PHASE CONTRAST IMAGING USING A SINGLE PICOSECOND X-RAY PULSE OF THE INVERSE COMPTON SOURCE AT THE BNL ACCELERATOR TEST FACILITY*

M. Carpinelli, P. Oliva, B. Golosio, Università di Sassari and INFN, Italy
I. Pogorelsky, V. Yakimenko, Brookhaven National Laboratory, Upton, NY, USA
P. Delogu, Università di Pisa and INFN, Italy
M. Endrizzi, Università di Siena and INFN, Italy

Abstract

Inverse Compton scattering (ICS) X-ray sources are of current interest due to their novel features that enable new methods in medical and biological imaging. As a compelling example of such a possibility, we present an experimental demonstration of single shot inline phase contrast imaging using the ICS source located at the BNL Accelerator Test Facility. The phase contrast effect is clearly observed in the obtained images. Further, its qualities are shown to be in agreement with the predictions of theoretical models through comparison of experimental and simulated images of a plastic wire. A phase-retrieval algorithm is used in the image processing to obtain an accurate estimation of the projected thickness of our sample. We also display an example of application of the technique to single shot phase contrast imaging of a biological sample.

INTRODUCTION

Inverse Compton Scattering (ICS) sources are capable of producing very short X-ray pulses characterized by high flux and brightness, tunable energy, quasi-monochromatic spectrum and small spot size. These properties can be exploited to realize high-quality X-ray imaging of particular interest for the biomedical applications [1, 2]. An application to in-line phase contrast imaging is here presented. In ICS sources photons are produced by the interaction of a laser beam with a highly focused electron beam [3]. If the electrons are ultra-relativistic the scattered radiation undergoes a strong upshifting frequency, and is predominantly emitted in a narrow cone of forward angles, less than γ^{-1} with respect to the motion of the particles [4]. Several ICS sources have been developed or are under development [1, 5, 6]. They are in principle characterized by high flux and brightness, quasi-monochromatic spectrum in the angular region $\theta < \gamma^{-1}$ with tunable mean energy, small source size and very short (few ps) pulses. Due to the small source size of ICS sources, it is possible to perform inline phase contrast (PhC) imaging, that allows enhancement of the resolution of low-contrast details, by detecting the phase shift together with absorption of the interacting X-rays [7]. Ikeura-Sekiguchi, et al., [8] have shown PhC images of rat lumbar vertebrae obtained at National

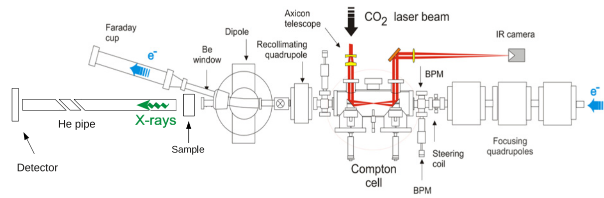

Figure 1: Schematic of the Inverse Compton source and beamline at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory.

Institute of Advanced Industrial Science and Technology (Japan) with 18,000 shots (total exposure time 54 ns and total elapsed time 1800 s). However, if the required number of photons is delivered in a single-shot, the pulsed nature of the beam opens the window to time-resolved imaging of fast processes. For example, living objects can be imaged without any artifact due to the motion. In this paper we show results of single-shot inline phase contrast imaging preformed at the inverse Compton source available at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory [6]. The parameters of the ICS source were optimized in order to maximize the peak brightness of the source with sufficiently large number of photons of the X-ray beam for the single shot operation. In order to evaluate the PhC effect using this source, we have produced radiographic images of a plastic wire. The experimental results obtained are compared with simulation of the expected signal. Phase retrieval algorithms enable the recovery of quantitative information from phase-contrast images. In this paper we use phase retrieval to accurately estimate the projected thickness of our sample [9].

Finally, to illustrate the biological imaging possibilities enabled by this kind of source, we show a single-shot image of a wasp.

EXPERIMENTAL SET-UP

Figure 1 depicts the experimental layout: the X-ray are generated inside the Compton chamber by a head-on collision of a bunch of relativistic electrons with an intense laser pulse. After the interaction the electron beam is deflected

* Work supported by INFN and Università di Sassari

by a dipole magnet into the beam stopper while the X-ray beam exits through the Be window and reaches the sample. A helium-filled pipe minimizes the intensity losses due to absorption while the beam propagates towards the X-ray detector. For a more accurate description of the beamline we refer the reader to a previous work [6]. The X-ray detector is a flat panel composed by a CMOS sensor and micro-columnar CsI scintillator (Hamamatsu C9728DK-10). The pixel size is 50×50 μm and the active area is about 5×5 cm. The detector has been characterized with respect to its Line Spread Function and energy response in order to perform quantitative measurements.

