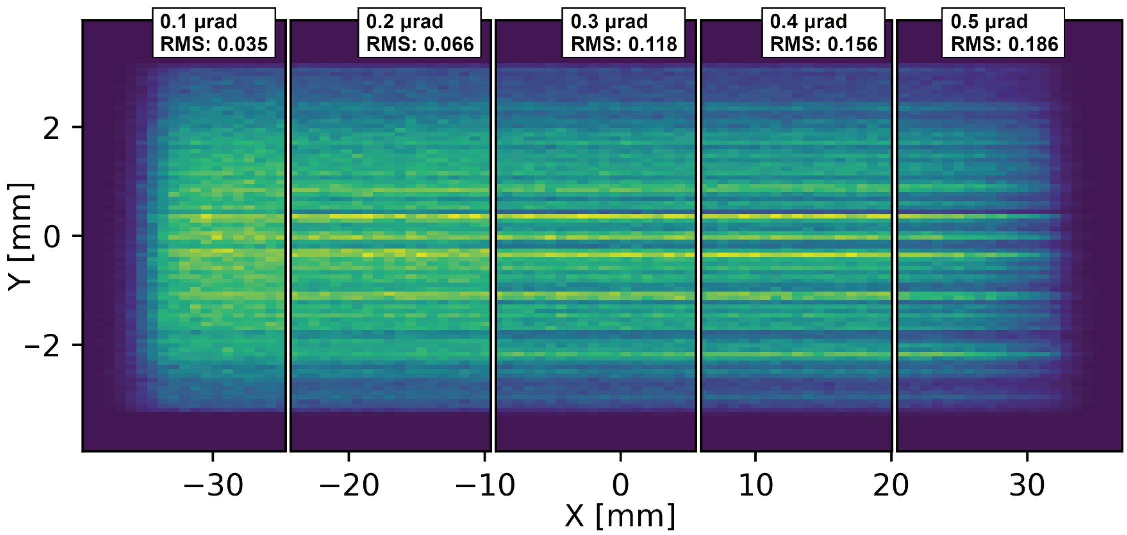

Figure 3: Monochromatic beam flat field snapshots at the sample position (43 m from source) for different multilayer mirrors slope errors. $[W/B_4C]_{100}$ bilayers with a d-spacing of 3.0 nm coated on $500 \times 25\ mm^2$ mirror surfaces are considered. The grazing angle is optimized for an energy of 45 keV ($\theta = 0.274°$). 16×10^6 rays are used for Monte Carlo simulations.

Table 2: Transverse Coherence Length at 20 keV; Comparison of BEATS with other Beamlines

Beamline	d [m]	σ_x [μm]	$l_{coherence}$ [μm]
ID19@ESRF	145.0	25	720.0
TOMCAT@SLS	34.0	140	30.2
SYRMEP@Elettra	23.0	197	14.5
BEATS	43.0	1978	2.7
BEATS - Slits @ 0.5 mm	34.6	500	8.6

RESULTS

The expected white beam flux delivered through a square millimeter at the sample position is as high as $1 \times 10^{10}\ Ph/s/mm^2$ in 0.1 % of the source bandwidth, for a maximum usable beam size of $72 \times 15\ mm^2$. With both multilayers, the expected energy resolution of the monochromatic beam is 3 %, for a total monochromatic photon flux at 20 keV of $3 \times 10^{11}\ Ph/s/mm^2$ through one square millimeter at the sample. Simulated monochromatic beam profiles at the sample are shown in Fig. 3 after double reflection by two multilayers with varying mirror surface slope error. The quality of the flat field deteriorates for mirror slope errors > 0.2 μrad. When the FE slits are closed to produce a secondary photon source, the beam size is also reduced, limiting the horizontal field of view for phase contrast imaging to 10 mm or less (Fig. 4). The reduction in photon flux density at the sample position when the FE slits are closed to 500 μm is estimated to be of the order of 70 %.

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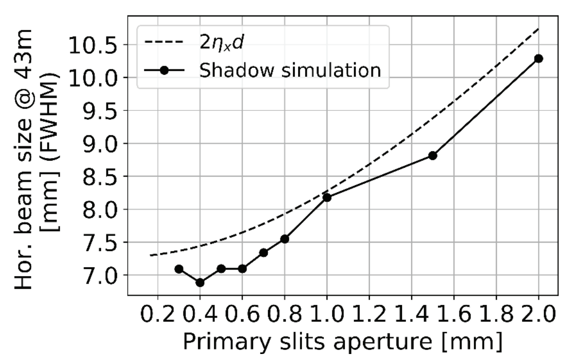

Figure 4: Horizontal beam size at the sample position when the FE slits aperture is reduced.

