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(出版者 / Publisher)
法政大学イオンビーム工学研究所

(雑誌名 / Journal or Publication Title)
PROCEEDINGS OF THE 34th SYMPOSIUM ON MATERIALS SCIENCE AND ENGINEERING RESEARCH CENTER OF ION BEAM TECHNOLOGY HOSEI UNIVERSITY (December 9, 2015)

(巻 / Volume)
34

(開始ページ / Start Page)
1

(終了ページ / End Page)
6

(発行年 / Year)
2016-02

(URL)
https://doi.org/10.15002/00030384

RADIOGRAPHY WITH HIGH-ENERGY PHOTON BEAM

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Novel radiography system for nondestructive inspection of industrial products was developed in AIST, using high-energy quasi-monochromatic photon beam in gamma-ray energy range. With a high-energy and narrow-beam configuration, radiography with a beam-scanning method and a first generation computerized tomography method were studied. Both methods showed good spatial and density resolutions.

I. Introduction

Nondestructive inspection (NDI) is an important technique to improve a reliability of industrial products. X-ray radiography is commonly used for NDI of various products in electronics, automobile, and aircraft industries. Conventional x-ray radiography systems use x-ray tube, which generates low to middle energy x-rays (a few to a few hundreds of keV). High-energy x-ray radiography using x-rays in MeV range is used for inspections of large industrial parts, such as engine and metal casting products, and for inspection of infrastructure such as roads, bridges and buildings.

As the importance of maintaining old concrete structures grows, detection of steel reinforcement bar arrangement and defects in concretes nondestructively is becoming important. Conventional NDI methods, such as electromagnetic measurements, radar, thermography are not sufficient to detect bar arrangements with sufficient accuracy at required measurement depths under most conditions.

II. Radiography system using laser Compton scattering

An industrial CT system using a high-energy photon beam was developed in AIST [1, 2], which can inspect a concrete specimen of a few tens centimeters to a few meters long. High-energy and quasi-monochromatic photon beam of 10 MeV with a few % energy spread was used for the radiography system.

Such a photon can be generated via the laser Compton scattering (LCS) [3]. It is a Compton scattering of laser photons of a few eV with electrons of sufficient kinetic energy and momentum. Because a part of the kinetic energy of the electrons is transferred to the laser photons via the interaction process, the energies of the scattered photons are up-shifted, and have energies in MeV range. Kinematics of the LCS is described with equation (1). It relates the energy of the Compton-scattered photons, E_γ with the scattered angles θ_1 and θ_2.

$$E_\gamma = \frac{E_L(1-\beta\cos[\theta_1])}{1-\beta\cos[\theta_2]+\dfrac{E_L(1-\beta\cos[\theta_2-\theta_1])}{E_e}}, \qquad (1)$$

$$\textit{where} \qquad \beta = \sqrt{1-\gamma^2}, \quad \gamma = \frac{E_e}{0.511} \ ,$$

θ_1 and θ_2 are the angles of the laser quantum before and after the Compton scattering, measured with respect to the motion of direction of the electron. E_γ, E_L and E_e are the energies of the Compton-scattered photon, a laser quantum and an electron, respectively in the unit of MeV. In AIST, a diode-pumped solid state laser and an 800-MeV electron storage ring “TERAS” (Tsukuba Electron Ring for Accelerating and Storage) 4) were used as the photon and electron sources, respectively to generate the laser Compton photons 5). Typical energy spectrum of the laser Compton photons is shown in Fig. 2. It was generated via the LCS of laser photons of 532 nm in wavelength with electrons of 575 MeV. The energy spectrum was measured for θ_2 of 300 micro-radians or smaller, with an anti-Compton shielded high-purity germanium detector 6).

