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ForMAX ENDSTATION – A NOVEL DESIGN COMBINING FULL-FIELD TOMOGRAPHY WITH SMALL- AND WIDE-ANGLE X-RAY SCATTERING

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Abstract

ForMAX is a new beamline at the MAX IV Laboratory for multi-scale structural characterization of hierarchical materials from nm to mm length scales with high temporal resolution. This is achieved by combining full-field microtomography with small- and wide-angle x-ray scattering (SWAXS) in a novel manner. The principal components of the endstation consist of two units of beam conditioning elements, a sample table, an evacuated flight tube and a detector gantry. The beam conditioning units include a diamond vacuum window, an attenuator system, a fast shutter, a slit collimation system, two sets of compound refractive lenses, three x-ray beam intensity monitors, a beam viewer and a telescopic vacuum tube. The sample table has been optimized with respect to flexibility and load capacity, while retaining sub-micron resolution of motion and high stability performance. The nine metre long and one metre diameter evacuated flight tube contains a motorised detector trolley, enabling the sample-detector position for small-angle x-ray scattering (SAXS) to be easily adjusted under vacuum conditions. Finally, a two metre high and two metre wide granite gantry permits independent and easy movement of the tomography microscope and wide-angle x-ray (WAXS) detector in and out of the x-ray beam. To facilitate propagation-based phase-contrast imaging and mounting of bulky sample environments, the gantry is mounted on motorized floor rails. All these characteristics will allow to combine multiple complementary techniques sequentially in the same experiment with fast efficient switching between setups. The ForMAX endstation is presently in the design and construction phase, with commissioning expected to commence early 2022.

INTRODUCTION

Many natural and man-made materials are hierarchical, exhibiting important structure at several different length scales. In order to understand the structure-function relationship in such materials, one needs to characterise the structure at all these different length scales with sufficient temporal resolution to follow processes *in situ*. The versatile ForMAX instrument will address this problem by combining two complementary techniques – full-field tomographic imaging on µm to mm and SWAXS on nm length scales.

The main technical challenge when combining full-field tomography and SAXS stems from space constraints behind the sample; in full-field tomography one monitors the x-ray beam transmitted through the sample in forward direction, while in SAXS one records the x-ray beam scattered at small angles $\leq 3^{\circ}$, i.e., in nearly forward direction. The novel approach at ForMAX is sequential tomography and SWAXS experiments, based on a motorized detector gantry that allows the tomography microscope (and WAXS detector) to be readily translated in and out of the x-ray beam, thereby allowing a fast and efficient switch of modes of operation.

In this conference paper, we outline the design of the ForMAX endstation. For an overview of the main components, see Fig. 1.

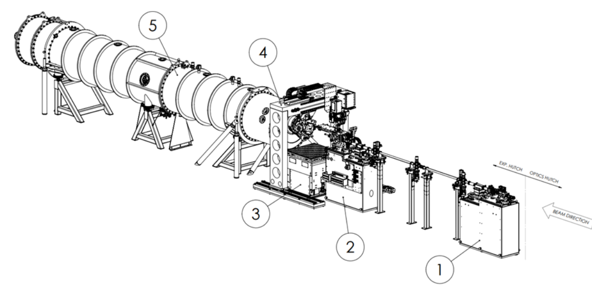

Figure 1: Main components of the endstation: (1) BCU I, (2) BCU II, (3) sample table, (4) detector gantry, and (5) flight tube.

BEAM CONDITIONING UNITS

Two beam conditioning units (hereafter BCU I and BCU II), located upstream of the sample table, include elements and equipment needed for fine-tuning the beam characteristics (final size, microfocus, beam positioning, attenuation, etc.) for each experiment performed in the endstation. Both units consist of two independent granite blocks grouted to the floor and with the different elements mounted on the top surfaces, facilitating alignment with the beam.

