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DESIGN OF INDIRECT X-RAY DETECTORS FOR TOMOGRAPHY ON THE ANATOMIX BEAMLINE

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Abstract

ANATOMIX is a new beamline for full-field tomography techniques at the French synchrotron SOLEIL. It will operate at photon energies from 5 to 30 keV and feature several operation modes via versatile optics configurations, including direct propagation of the polychromatic ("white") undulator beam to the experiment position. Two different experimental methods will be used: parallel-beam X-ray shadowgraphy, for spatial resolution down to the sub-micron range, and full-field transmission X-ray microscopy down to a spatial resolution of less than 100 nm. To cover the large panel of experimental possibilities, four dedicated indirect X-ray detectors have been designed. For pixels in the sub-micron size range, a micro-tomography revolver camera for versatility, a high-efficiency camera for flux-limited experiments, and a high-resolution camera for the largest optical magnifications will be available. For experiments with a large X-ray beam and pixel sizes from several microns upward, a "large-field" camera completes the set.

INTRODUCTION

Indirect X-ray image detection is the standard concept used today for full-field tomography techniques on hard X-ray synchrotron beamlines. Detectors based on this principle have been commonly used for 20 years [1,2]; they can be in-house developments [3-4] or commercially supplied (for example from Optique Perter, Lentilly, France or Hamamatsu Photonics, Hamamatsu, Japan). They convert the X-ray image to visible light with a scintillator screen and project the visible-light image on the sensor of a digital camera using visible-light lenses.

To match the large variety of needs of the new tomography beamline ANATOMIX [5] at the French synchrotron SOLEIL, the Detector Group, the Mechanical Engineering Group and beamline team have designed four models of indirect detectors. The "Revolver X-Ray Camera", a versatile assembly composed of a revolving cylinder with four microscope objectives, the "High-Resolution X-ray Camera" equipped with a very high resolution microscope objective, the "High-Efficiency X-ray Camera" for applications limited by X-ray flux and the "Large-Field X-Ray Camera" for fields of view of several centimeters width. Each of these models accepts different digital cameras and, with the exception of the "high-resolution" model, all are compatible with the intense white X-ray beam. In this article, we report on the different designs with the detailed components and expected performance of each solution.

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INDIRECT X-RAY CAMERAS

Common Specifications

All X-ray detectors have been made to be easily customizable. The camera, objective, scintillator or mirror can be simply disassembled and changed.

The four X-ray detectors can accept different models of commercially-available digital cameras which can be plugged through a standard support (Fig. 1). Three different camera models are currently used at the beamline to cover the range of parameter space required by the user community.

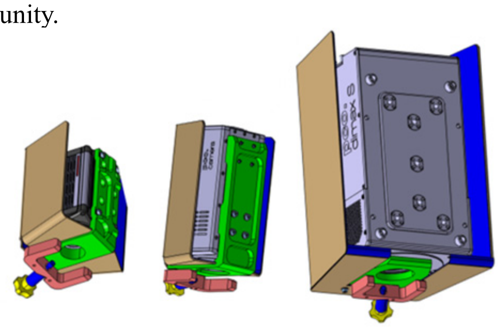

Figure 1: Standard camera support for ANATOMIX X-ray detectors. Left to the right: ORCA Flash4, PCO4000 and DIMAX HS4.

Firstly, the ORCA Flash 4 (Hamamatsu Photonics, Hamamatsu, Japan), with a scientific CMOS sensor array of 2048×2048 pixels of relatively small size of (6.5 µm) is a polyvalent camera with low readout noise (1 e^- rms) and high frame rate of 100 Hz. Secondly, the DIMAX HS4 (PCO AG, Kelheim, Germany), a high-speed CMOS camera with 2 kHz frame rate, 2048×2048 pixels (11 µm pixel size), especially used with the high X-ray beam flux to preform very quick tomography. Finally, the PCO 4000 based on a large CCD sensor (4008×2672 pixels of 9 µm size, sensor area 36×24 mm²) with a low dark noise < 0.05 e^-/s. The camera bracket support is installed on a motorized rotation stage to align the pixel matrix with the tomography rotation axis (Fig. 2b).

The detectors (excepting the "high-resolution" model) have been also made to accept a polychromatic X-ray beam, so as to prevent radiation damage in lenses or electronics; all models have an L-shaped optical path, with the camera placed vertically, away from the X-ray beam path. A mirror between the scintillator screen and the objective redirects the visible light path toward the sensor (example in Fig. 2d for the revolver camera). The objectives are protected by millimeter-thick lead-glass windows which absorb the X-ray scattering from the air and mirror while remaining totally transparent to the visible.