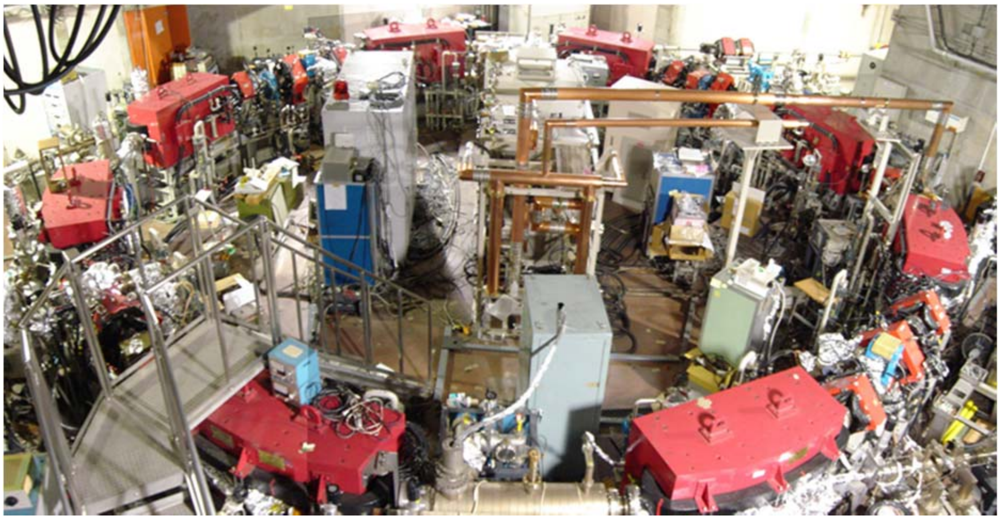

Fig. 1: Electron storage ring “TERAS” of AIST.

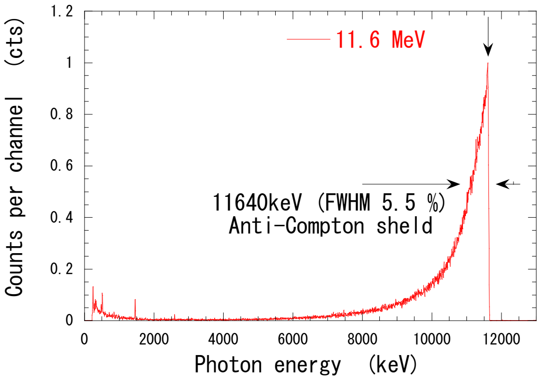

Fig. 2: Typical energy spectrum of the laser Compton photons in AIST.

Figure 3 shows a setup for the radiography experiment that was done for the first time in AIST. The specimen was a lead bar of 10 mm in diameter and 100 mm in length, which was embedded in a paraffin rod of 50 mm in diameter and 400 mm in length. Figure 4 shows radiographs of the specimen, which were measured with 5, 10, and 20 MeV laser Compton photons, respectively. The spatial resolution was about 5 mm.

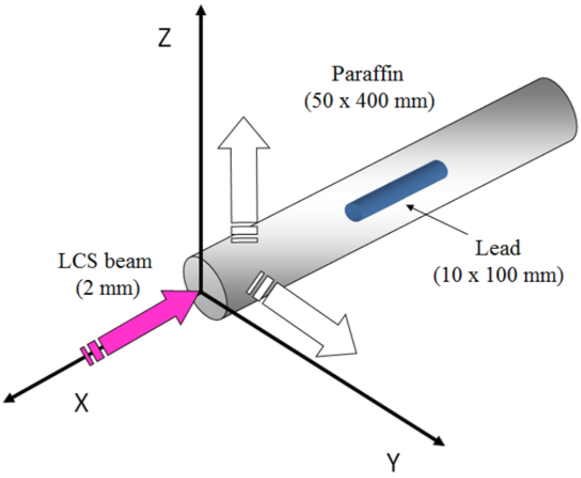

Fig. 3: Setup for the first radiography experiment in AIST.

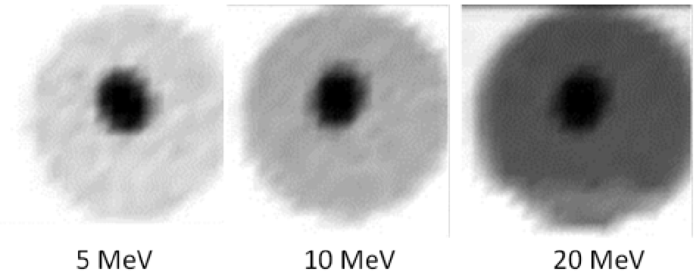
5 MeV 10 MeV 20 MeV

Fig. 4: Radiographs measured with 5, 10 and 20 MeV LCS photon beam.

