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Coherent Hard X-ray Multiprojection Imaging

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Three-dimensional (3D) and dynamical understanding of nature is crucial to address scientific questions. Hard X-rays with their penetration power and short wavelengths offer a unique opportunity to study systems in a non-destructively manner in their native environments at resolutions up to the atomic scale. Well-established 3D approaches like tomography [1] or confocal microscopy [2] scan the sample angularly or through the focus, respectively, requiring long acquisition times and limiting the temporal resolution to milliseconds. On the other hand, single-view 3D approaches, like ankylography [3], have the potential to retrieve microseconds temporal resolutions exploiting the MHz repetition rate of storage rings and novel X-ray free-electron lasers (XFELs) like the European XFEL up to femtoseconds resolution using single pulses. Nevertheless, approaches like ankylography are only applicable to objects which are approximately two-dimensional [4]. Here we present a novel X-ray imaging technique which acquires simultaneously up to nine projections of the object at significant tomographic angles allowing the study of relevant 3D processes at microseconds to femtoseconds temporal resolutions. We confirm the capability of the proposed technique to generate nine beams from a single incoming beam using a crystal as beam splitter. We have performed synchrotron experiments which provide a preliminary demonstration of the capabilities of this setup to retrieve different projections and resolutions of the object with two different imaging techniques: i) propagation-based phase-contrast X-ray imaging with micrometers resolution and ii) coherent-diffraction imaging with nanometers resolutions. We anticipate our work to be the starting point to develop instruments at diffraction limited synchrotrons and XFELs capable to study 3D processes from microseconds to femtoseconds and micrometers to nanometers.

The key element of our multiprojection approach is to design a beam splitter which generates several beams at relevant tomographic angles for hard X-rays. We have achieved this goal by using silicon or diamond (face-centered-cubic lattice) crystals as beam splitters. In general, one cannot achieve more than two deflected beams with a crystal. Thus, to generate multiple beams, one has to exploit the symmetries of the crystal lattice, which at specific X-ray energies can set a family of crystallographic planes in Bragg condition. For example, eight deflected beams can be generated by the family of planes (131) for silicon and diamond. Specifically, for the case of silicon at 12.57 keV the eight beams will be deflected 35.1º respect to the direct beam as depicted in Fig. 1. Table 1 reports different crystallographic families for silicon and diamond which produce several beams at hard X-ray energies with relevant diffraction angles.

Reflection	Symm. Direction	Refl. multiplicity	Energy (keV)	Deflection angle
Si (131)	(001)	8	12.57	35.1 º
Si (331)	(001)	8	13.7	48.2 º
C ($\bar{3}$11)	(011)	6	13.52	50.5 º
C (1$\bar{1}\bar{1}$)	(111)	3	9.03	38.9 º
C ($\bar{1}$1$\bar{3}$)	(111)	6	11.04	63.0 º

Table. 1. Crystallographic families in Bragg reflection for diamond and silicon (face-centered cubic lattice) suitable for multi-beam generation for hard X-rays at relevant tomographic angles.

The presented multiprojection technique can be applied to retrieve three-dimensional information of an object from a single pulse using different imaging techniques. First, we have performed micrometer resolution experiments exploiting propagation-based phase contrast [5] at the TOMCAT beamline at the Swiss Light Source (SLS). From this experiment we have demonstrated the capability of this approach to retrieve 3D information from a single beam at the μm scale. Finally we have also performed a high resolution experiment at the ID-01 beamline at the European Synchrotron Radiation Facility (ESRF). Using the diffractometer and high coherence of ID-01, we have performed coherent diffraction imaging [6] experiments on the different beams produced by a silicon crystal at 12.57 keV, which were accessible by the diffractometer. We have successfully performed phase reconstructions on the different beams retrieving different projections of our studied sample positioned after the crystal and illuminated by the different beams. The reconstructions of the sample from the different beams have been compared with a three-dimensional simulation of the object. The results show good agreement at resolutions below 100 nm. Further results and reconstructions for both experiments will be provided during the presentation.

In view of the capabilities of this technique, we propose to implement this technique at diffraction limited synchrotrons like MAXIV and future upgrades of ESRF and PETRA IV. This technique will increase the time resolution of three-dimensional processes from millisecons to microseconds. Furthermore, this technique in combination with MHz free-electron lasers like the European XFEL and the future LCLS-II can provide three-dimensional characterization of non-reproducible samples and stochastic event from microseconds to femtoseconds resolution.

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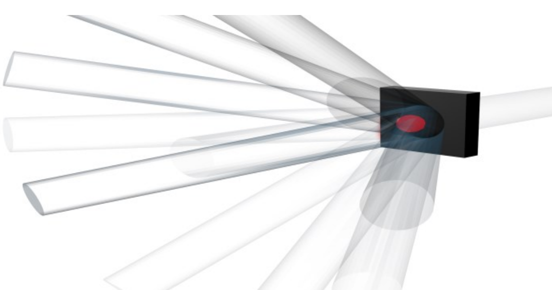

Figure. 1. Concept design for the used multiprojection-imaging setup. A crystal like silicon or diamond splits the incoming beam into 8 deflected beams, which illuminate simultaneously the sample.

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