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Abstract:
The European Horizon 2020 project BEAmline for Tomography at SESAME (BEATS) aims to design, procure, construct and commission a beamline for hard X-ray full-field tomography at the SESAME synchrotron in Jordan. The beamline will become operative in summer 2022 as the first synchrotron tomography station in the region. Experiments at BEATS will generate large amounts of raw data and require a high-end computational infrastructure to acquire, store, process and manage the collected information. In this paper, we present the design of a pipeline for the acquisition and storage of tomographic scans capable of reaching the required performance. Hardware and software solutions currently under commissioning for image acquisition, tomographic reconstruction and quantitative analysis of 3D data-sets are also described. The BEATS beamline will enable a large variety of applications of X-ray tomography to the user community of SESAME.

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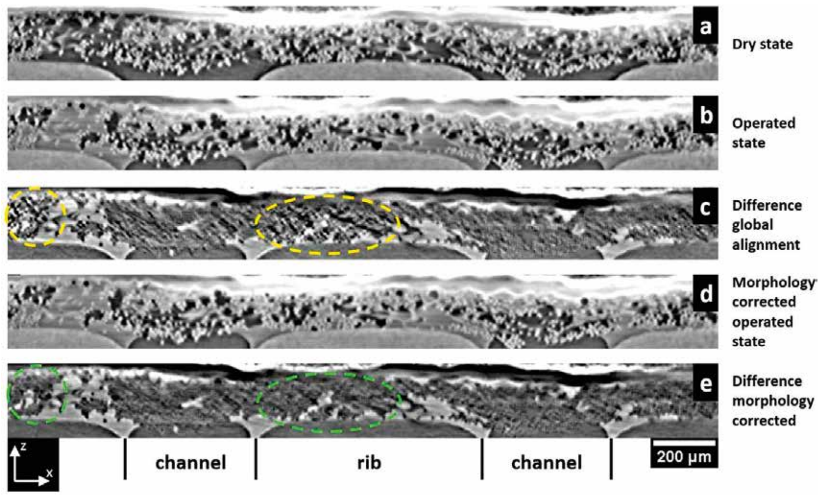

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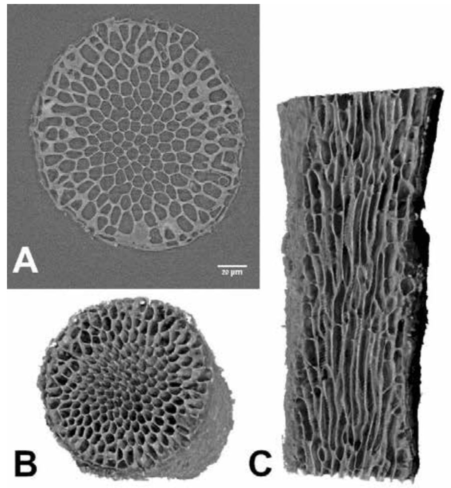


New beamline set to open up new research horizons

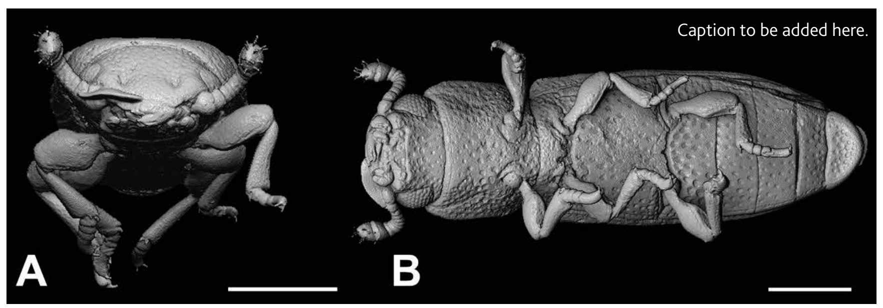
Synchrotron radiation helps researchers across a wide variety of disciplines gain fresh insights. The aim of the BEATS project is to design and construct a new beamline for tomography at the SESAME synchrotron facility in Jordan, which will open up new opportunities to researchers across the Middle East, as Dr Axel Kaprolat, Dr Gianluca Iori and Dr Andrea Lausi explain.

