

Picosecond Switching of X-rays using the Borrmann Effect

M.F. DeCamp,¹ D.A. Reis,¹ P.H. Bucksbaum,¹ R. Clarke,¹ R. Merlin,¹ A. Cavalieri,¹
A. Lindenberg,² A. MacPhee,² E.M. Dufresne,^{1,3} D.A. Arms^{1,3}, Z. Chang⁴

¹FOCUS Center, University of Michigan, Ann Arbor, MI, 48109

²University of California, Berkeley, CA, 94720

³MHATT-CAT, Argonne National Labs, Argonne IL

⁴Physics Department, Kansas State University, Manhattan, KS, 66506

Introduction

In time-resolved x-ray studies, the temporal resolution is often limited by the duration of the x-ray pulse. One method of generating an ultrashort x-ray pulse is to cut a 'long' synchrotron pulse using a fast x-ray switch. Previous work has demonstrated nanosecond switching of x-rays [1,2,3]. Recent work done by scientists at MHATT-CAT has demonstrated coherent switching of x-ray intensity on a sub-nanosecond timescale [4]. In that work, a fast transient effect following laser excitation was seen to switch the intensity between two diffracted x-ray beams. The measured time scale of this effect was limited by the ~100ps x-ray pulse duration of the APS. In this work, the transient is temporally resolved using an x-ray streak camera and is shown to be an efficient picosecond switch for monochromatic x-rays.

Methods and Materials

Coherent acoustic phonons are impulsively generated in a 280 μm thick sample of (001) Ge using a 50fs, 0.75mJ, 800 nm laser operating at 1kHz. The phonon wavepacket is spatially short compared to the x-ray scattering length (i.e. Pendellösung depth) and travels into the crystal bulk at the sound speed of the material. The laser system is phase-locked to the RF accelerating cavities of the APS to ~20ps. 10keV X-rays emitted from an undulator are spectrally filtered using a cryogenically cooled Si 111 monochrometer.

The Ge crystal is oriented in the Laue geometry to diffract from the asymmetric (202) diffraction planes. At the crystal output there exists two diffracted beams; a forward diffracted and a deflected diffracted beam. The Ge crystal is thick when compared to the x-ray absorption depth making normal x-ray transmission negligible. At the Laue condition, two linearly independent wave solutions propagate through the crystal. These two solutions are transverse standing waves of x-ray intensity. One solution has its nodes lie in regions of high electron density, i.e. the lattice planes. This has the effect of producing an x-ray waveguide such that the x-ray intensity may be transmitted through 'thick' crystals with very little attenuation, this is known as the Borrmann effect. The other solution has its anti-nodes lie in regions of high electron density, thus it propagates with enhanced absorption.

The temporal response of the forward diffracted beam to the acoustic pulse is measured using a picosecond x-ray streak camera operating in averaging mode resulting in a temporal resolution of ~5ps [5].

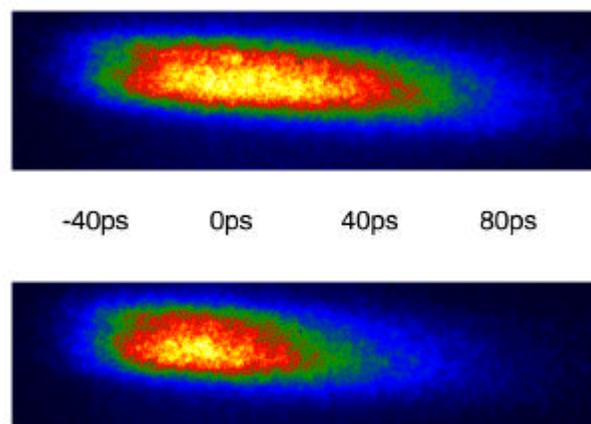


Figure 1. Streak camera images of the transmitted x-ray pulse. Undisturbed crystal (top), Laser excited crystal (bottom). 0ps corresponds to the laser arrival time.

Results

Figure 1 shows time-resolved diffraction data from the x-ray streak camera. The top figure is the streak image of an x-ray pulse after traversing the unperturbed crystal. The effective x-ray pulse width emitted from the APS is ~100ps FWHM. Upon laser excitation, the disturbed crystal switches the x-ray intensity of the forward-diffracted beam. Up to 75% of the incident x-ray intensity is switched off in <40ps, effectively reducing the x-ray pulse width to ~60ps. This energy loss is recovered by the deflected diffracted beam, which increases at the same rate. Rotating the crystal to diffract in the opposite asymmetry produces the opposite effect; the increase of x-ray intensity of the forward diffracted beam is on a 40ps timescale. Other crystalline compounds have demonstrated switching times as fast as 15ps. Both the switch efficiency and time constant are dependent on the incident optical intensity.

Discussion

In dynamical diffraction, the natural length scale of diffraction is the Pendellösung depth. To efficiently switch x-rays with acoustic disturbances, the short acoustic pulse must travel into the crystal about one quarter of a Pendellösung depth, or about ~400ps for the current conditions [4]. The observed picosecond time dependence, however, indicates that a strain pulse propagates at supersonic speeds.

Because the laser photon energy is larger than the bandgap in Ge, a large fraction of the optical intensity is absorbed on the crystal surface. This leads to the generation of an electron-hole plasma at the crystal surface [6]. To relieve the density gradient of the electron-hole plasma, the plasma diffuses rapidly into the crystal bulk. The propagation speed of the resulting strain field is governed by ambipolar diffusion of the laser-generated electron-hole plasma, which is much larger than the acoustic velocity. As the electron plasma propagates into the crystal, a strain field is generated deep within the crystal. This strain changes the diffraction enough to change the relative intensities of the diffracting beams. This ambipolar diffusion is suggested to be the method by which this fast switching transient is generated.

Further improvements to the experiment, including generating coherent lattice motion at THz frequencies, have the potential of generating a sub-picosecond x-ray switch.

Acknowledgements

This work was conducted at the MHATT-CAT 7ID beamline at the Advanced Photon Source and was supported in part by the U.S. Department of Energy Grants DE-FG02-00ER15031 and DE-FG02-99ER45743 and from the NSF FOCUS Physics Frontier Center. We thank Lawrence Berkeley National Lab for allowing use of the picosecond streak camera. We would also like to thank Jin Wang for allowing us to use the Andor CCD camera. Use of the Advanced Photon source was supported by the U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

References

- [1] A. Hauer and S. Burns, *Appl. Phys. Lett.* **27**,526 (1975).
- [2] A. Hauer, U.S. Patent No. 3991309, (1976)
- [3] J.S. Wark, A. Hauer, and J.D. Kilkenny, *Rev. Sci. Instr.*, **57**, 2168-2170 (1986).
- [4] M.F. DeCamp *et al.*, *Nature*, **413**, 825 (2001).
- [5] J. Larsson *et al.*, *Opt. Lett.*, **22**, 1012 (1997).
- [6] J.F. Young and H.M. Van Driel, *Phys. Rev. B*, **26**, 2147 (1982).