BCU I is located 5 metres upstream of the sample table and includes a diamond vacuum window, an attenuator system, a fast shutter, horizontal and vertical slits and a set of beryllium compound refractive lenses (CRLs). The CRLs permit expansion of the beam during tomography experiments and their position is motorized in order to facilitate alignment in the beam.

BCU II is located directly upstream of the sample table and includes a motorized set of CRLs for microfocusing during SWAXS experiments, a beam diagnostic module, horizontal and vertical slits and a telescopic vacuum tube, permitting the users to minimize the x-ray beam path in air. The beam diagnostic module includes three x-ray beam intensity monitors and a YAG crystal screen.

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All the elements of the BCUs are designed for operation under high vacuum. Table 1 shows the respective position of the elements from the beam source.

Table 1: BCU Elements and Their Distance From Source

BCU elements	Distance from source (mm)
Diamond window	35750
Attenuator system	35900
Fast shutter	36100
Slits (BCU I)	36300
Tomography CRLs	36500
µfocus CRLs	40500
Beam diagnostic module	40700
Slits (BCU II)	41500
Telescopic vacuum tube	41600-42000

SAMPLE TABLE

The sample table, centred at 42 metres downstream of the source, will support the sample environments, sample manipulation stages and other equipment needed to perform SWAXS and tomography experiments. It has an available top surface of 800 × 800 mm and permits positioning of the sample environment in vertical, lateral and pitch. It is based on the "skin" concept design developed at the ALBA Synchrotron, which provides high stability and excellent resolution performances [1].

It consists of a granite block base grouted to the floor with two movable lateral plates driven by ball screws with linear guides actuated by stepper motors. Lateral plates are linked together by a top plate articulated by flexure hinges, providing vertical and pitch motions. The lateral motion stage, also driven by a ball screw with linear guides, is added on top of the previously described assembly. The granite block functions as a stable and stiff reference for the whole system. The ball screws have low axial clearance in order to assure good repeatability, while the linear guides are slightly preloaded for stiffness. Finite element analysis (FEA) shows the first mode of vibration to be above 65 Hz.

Table 2 shows the range and resolution for the respective motions of the sample table. The load capacity of the table is 200 kg.

Table 2: Ranges and Resolutions of Sample Table Motions

Axis[1]	Range	Resolution[2]
X	±100 mm	0.3125 µm
Y	±105 mm	0.3125 µm
Pitch	±10 mrad	0.42 µrad

DETECTOR GANTRY

The granite detector gantry is located around the sample position, 42 metres from the source. The tomography microscope and the WAXS detector, both commercial but specifically designed for the ForMAX beamline, will be mounted on the gantry. Two independent linear stages, installed on the gantry lintel, permit easy and independent lateral movement of microscope and detector, in and out of the beam. Additionally, two independent vertical stages permit vertical adjustment of the microscope and the detector. The whole system is mounted on motorized floor rails. All the stages consist of low axial clearance ball screws and preloaded linear guides driven by stepper motors.

The motorized floor rails along the beam (between 41 and 42.5 metres from the source) facilitate propagation-based phase-contrast imaging and mounting of bulky sample environments on top of the sample table. Furthermore, the two independent lateral linear stages allow users to combine multiple complementary techniques sequentially in the same experiment, with fast efficient switching between modes of operation. The range and resolution for the respective motions of the detector gantry are shown in Table 3.

Table 3: Ranges and Resolutions of Detector Gantry Motions

Axis[1]	Range	Resolution[2]
Gantry Z	1500 mm	10 µm
WAXS X	670 mm	10 µm
WAXS Y	±10 mm	10 µm
Microscope X	670 mm	1 µm
Microscope Y	±15 mm	1 µm

The overall design is optimized to permit free access for users to the sample table from the outboard side of the end-station.

The system includes three modes of operation. First, a parking mode where the gantry is in an upstream position with the microscope and detector out of the beam and their lateral motions are disabled, thus avoiding collisions with BCU I. Second, a microscope operation mode with the WAXS detector in parking position. In this case only the lateral motion of the detector is disabled and any collision with the flight tube is avoided. Third, an operation mode where the microscope and the WAXS detector are free to move in and out of the beam. Detector gantry is shown in Fig. 2.