SESAME is an important scientific resource for researchers across the Middle East, producing a spectrum of electromagnetic radiation that supports investigation in disciplines from materials science to cultural heritage. In a synchrotron facility, electrons circulate in a storage ring at close to the speed of light. "When these electrons move at the speed of light and are made to change direction to follow a quasi-circular path, they emit a very intense and brilliant photon beam. The spectrum of this radiation beam ranges from the infra-red to high-energy X-rays," explains Dr Axel Kaprolat of the European Synchrotron (ESRF). As coordinator of the EU-funded H2020 BEATS project (Beamline for Tomography at SESAME), Dr Kaprolat is working to help design and construct a new beamline for X-ray tomography at SESAME. "For the sustainable operation of a synchrotron facility it is important to have a certain number of operational beamlines that constitute a critical mass. Currently SESAME is enhancing the number of beamlines to go beyond this threshold, with the BEATS project being a major part of this process," he outlines.

Cultural heritage and archaeology

BEATS will be a state-of-the-art beamline, or experimental station, for tomography at SESAME. It will primarily cater for researchers in cultural heritage and archaeology. The beamline is designed to have only those optical elements that are absolutely necessary, and will have two operational modes. "One is that we have the beam as it comes from the storage ring, modified only by absorbers allowing us to shape the spectrum according to needs. The other mode involves using a monochromator, selecting a smaller band of energies which enables what we call phase and coherence-dependent experiments," says Dr Gianluca Iori, a beamline scientist at SESAME. In this second operational mode a double multilayer monochromator will enable researchers to see subtle or seemingly minor details in a sample that would not be apparent using standard tomography. "Even small contrasts in a sample can be enhanced, which you cannot do with standard methods," explains Dr Iori.

The beamline is being developed on the basis of existing technology, drawing particular inspiration from the TOMCAT beamline operational at the Swiss Light Source, although the BEATS experts have to adapt to SESAME's local framework (space considerations, technical standards). One important consideration in development is how many photons are available per second at the beamlines' sample position. "The more the better, as the more intense the light is, the more experiments you can do more quickly," says Dr Iori. Further to the challenge of providing the experimental station with an intense beam of energy sufficient to enable researchers to look at highly absorbing samples, the overall design also has to comprise the sample station, where samples under investigation are rotated with respect to the incoming beam. Here, suitable detector assemblies record series of images, which in turn are used to reconstruct 3d tomography results. Also, the computing infrastructure needed to perform the necessary computations is part of the overall design. "Tomography beamlines produce huge amounts of data, in the region of several terabytes per day, so highly sophisticated computing is required," continues Dr Iori. "One important question is how fast can we do 3-dimensional reconstructions? This is about making the best possible use of all the information available."



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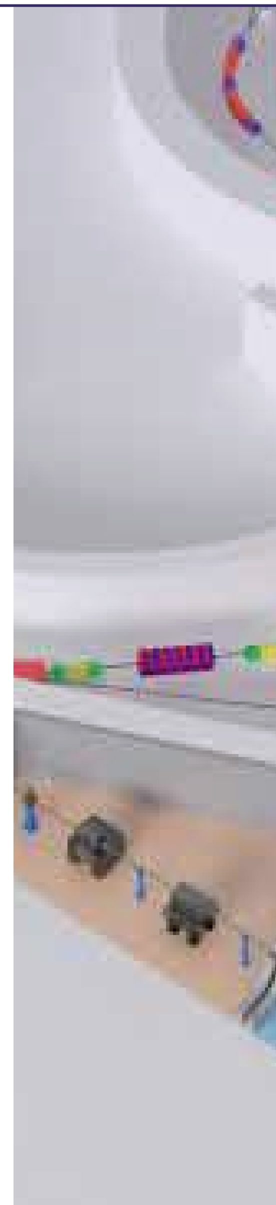
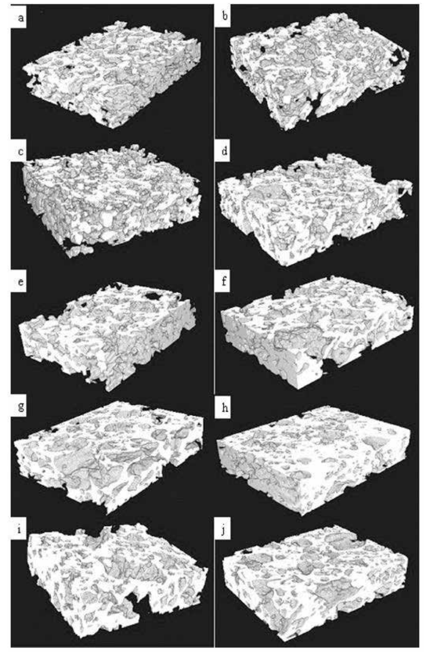


A further dimension of the project involves building up a community to use the beamline over the longer term. By heightening awareness of the beamline and the opportunities that it offers to researchers in cultural heritage and archaeology, the BEATS project aims to help put the facility on a sustainable long-term footing. "We need to let potential users know what the beamline can do," outlines Dr Andrea Lausi, Science Director of SESAME. The European Commission has a history of supporting the development of SESAME, and the emphasis now is on building local capacity to use and maintain the beamline, so reducing the need for outside support. "The ESRF was proposed as coordinator for this project, as they have a lot of recent experience in upgrading and constructing beamlines, which could benefit other synchrotrons. We learn from each other in this process," stresses Dr Lausi. "The project is based on three pillars of equal importance: i) design, construction, and commissioning of the beamline, ii) establishing means of sustainable operation and user community building, and iii) knowledge transfer between the partners of the BEATS project."

