INVERSE COMPTON SCATTERING BY LASER ACCELERATED ELECTRONS AND ITS APPLICATION TO STANDOFF DETECTION OF HIDDEN OBJECTS*

Y. Mori†, K. Fujita, R. Hanayama, K. Ishii, Y. Kitagawa, GPI, Hamamatsu, Japan
H. Kuwabara, IHI, Yokohama, Kanagawa, Japan
T. Kawashima, Hamamatsu Photonics K. K., Hamamatsu, Japan

Abstract

An ultra-intense laser can produce extremely short and directional radiations, that is the inverse Compton scatterings useful for the backscattering system. Ultra-intense laser-produced sub-ps X-ray pulses were used to detect backscattered signals from objects hidden in a container with the coincident technique. The coincident measurement with primary X-rays enabled differentiation between the object materials, that is, acrylic, copper, and lead blocks inside the aluminum container. Laser-based electron acceleration is examined for the investigation of the inverse Compton scattering. The laser-wake field accelerated 13 and 22 MeV mono-energetic electrons, these electrons can scatter the same laser light into 5 an 14 keV X-ray with divergence of less than 4 mrad. This achievement is an important step toward the remote inspection of any unknown or hidden object, with great potential for homeland security or disaster relief.

INTRODUCTION

The safety inspection of public transport facilities, such as the airport or seaport buildings, is a big problem for national security. Meanwhile, the security guards and inspectors must be protected from potential dangers. Hence, a technique for remote detection of hidden objects is an urgent issue, but is not yet realized, because a source and a sensor must be located on the same side of the object. An ultra-intense laser can produce extremely short and directional radiations, that is the inverse Compton scatterings applied for the backscattering system.

Backscattered X-ray inspection is the only inspection technique that meets these requirements. The current X-ray tube, however, does not provides a standoff distance of longer than 1.5 m[1, 2, 3], because X-ray beam intensities decrease inversely with distance, which makes it difficult to detect sufficient backscattered signals exceeding natural radiation in the environment[4]. Pulse operation provides a powerful solution to the above-mentioned problems, as it enables us to catch weak yet meaningful pulses in a narrow window coincident to the incident pulse. An ultra-intense laser produces extremely short (less than 1 ps) X-ray pulses, which reduces natural radiation to the zero-count level. It provides a very small spot source of less than a few hundred micrometers, and thus is an environmentally safe radiation source.

In a previous study on backscattered X-ray standoff inspection using laser-produced X-ray pulses[5], we demonstrated that when objects are arrayed side by side, backscattered X-rays can reconstruct the array image. Extremely short X-ray pulse measurement has the advantage of detecting very weak backscattered signals by means of the coincident measurement technique.

In this report, we present (i) standoff detection of hidden object using backscattered ultra-intense laser-produced X-rays and (ii) investigation of inverse Compton scattering by laser accelerated electrons.

STANDOFF DETECTION OF HIDDEN OBJECTS USING BACKSCATTERED X-RAY

A 1.2-TW tabletop Ti:Sapphire chirped pulse amplification (CPA) laser is focused on a thin foil, generating Bremsstrahlung X-rays with 1 ps duration. The laser has a wavelength of 800 nm, pulse duration of 200 fs, and energy of 62 mJ[6]. The beam is focused using a 138-mm focal length ($f/3.9$) off-axial parabola on a 0.5-mm-thick aluminum target at 30-degree incidence (p-polarization) in a stainless steel vacuum chamber with a diameter of 80 cm[5]. The target moves during the shot interval with a velocity of 50 μm/s, which allows irradiation for a few minutes, or 1000 shots. The laser spot size is 8 μm. The focal intensity I is 6.2×10^{17} W/cm^2, which accelerates electrons on the target surface to an energy of around the photon pressure $[(1+I/(1.37\times10^{18}))^{1/2}-1]\times511 \sim 104$ keV[7]. The accelerated electrons pass through the target and emit Bremsstrahlung X-rays with energies of up to a hundred keV at a subpicosecond duration ; the electrons are extracted through a vacuum window[8].