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Furthermore, a large lead frame around the objective and the camera has been added. Finally, the scintillator screen can be flushed with an inert gas to prevent degradation, especially with the white X-ray beam (Figs. 2e & 4).

The scintillator screen material is chosen as a function of the X-ray photon energy and the flux. The single-crystal scintillator materials used include YAG:Ce or LuAG:Ce supplied by Crytur (Turnov, Czech Republic) or LSO:Tb supplied by the ESRF (Grenoble, France) [6]. The scintillator thickness is optimized so as not to affect the effective spatial resolution [7].

The "Revolver X-Ray Camera"

The ANATOMIX "Revolver X-Ray camera" (Fig. 2a) is a modular indirect detector for microtomography at sub-micrometer pixel size. Its scintillator can be adapted to the experiment needs; typically, it is a thin freestanding YAG:Ce or LuAG:Ce crystal down to 20 µm thickness. The orientation of the scintillator support is adjustable in the two tilt axes (Fig. 2e). Four microscope objectives are mounted vertically into a motorized cylinder that allows easy selection and change of objective (and, thus, magnification) (Fig. 2c). The objective is focused to the scintillator screen through a mirror by a fine motorized translation. The objectives used in the revolver model are infinity-corrected with a working distance down to 20 mm. Especially, the Mitutoyo (Kawasaki, Japan) objectives as the M PLAN APO with a magnification of 2× to 10× and the super long working distance M PLAN APO SL 20× coupled with a tube lens ×1 can be installed. Between the microscope objective and the tube lens, a filter can be added to select the scintillation wavelength range used via a fine bandpass. Three different filters are mounted in a manually-rotated cylinder.

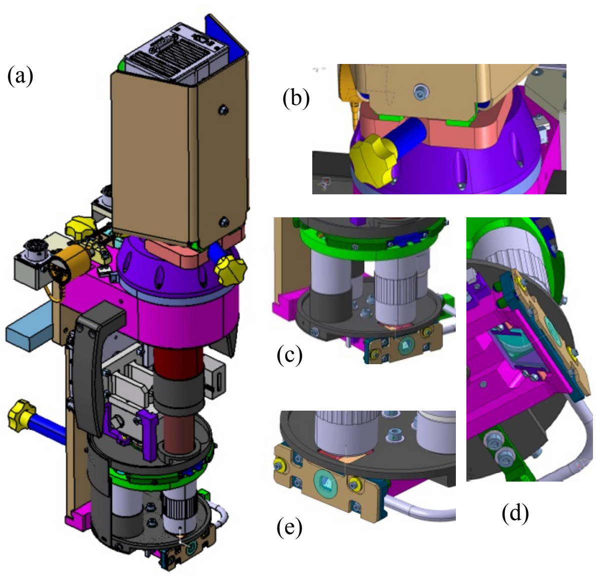

Figure 2: Revolver X-Ray Camera. (a) Complete system coupled to the PCO 4000. (b) Camera rotation stage. (c) Cylinder with four objectives mounted. (d) Support of 45° glassy carbon mirror. (e) Scintillator support, inert gas entrance tube and lead glass emplacement.

Then, the revolver X-ray camera is a relatively compact system with a large modular configuration possible.

Coupled with the ORCA Flash 4, effective image pixel sizes can be realized in a range between 3.25 and 0.325 µm, with an effective resolution of 1 µm (value for the MTF at 10 % with Mitutoyo ×10 with NA 0.28 and a scintillator thickness of 20 µm).

The "High-Resolution X-Ray Camera"

The ANATOMIX "High-Resolution X-Ray Camera" (Fig. 3a) gives access to very high-resolution objectives, that means with a very high Numerical Aperture, but with a very short working distance. The optical design is similar to that of the Revolver X-Ray Camera but the mirror is placed between the tube lens and the camera. This means that the objective lens is in the beam propagation axis and the working distance is not limited by the mechanic. Objectives compatible with this model are the 20×, 50× or 100× and also the high-resolution objectives such as HR 5×, HR 10× or HR 50× from Mitutoyo. The design is made to be very rigid with optimized alignment of the different planes (sensor, objective and scintillator). Coupled with the ORCA Flash 4 CMOS camera and a very thin scintillator layer (<1 µm) on a substrate, the spatial resolution expected with this design should attain values smaller than 1 µm.