The X-ray beam used in this experiment provides about 2×10^8 photons/pulse with a divergence of 5 mrad, a peak energy of about 10.4 keV and an energy spread of about 0.6%. The pulse duration is about 1 ps. The estimated number of photons scattered into 1 mrad^2 is about 2×10^6 per pulse. The flux density for a single-shot is approximately 7×10^{16} ph. s^{-1}mrad^{-2}(0.1%bw)$^{-1}$.

The simplest phase-sensitive X-ray imaging method is the free-space propagation, or inline phase contrast technique [7]: the sample is positioned between the source and an imaging detector. X-rays interact with the sample and different variations of the phase of the radiation are induced by the details. The resulting interference patterns increases the visibility of the border of structures inside the object having a refractive index different from adjacent material. This increase of the contrast over that of conventional radiographic images is called edge-enhancement effect.

RESULTS

A single-shot exposure of a PMMA (polymethyl methacrylate) wire with diameter 1124 μm is shown in Fig. 2; the image is only corrected for the dark current. The intensity distribution without the object is estimated with a two-dimensional Gaussian fit using all the pixels that do not contain any sample detail. With this approximation to the fat-field the raw image can be equalized. The fitting procedure for the flat-field is required due the shot-to-shot fluctuations of the beam (intensity, position and shape). A simulation is also compared to the normalized intensity profile. In Fig. 2a the wire profile, together with the simulated one are presented. The raw (2b) and normalized (2d) experimental images are also shown, together with the corresponding simulated images (2c and 2e respectively). The source is modeled as a superposition of independent point sources, Gaussian distributed with a Full Width Half Maximum of 80 μm. The spectrum is chosen as quasi-monochromatic with mean energy 10.4 keV and standard deviation 0.04 keV. The detector Line Spread Function is modeled with two Gaussian functions (σ 93 and 238 μm relative amplitude 0.4). The normalized intensity profile is then processed with a phase-retrieval algorithm [9] based on the monochromatic Transport of Intensity Equation (TIE) for a homogeneous object. From the phase-retrieved image the projected thickness of the wire can be accurately estimated as shown in Fig 3. A single-shot image of a wasp is shown in Fig 4. Absorption contrast dominates in the central part of the sample while phase effects are visible at the edges of the legs, mesosoma and wing. The noise pattern present at the corners is a consequence of the normalization procedure in a region of intensity fall-out.

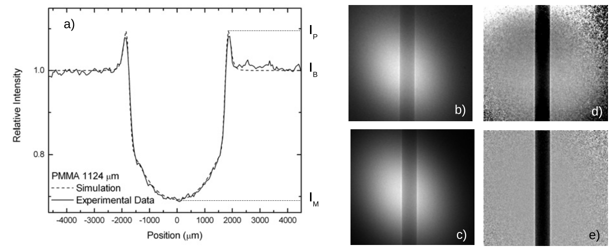

Figure 2: Experimental and simulated images for the PMMA wire. (a) Comparison of the wire profiles in a central portion of the beam. Experimental (b) and simulated (c) images, normalized experimental (d) and simulated (e) images.

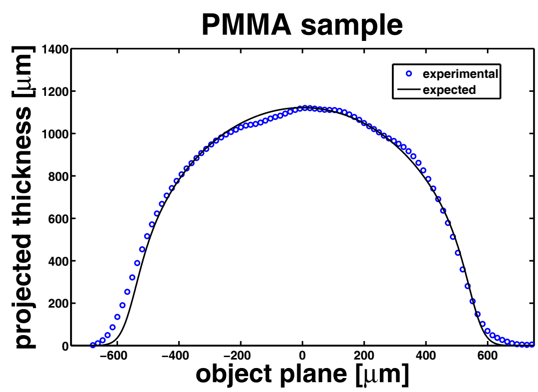

Figure 3: Reconstructed projected thickness at the object plane. PMMA wire, diameter 1124 μm. The reconstruction after phase retrieval is compared to the reconstruction using only absorption.