We can shape and scan primary X-ray beams for backscattering experiments, as shown in Fig. 1. The X-rays are passed through a lead collimator 90 cm away from the source, and are capable of scanning objects at 132.5 cm. The collimator is made of 50-mm-thick lead blocks and has a 5-mm-wide and 100-mm-high aperture that focuses the beam into a rectangle. The object scatters most of the beam forward, but a small fraction, occasionally of the order of a single photon, travels backward. Coincident

* Work supported by the Grants-in-Aid for Scientific Research of MEXT #21244088, the Science Research Promotion Fund of the Promotion and Mutual Aid Corporation for Private Schools of Japan, and the GPI-IHI research collaboration as well as the research collaboration of the ILE, Osaka University #B2-41.

† ymori@gpi.ac.jp

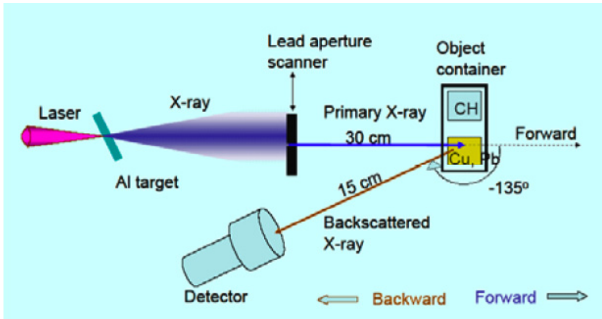

Figure 1: Setup for backward imaging experiments. A laser (left) is focused on an aluminum target, generating picosecond pulse X-rays, which travel through a movable lead collimator (center) to scan the objects in an aluminum container (right). Backscattered X-rays reach the scintillation detector (center-bottom).

measurement using primary X-rays allows a backside scintillation detector to detect a backscattered signal of even a single photon without loss in natural radiation noise[8]. A 2-mm-thick lead shield covers both object and detector to prevent laser-produced X-ray leakage from undesired vacuum chamber ports, as reported previously[5]. To scan an object, we sweep the collimator transversely to the beam line, as shown in Fig. 1. The detector is a fast plastic scintillator (BC-404, Saint Gobain K.K.) with a diameter of 90 mm and thickness of 100 mm, coupled to a photomultiplier (H8443, Hamamatsu photonics K.K.). It is set at -135 degrees to the beam incidence and 15 cm away from the object. For coincident measurement, a 1-GHz digital oscilloscope (DP07104, Tektronics Inc.) detects the backscattered signals only when they pass through a 200-ns window triggered by the laser pulse. The laser pulse frequency is 10 Hz. The laser pulse incident onto a Si photodiode drives the trigger sequence function of the oscilloscope to open the window, into which the backscattered signals come. We measured natural radiation using the same scintillator system, confirmed that a time interval of less than a few hundred nanoseconds is sufficiently short to reduce natural noise to the zero-count level. The CdTe photodiode also analyzed the primary X-ray spectrum.

Figure 2 shows the container box, and box contents: a block of acrylic resin and another block of either copper or lead. The lead shield, containing the objects and X-ray detector, prevents X-ray leakage from the laser irradiation chamber, as mentioned above. We stress that not the lead shield but the coincident measurement suppresses natural radiation.