This is part of the wider aim of building capacity and opening up new opportunities for researchers, with the project bringing together partners from across the Middle East.



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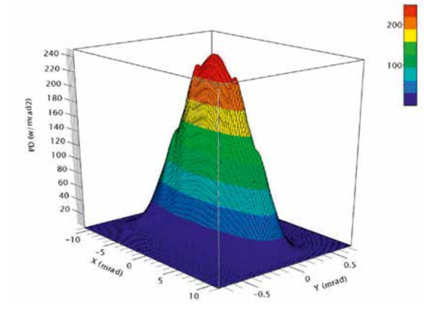

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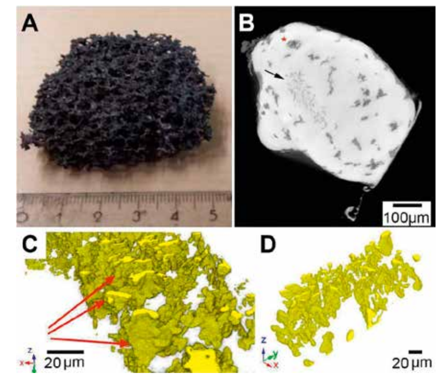

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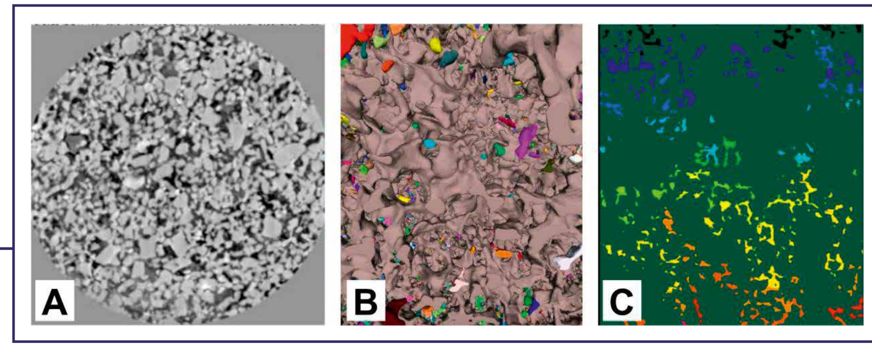
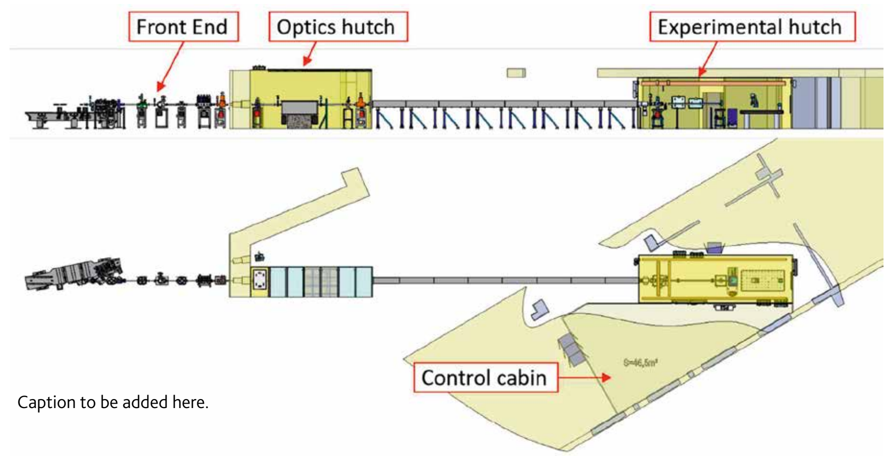


While researchers can apply for beamtime at other synchrotrons, Dr Lausi believes the local research community will benefit greatly from the addition of a hard X-ray tomography beamline at SESAME. "The best thing is that you have a beamline close by, then we can provide training on how to use it," he says. The beamline itself is quite versatile, and while it is intended primarily for cultural heritage and archaeology research, it has a wider range of potential applications, including in the oil and gas industry. "We cover the whole spectrum of problems related to determining the 3-D structure of a sample. That could be a painting, or composite materials," outlines Dr Lausi. "With X-ray tomography the sample comes back unharmed, which is very important for very rare cultural artefacts."