In AIST, the laser Compton photon beam was shaped with a pin-hole collimator made of lead of 20 cm in length to make the beam right circlar. Typical beam divergence was a few part of milliradian. Beam-scan method was employed to the radiography to achieve a good spatial resolution. Figure 5 shows a typical experimental setup for the radiography experiment. The object was mounted on a CT stage that translates, rotates and moves up and down, with respect to the photon beam. While a narrow beam gives good spatial resolution, the photon intensity becomes low. It is a trade-off among the beam size, image quality such as noise and contrast, spatial resolution, and measurement time (time resolution). In the present study, the measurement time was on the order of a few hours. The spatial resolution of the system was 0.5 mm.

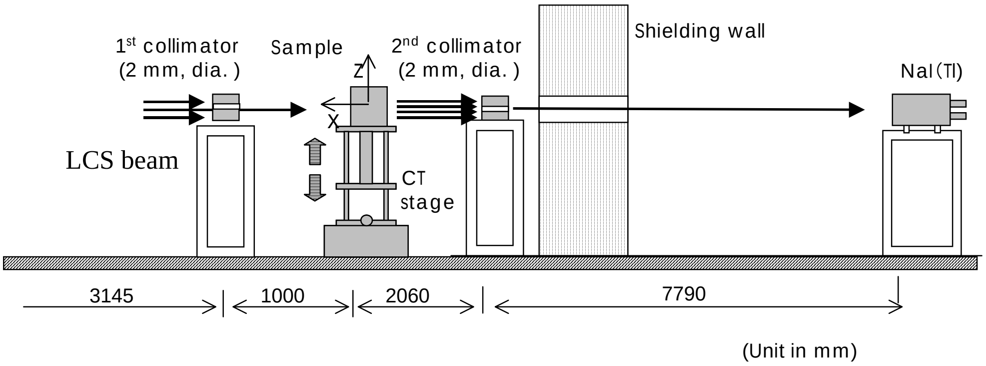

Fig. 5: Experimental setup for the radiography using the laser Compton photon beam.

A computerized tomography (CT) was introduced to measure a cross-sectional image of the sample. In AIST, the first-generation CT was the best to obtain a CT image with high spatial resolution with high detection efficiency, because the narrow-beam system showed a good performance in radiography.

A concrete specimen (100 mm × 100 mm × 150 mm) containing coarse aggregates made of iron ores were prepared, and was inspected with the present CT system. The CT image is shown in Fig. 6. A laser Compton photon beam of 10 MeV with 2 mm in diameter was exposed on the specimen, and 200 projections for 360 degrees were measured to reconstruct a CT image. The CT reconstruction was done using a filtered back-projection (FBP) method.

Fig. 7 shows a distribution of the grey level of the CT image shown in Fig. 6. Peaks in the distribution corresponded to mortar, iron ores of low density, iron ores of high density, and reinforcement bar, respectively. The iron ores of high and low densities were distinguished.

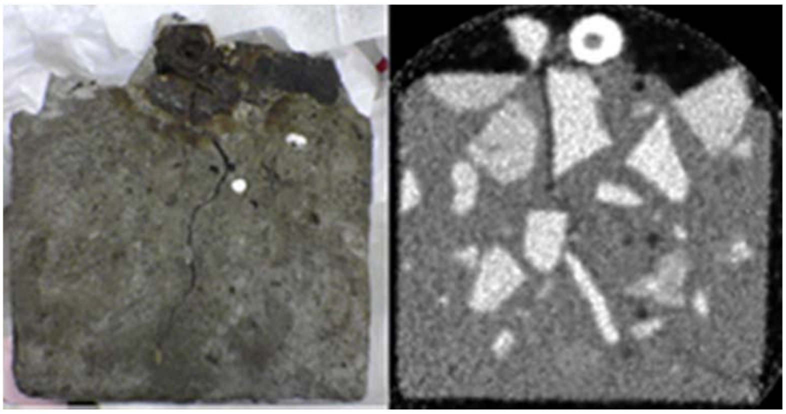

Fig. 6: Photograph of a specimen (left) and a CT image (right).