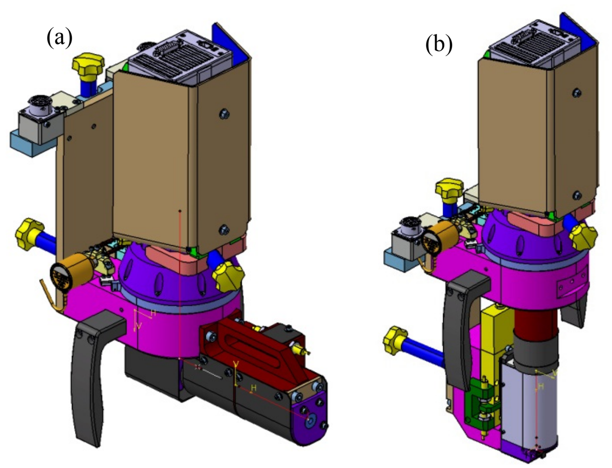

Figure 3: (a) High-Resolution and (b) High-Efficiency X-Ray Camera, both shown with the ORCA Flash 4.

The first test result (Fig. 4) using a 20× objective, at 10 keV photon energy, shows a resolution of 0.5 µm on a test chart (model XRESO-100 from NTT-AT, Kawasaki, Japan).

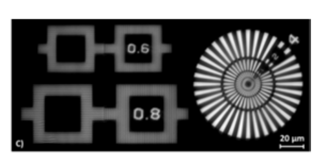

Figure 4: Radiograph of an X-ray test chart (NTT XRESO-100) with the High-Resolution X-ray Camera.

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The "High-Efficiency X-Ray Camera"

The ANATOMIX "High-Efficiency X-Ray Camera" (Fig. 3b) bears features of both the revolver and the "high-resolution" designs. It differs from the revolver model by a smaller and lighter design but keeping the protections against X-ray scatter radiation. Only one microscope objective can be mounted but the minimum working distance is shorter to accept objectives with very high numerical aperture, such as the Mitutoyo HR10×.

This detector is optimized to collect a maximum of visible light from the scintillator and is primarily aimed at application in low-flux experiments, such as full-field transmission X-ray microscopy. A small mirror is placed between the scintillator and the objective, and the scintillator support is positioned very close to the mirror without any position adjustment. Coupled with the ORCA Flash 4 camera, the resolution is limited but allows a two times higher sensitivity than with the classical 10× objective.

The "Large-Field X-Ray Camera"

The ANATOMIX "Large-Field X-Ray Camera" (Fig. 5) completes this panoply of indirect X-ray detectors with a design aimed at imaging a large field of view. The optical design is based on a tandem of photographic objectives with high aperture and very low distortion (Hasselblad, Gothenburg, Sweden). The design delivers an efficient detector for magnifications down to 0.48×. Coupled with the PCO 4000 camera, the field of view is 74 mm (H) × 51 mm (V). On the beamline, the field of view is actually limited by the X-ray beam size (57 mm × 18 mm, H×V).

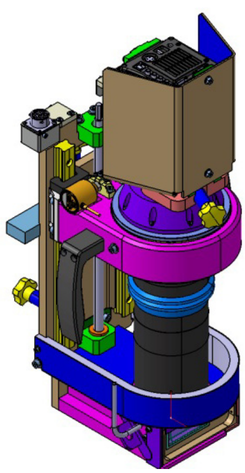

Figure 5: Large-Field X-Ray Camera (shown with Hamamatsu ORCA Flash 4 camera).

CONCLUSION

Four dedicated indirect X-ray detectors have been designed for new tomography beamline ANATOMIX at SOLEIL. A summary of the specifications and elements is given in **ANNEX A, Table 1**. These detectors match the wide variety of scientific requirements on the beamline; they remain totally upgradable for new generations of cameras, scintillators or lenses. The first specimen of the High-Resolution model is currently under commissioning.

ACKNOWLEDGEMENTS

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ANNEX A

Table 1: Main Specifications of the ANATOMIX Indirect X-ray Detectors

X-ray camera	Large Field	Revolver	HR	HE
X-ray beam type	10 keV – 30 keV Pink or monochromatic beam			
Objectives WD (mm)	≥ 60 mm	≥ 20 mm	≥ 1 mm	≥ 15 mm
NA	0.1 to 0.22	0.05 to 0.28	0.42 to 0.75	0.42
Mag.	0.48× to 3.5×	2× to 20×	2× to 100×	10× to 50×
Expected resolution	10 µm	1 µm	< 1 µm	1 µm
Scintillator material	LuAG:Ce, YAG:Ce, LSO:Tb, …			
Scinti. thickness	1000 µm down to 60 µm	250 µm down to 20 µm	Down to few µm on substrate	20 µm
Camera	Hamamatsu ORCA Flash 4 v2, PCO 4000, PCO DIMAX HS4 and other camera with T-mount.			
Other specs	Camera motorized orientation Fine focus motorized adjustment Lead glass & lead shielding Inert gas input			