For the **sustainable operation** of a **synchrotron facility** it is important to have a certain number of **operational beamlines** that constitute a critical mass. Currently **SESAME is enhancing the number of beamlines** to go beyond this threshold.

New beamline

The project is set to conclude around the middle of 2023, when the new beamline becomes operational, yet this will not mark the end of collaboration between the BEATS project team and SESAME. The staff that have worked to



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BEATS

BEAmline for Tomography at SESAME

Project Objectives

The BEATS project has the aim to design, procure, construct and commission the first beamline for X-ray tomography in the Middle East. The main objectives include developing the scientific case and building a user community, ensuring the transfer of knowledge to SESAME staff and addressing the issue of sustainability and post-project operation of the beamline.

Project Funding

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Project Partners

https://beats-sesame.eu/partners/

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Axel Kaprolat

Axel Kaprolat started his career as a solid state matter experimental physicist and worked in several third generation synchrotron sources before joining the ESRF in 2002. He evolved towards the coordination of scientific projects with collaborating researchers. In recent years, he has coordinated several European projects, today focussing on BEATS.

BEATS

European Commission | Horizon 2020 European Union funding for Research & Innovation

BEATS Team

create the beamline will continue to support its operation beyond the end of the project, an approach that aligns well with the overall mission of the ESRF, which includes fostering research using synchrotron radiation. The construction of a further beamline at SESAME, with a growing community of users, will also help strengthen the facility as a whole and put it on a more stable footing, less vulnerable to shifting priorities.

This will help secure the long-term future of SESAME and widen the opportunities available for researchers across the Middle East, a region with a rich cultural and archaeological heritage. While SESAME itself is based in Jordan, eight member countries contribute to its funding, including several with a history of tense relations, reflecting the founding spirit of the facility. "This spirit is about bringing people together to work on similar scientific projects for the benefit of humanity," says Dr Kaprolat. The European Organisation for Nuclear Research (CERN) was founded in a similar spirit in the aftermath of the Second World War, and Dr Kaprolat says the two institutions are linked in other ways. "Traditionally the President of the Council of SESAME is always a former Director-General of CERN. The development of SESAME has been guided by Unesco," he outlines.

The long-term hope is to build more beamlines at SESAME, further diversifying the reach of scientific research and helping to secure its future as part of a wider network of facilities. Compared with other synchrotron facilities, SESAME currently has a rather low nominal annual budget. "BEATS will be the fifth beamline to enter operation at SESAME" continues Dr Kaprolat. "The hope is that the addition of more beamlines over the next few years would strengthen the position of SESAME in the global and regional research landscape"

This has been the experience of many European synchrotrons, which started with a relatively small number of beamlines and then gradually grew over time. Staff from well-established synchrotrons in other parts of the world have made important contributions to BEATS, sharing their knowledge and expertise. "Coordinating this kind of project is a challenge, as it involves partners from several countries and cultures as well as using various different technologies, but it has been rewarding. The partners have worked very well together in BEATS," says Dr Kaprolat.

BEATS: Supporting Scientific Excellence

SESAME (Synchrotron-light for Experimental Science and Applications in the Middle East) was officially opened in 2017. It is a 'third-generation' synchrotron light source and the region's first major international centre of excellence. Now, five years on, the BEATS project aims to further improve the facility, marking another step forward in its development.

This is very much a team effort, with scientists from different countries and cultural backgrounds working together and sharing ideas, helping to shape a truly world-class facility. The aim is to create a state-of-the-art beamline that can support research in not only cultural heritage and archaeology, but a wide range of other disciplines too, from geology to materials science.

The first two years of the project were devoted to the design of the beamline, but with the construction phase now underway, the vision is closer to becoming a reality. The beamline no longer exists just on paper or computer simulations, but is beginning to take tangible shape as the newest addition to the SESAME facility.

It's an exciting time for everybody involved in BEATS to see the design, drawings and calculations take form inside the SESAME storage ring and experimental hall. Many support teams work together during the machine shutdowns at SESAME to install equipment such as the source, vacuum chambers, front end, optics and experimental equipment. Several campaigns are planned, until around the Spring of 2023, before the beamline eventually enters operation.

This will mark the formal conclusion of the BEATS project, but also the start of a new era at SESAME, with the addition of a tomography beamline opening up new opportunities for researchers across the Middle East. This will ultimately support scientific excellence in the region and help establish SESAME as an integral part of a wider global network of synchrotron facilities.