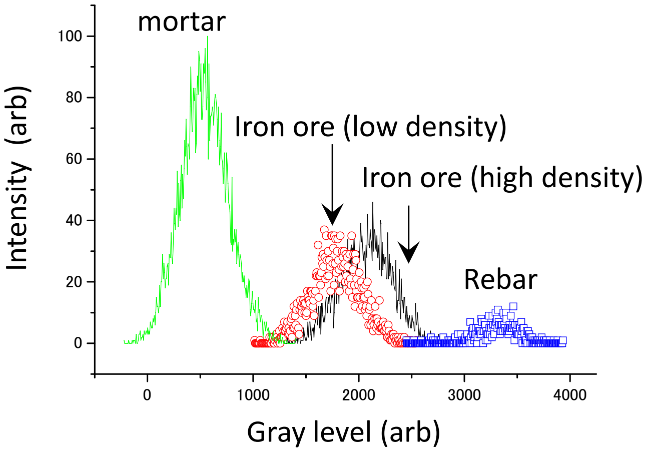

Fig. 7: Distribution of the grey level of the CT image.

A reinforced concrete of 2-meters in diameter, which simulated a bridge pier was inspected. Because the CT stage was smaller than the specimen, the concrete specimen was cut in three parts: front, core, and rear parts, respectively. The CT image of the core part was measured. The laser Compton photon beam was attenuated by the front concrete part, and incident on the core part. The photon beam was, then, attenuated with the rear part, so that the total penetration distance was two meters (Fig. 8). Figure 9 shows the CT image of the core part, which is a triangular prism made of reinforced concrete, whose sides are 35 cm x 38 cm x 52 cm. It took 10 hours for single slice CT image.

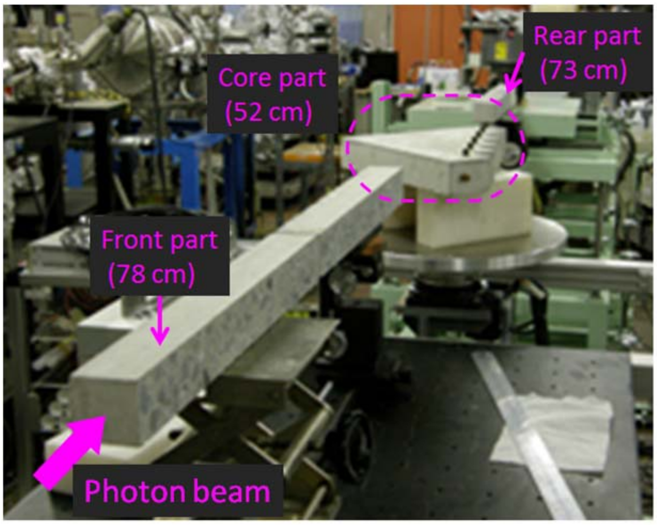

Fig. 8: Setup for the CT experiment of two-meters-long specimen.

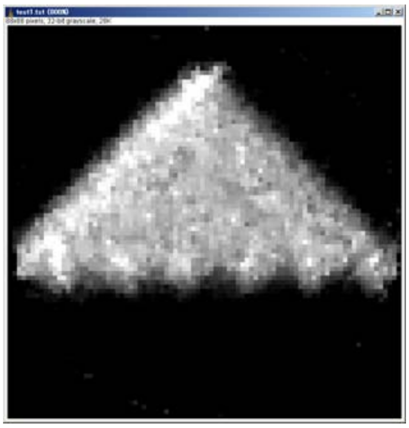

Fig. 9: CT image of the core part.

III. Discussion

It was demonstrated that high-energy quasi-monochromatic photon beam was useful for nondestructive inspection of industrial products, and the CT image as large as 2 m in diameter was successfully obtained. Coarse aggregates and mortars were clearly distinguished in the CT image for the concrete specimen containing iron ores.

The linear attenuation coefficient and the average density of concrete was 0.05 cm^{-1} for 10 MeV photons and 2.3 g/cm^3, respectively. Assuming densities of mortar and coarse aggregates of approximately 2.2 g/cm^3 and 2.7 g/cm^3, the difference of the linear attenuation coefficients for those two materials is calculated to be 0.01 cm^{-1}. Because the low contrast resolution of the present CT system was measured to be 7.4×10^{-3} cm^{-1} 7), it is understood that the difference was detectable with the present CT system.

Enhancement of the photon yield is required to apply the present method to a practical application. A high power and compact laser source, a table-top electron accelerator, and a state-of-the-art radiation measurement technique are expected to be integrated to realize such a CT system, in the near future. The present radiography system can be expected to be applied for a precise NDI to check homogeneity, voids, crack and defects in sintered materials, die-cast products, concretes and industrial products made of composite materials.

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