CONCLUSION

Single-shot phase-constrast images have been experimentally generated with an Inverse Compton Scattering X-ray source using in-line geometry on a very short time scale. Due to the high-brightness e-beam and high-energy CO_2 laser available at the facility, it was possible to obtain the appropriate energy, monochromaticity and the required number of photons per ICS shot. The images clearly show the edge-enhancement effect. The quantitative analysis of a homogeneous sample is in good agreement with the expectations, the object thickness has been accurately reconstructed with a great improvement with respect to the results obrtained using only the absorption data. Images

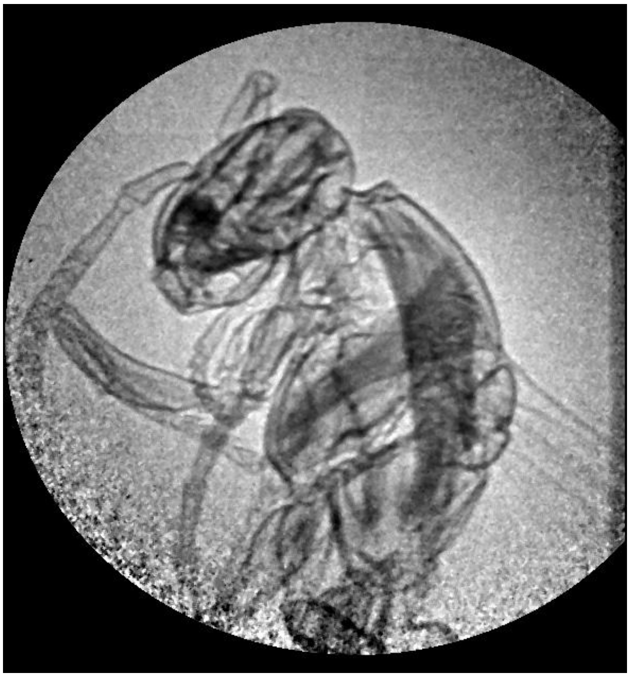

Figure 4: Normalized single-shot image of a wasp. Inline phase contrast is clearly visible on the border of the back of the insect.

on a biological sample were obtained, showing that imaging applications in medicine and biology can be enabled by this state-of-the-art ICS source. These results are encouraging for future biomedical application of this kind of X-ray sources.

REFERENCES

[1] E. Carroll, M. H. Mendenhall, R. H. Traeger, C. Brau, and J. W. Waters, American Journal of Roentgenology 181, 1197 (2003).

[2] Oliva P, Golosio B, Stumbo S, Bravin A, Tomassini P., Med Phys. 36(11) (2009) 5149-61.

[3] E. Esarey, S. K. Ride, and P. Sprangle, Physical Review E 48, 3003 (1993).

[4] P. Tomassini, A. Giulietti, D. Giulietti, and L. Gizzi, Journal of Applied Physics B 80, 419 (March 2005).

[5] P. Oliva, A. Bacci, U. Bottigli, M. Carpinelli, P. Delogu, M. Ferrario, D. Giulietti, B. Golosio, V. Petrillo, L. Serani, P. Tomassini, C. Vaccarezza, C. Vicario, and A. Stefanini, Nuclear Instruments and Methods in Physics Research A 615, 93 (2010).

[6] I. V. Pogorelsky, I. Ben-Zvi, T. Hirose, S. Kashiwagi, V. Yakimenko, K. Kusche, P. Siddons, J. Skaritka, T. Kumita, A. Tsunemi, T. Omori, J. Urakawa, M. Washio, K. Yokoya, T. Okugi, Y. Liu, P. He, and D. Cline, Physical Review ST AB 3 (2000).

[7] Oliva P., Carpinelli M., Golosio B., Delogu P., Endrizzi M., Park J., Pogorelsky I., Yakimenko V., Williams O., Rosenzweig J., Applied Physics Letters 97(13) (2010), 134104

[8] H. Ikeura-Sekiguchi, R. Kuroda, M. Yasumoto, H. Toyokawa, M. Koike, K. Yamada, F. Sakai, K. Mori, K. Maruyama, H. Oka, and T. Kimata, Applied Physics Letters 92 (2008), 131107

[9] Endrizzi M, Gureyev TE, Delogu P, Oliva P, Golosio B, Carpinelli M, Pogorelsky I, Yakimenko V, Bottigli U., Opt Express. 19(3) (2011) 2748-53