[1] With Z axis following beam direction, Y axis vertical direction and X axis perpendicular to both.
[2] Resolution defined as minimum incremental motion per full step.

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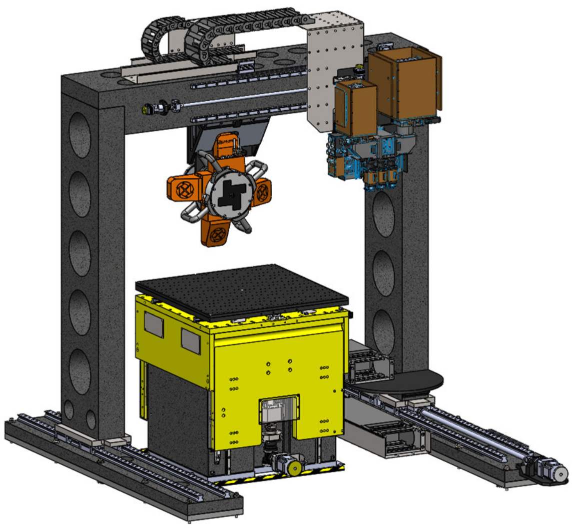

Figure 2: Sample table, detector gantry, tomography microscope and WAXS detector.

FLIGHT TUBE

A critical component of the endstation is the evacuated flight tube between the sample and the SAXS detector, which minimizes parasitic scattering and absorption of the x-ray beam between the sample and the detector. The flight tube consists of a stationary, eight metre long and one metre diameter vacuum chamber, with the SAXS detector installed inside it on motorized rails.

Similar flight tube concepts have been developed at other SAXS beamlines [2]. The vessel is built up of five sections: a 1 metre long upstream end section, two 0.5 metre long downstream end sections, and two long middle sections with a combined length of 6 metres. The two downstream end sections can be easily removed for maintenance tasks. Additionally, the flight tube is equipped with a quick release door in the upstream and inboard side. For an overview of the flight tube, see Fig. 3.

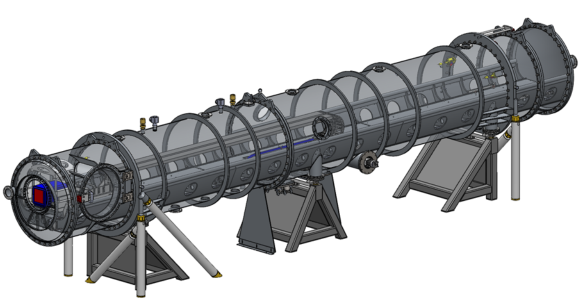

Figure 3: Flight Tube and SAXS detector.

The motorized rails along the beam are driven by a belt system and a servo motor located outside of the vacuum chamber by means of a rotary feed-through. The whole system is supported by a rigid girder mechanically decoupled from the vacuum chamber through vacuum bellows. This characteristic keeps the girder isolated from the vibration behaviour of the vacuum chamber. Moreover, the SAXS detector is equipped with two additional motions, vertical and lateral, for adjusting position in the beam.

Personal safety is guaranteed by the MAX IV Personal Safety Systems. A search procedure and emergency pull-wire switches inside of the chamber guarantee no personnel can be trapped inside. The flight tube is designed for operation under rough vacuum.

CONCLUSIONS

We have presented the ForMAX endstation, with a focus on the novel design for multi-scale structural characterization by combined full-field tomography and SWAXS. The versatile sample table and flight tube designs will permit state of the art SWAXS experiments to be performed with a wide range of different sample environments. The detector gantry will allow full-field tomography and SWAXS experiments to be combined sequentially in the same experiment with fast and efficient switching between setups. The ForMAX endstation is presently in the design and construction phase. Commissioning and user operation is expected to commence early and autumn 2022, respectively.

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