We swept the incident beam transversely on the container surface. The incident photons on the container measure about 1000 counts in 100 s. As shown in Figs. 3a and b, backscattering detects the objects hidden inside the container, even though the detected photons measure only 15 counts for acrylic resin, 5 for copper, and 2 for lead. Background, shown as the horizontal dashed line in Fig. 3a, is 1 count, close to the scattering level without the container. When the coincidence technique is not used, the backscattered signals should be masked by natural radiation. In the figure, the left-hand boundaries of each object show small but sharp peaks: x = -70 mm for acrylic in a and b, z = +25 mm for copper in a, and x = +25 mm for lead in b. These features appear probably because the primary X-rays were not incident normal to the objects, but tilted slightly to the right. Three repeated scans yielded the vertical error bars in Fig. 3a, and five yielded the result in Fig. 3b. The primary beam shape yielded a horizontal resolution of 5.8 mm. Note that the scatterings inside the object are attenuated again by the same object. The deeper the scattering point is, the more is the attenuation of the backscattering. Furthermore, for a low-Z material such as acrylic, attenuation is small; thus, the backscattered yield is almost proportional to the thickness of the scattering object. For a high-Z material such as lead, attenuation is high. We thus consider that yield is larger for lower-Z materials.

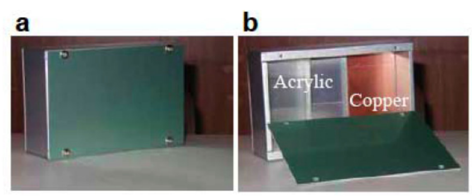

Figure 2: Sample aluminum container in which the objects are hidden. (a) The container size is 150 mm × 100 mm× 50 mm. (b) Inside the container, 30-mm-thick acrylic resin (left) and a 5-mm-thick copper or 1-mm-thick lead block (right) are present.

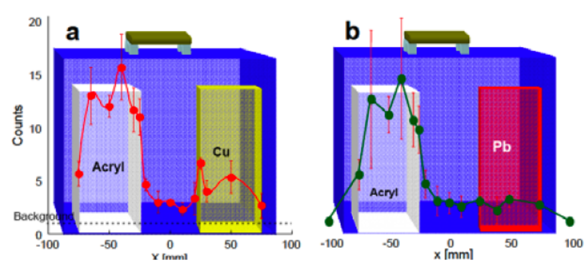

Figure 3: Backscattered X-ray images showing the inside of the container. The backscattered signals are different for (a) acrylic resin CH (left) and copper (Cu, right) and (b) acrylic (left) and lead (Pb, right).

PRESENT STATUS OF LASER DRIVEN INVERSE COMPTON SCATTERING

Figure 4 shows experimental setup of on-going laser driven inverse Compton scattering. 3 TW OPCPA Ti:sapphire laser BEAT (0.5J output, wavelength 815 nm, and pulse duration 150 fs) is divided into two beams. A 0.4-J beam(called as the main beam) is focused to an entrance edge of helium gasjet to accelerate electrons via wakefield and the other 0.1-J beam(called as the counter beam) is focused to the exit of the plasma channel from the opposite direction.

A leakage of the compressed beam is converted to 407 nm and is used to probe the gasjet plasma channel perpendicularly to the main beam. This probe beam is also useful for laser alignments between the main and the counter beams. To the downstream direction of the main beam, a CdTe detector (Si-PIN Photo Diode XR-100CR FWHM 149 eV) is set to analyze the Compton spectrum under a photon counting mode[3] in the range of 1 keV to 20 keV. We put an ESM, consisting of a dipole magnet and an IP film on the down flow line of the main beam to catch the electrons up to 30 MeV. When we inject the counter beam, we remove the ESM instead, install a dipole magnet, which avoids the electron beams hit directly the CdTe detector. In Fig. 5 (a) IP image of ESM is shown up to 30 MeV. Gas jet is backpacked with 80 atm He. In Fig. 5 (b) are plotted electron spectra. Green dots are raw plots, blues are background and red line is net signal (after extracting the blue data from the green data), showing mono-energetic peaks at 13 and 22 MeV, respectively. Gas jet below 80 atm He indicated no clear mono-energetic features. According to the Klein and Nishina formula[9], electrons with the relativistic energy γ enables to scatter a photon with energy ϵ_L into the high energetic one of energy $E_r \sim 4\gamma^2\epsilon_L$ with scattering angle $\theta \sim 1/\gamma$. In our case, accelerated mono-energetic electrons can scatter the same laser light into 5 and 14 keV X-ray with scattering angle of less than 4 mrad.

