MHz X-ray Tomoscopy: rotation-free 4D imaging with diamond Bragg beam-splitter optics at the European XFEL

Patrik Vagovič[1], Wolfgang Voegeli[2], Alexander Korsunsky[3], Jayanath Koliyadu[1], Pascal Kaul[4], Mohammad Shahsavari, Pontus Fischer[1], Daniel Mosko[5], Peter Szeles[6], Sotirios Damianos[7], Manolis Gavaises[8], Tomas Burian[9], Zuzana Kuglerova[10], Jaromir Chalupsky[10], Libor Juha[10], Yashiro Wataru[11], Hitoshi Soyama[11], Liubov Samoylova[12], Rita Graceffa[12], Luigi Adriano, Chan Kim[12], Igli Draci[6], Jozef Ulicny[6], Vid Angrez[13], Jaka Mur[13], Patricia Pfeiffer[14], Claus-Dieter Ohl[14], Egor Sobolev[12], Tomas Popelar[12], Richard Bean[12], Henry Chapman[15], Tokushi Sato[12], Daniel Eakins[16], Alke Meents[1]

[1] Center for Free-Electron Laser Science, DESY, Germany
[2] Tokyo Gakugei University, Japan
[3] Trinity College, United Kingdom
[4] Suna Precision GmbH, Germany
[5] University of Pavel Jozef Safarik, Germany
[6] University of Pavel Jozef Safarik, Slovakia
[7] City St George's, University of London, United Kingdom
[8] City St George's, University of London, Germany
[9] Institute of Physics, Czech Academy of Sciences, Germany
[10] Institute of Physics, Czech Academy of Sciences, Czech Republic
[11] Tohoku University, Japan
[12] European XFEL GmbH, Germany
[13] University of Liubliana, Slovenia
[14] University of Magdeburg, Germany
[15] Center for Free-Electron Laser Science CFEL, Deutsches Elektronen-Synchrotron DESY, Germany
[16] University of Oxford, United Kingdom

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Capturing three-dimensional dynamics that evolve faster than a sample can be rotated is a long-standing limitation of time-resolved X-ray tomography. Tomoscopy, volumetric imaging of fast dynamic processes, can be realised by fast sample rotation or, rotation-free, by simultaneous multi-projection imaging, originally proposed using Laue beam splitters. We present a rotation-free X-ray tomoscopy in which a cascade of thin diamond high-pressure high-temperature type-IIa crystals, operated in Bragg geometry, splits a single X-ray pulse into several mutually inclined, monochromatic beamlets and redirects them through a common point at the sample. Each beamlet is recorded simultaneously on its own ultrafast detector, so a complete set of angular projections of one identical sample state is acquired in a single exposure. Because every projection originates from the same pulse, the volumetric frame rate is set by the source repetition rate rather than by mechanical motion.

The crystal optics are central to the method. Operating in the vertical diffraction plane (sigma-polarisation, polarisation factor C = 1) and using diamond for its high reflectivity and thermal stability under the XFEL pulse train, the inline Bragg-splitter cascade is photon-energy tunable and scalable toward about ten projections at hard X-rays. This overcomes the low throughput and lack of photon-energy tunability of earlier Laue-splitter realisations of multi-projection imaging, which limited that approach at large-scale facilities. Here, the (111), (220), (311) and (422) reflections provide four simultaneous views at 10 keV.

We report the first fully functional four-projection MHz tomoscopy system at the SPB/SFX instrument of the European XFEL, developed within the EIC Pathfinder project MHz Tomoscopy, with first feasibility at the European XFEL and a subsequent synchrotron demonstration. At storage rings the roughly one billion photons per pulse provide only a million to ten million photons per beamlet, so imaging there must integrate over many pulses and is confined to kilohertz rates. Exploiting the high single-pulse flux of the XFEL, tomoscopy reconstructs a full volume from every femtosecond pulse at the 1.128 MHz intra-train rate, two to three orders of magnitude faster. Using inline phase contrast and per-pulse reconstruction, we follow the complete nucleation, expansion and collapse of a laser-induced cavitation bubble in water. Tomoscopy further offers an intrinsic split-and-delay capability, with geometrical inter-beamlet delays of about 50 to 500 picoseconds for single-shot imaging of ultrafast phenomena relevant to fusion research. The apparatus is protected by patent EP4160623A1.