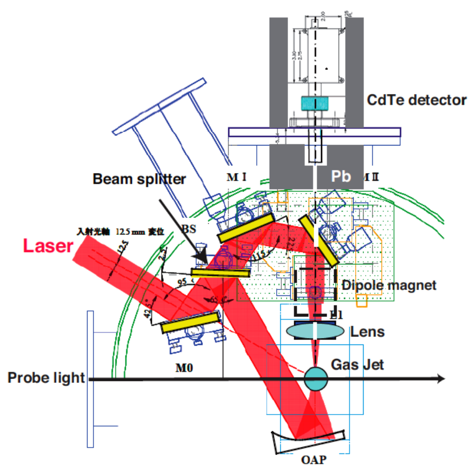

Figure 4: Experimental setup for laser driven inverse Compton scattering.

CONCLUSIONS

We have demonstrated standoff imaging of hidden objects by coincidently measuring primary and backscattered X-rays. Coincident measurement with primary X-rays enables a few backscattered photons to differentiate between

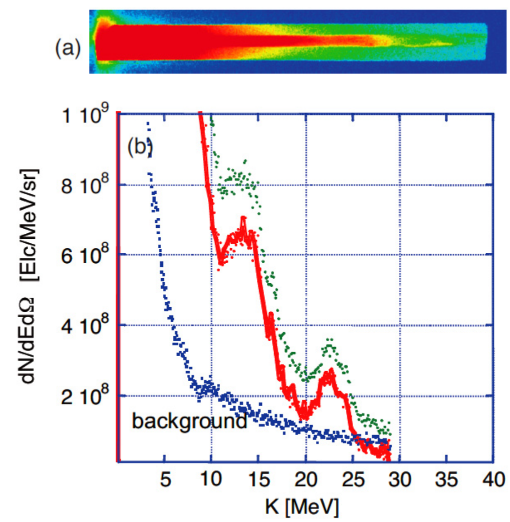

Figure 5: (a) IP image of ESM:He 80 atm. (b)Analyzed electron spectra show mono-energetic peaks at 13 and 22 MeV, respectively: Green dots are raw plots, blues are background and red line is net signals.

acrylic, copper, and lead blocks inside an aluminum container. We have examined laser-based electron acceleration for the investigation of the inverse Compton scattering. The laser-wake field accelerated 13 and 22 MeV mono-energetic electrons, these electrons can scatter the same laser light into 5 and 14 keV X-ray with divergence of less than 4 mrad. This achievement is an important step toward the remote inspection of any unknown or hidden object, with great potential for homeland security or disaster relief.

REFERENCES

[1] L. R. Lawson, Materials Evaluation 60 (2002) 1295.

[2] R. D. Swift, Proceedings of SPIE, Intern. Soc. Op.t Eng. 2936 (1997) 124.

[3] Ryu J.S., Park S.W., Kim M.S., and Yi Y., Proc. IEEE Eng. Med. Biol. Soc. 2 (2005) 1838.

[4] K. Fujitaka and M. Abe, The Third Int. Symp. Adv. Nucl. Engy. Res., Global environment and Nuclear Energy (1991) 76.

[5] H. Kuwabara, Y. Mori, and Y. Kitagawa, Plasma Fusion Res. 3 (2008) 003.

[6] Y. Mori, Y. Sentoku, and Y. Kitagawa, International J. Mod. Phys. B 21 (2007) 572.

[7] S. C. Wilks, W. L. Kruer, M. Tabak, and A. B. Langdon, Phys. Rev. Lett. 69 (1992) 1383.

[8] H. Kuwabara, Development and marketing of the background X-ray imaging for distant objects by mean of ultra short pulse X-ray source, Doctorial Thesis to the Graduate School for the Creation of New Photonics Industries (2008).

[9] V. O. Klein, and Y. Nishina, Phys. 52 (1929) 853.