MATERIAL RECOGNITION SYSTEM USING 950 KEV X-BAND LINAC WITH DUAL ENERGY X-RAY SCINTILLATOR ARRAY

Kiwoo Lee[#], Takuya Natsui, Shunsuke Hirai, Mitsuru Uesaka, Tomohiko Yamamoto, The University of Tokyo, Ibaraki-ken, Japan
Eiko Hashimoto, JAEA, Ibaraki-ken, Japan

Abstract

Dual energy X-ray system using high energy X-ray from linear accelerator (Linac) applies two times X-ray irradiation which has different energy spectrum each other in many cases. Two different X-rays yield two tomography images which are analyzed through numerical calculation with pixel values for material recognition of an object. However if the X-ray generation is not stable, the results of numerical calculation shows irregular tendency during the inspection. We propose the two-fold scintillator array in detection part, because two tomography images are obtained by just one irradiation. That leads to the time saving during inspection and the cost down for additional facilities. The optimal condition is researched to increase the ability of material recognition in interesting materials designing the detector with CsI and CdWO$_4$ scintillators. We focus on the discrimination between heavy materials and light materials with the system in the research. X-ray source is 950 keV X-band Linac we developed for industrial application, which produce pulsed X-ray, 10 pps with around 400 mA beam current..

INTRODUCTION

According to the development of linear accelerator which produces high energy X-ray, the new possibility in the field of X-ray imaging is greater than before because, the higher energy X-ray can penetrate the thicker target material. Practically, the inspection system for containers in a port using Linac as X-ray source, 4 ~ 9 MeV accelerating energy, have been introduced in several countries [1, 2]. They show the discrimination between several materials which has atomic number range from 5 to 82 effectively. That was impossible with lower energy X-ray source below 500 keV, which is popular for baggage custom inspection in an airport.

Dual energy X-ray concept is applied with Linac for material recognition. Through the numerical calculation of contrast in each pixel in two images of a target material, colorized image which has atomic number information is reconstructed. Two images are obtained by dual energy X-ray which has different energy spectrum from Linac normally. Monochromatic dual energy X-ray provides definite separation all of materials theoretically. However monochromatic X-ray cannot be applied easily, because it is produced from a big ring accelerator, synchrotron radiation or from a big Linac, undulator radiation.

Therefore we suggest a new idea for dual energy X-ray with two-fold scintillator detector (Fig. 1).

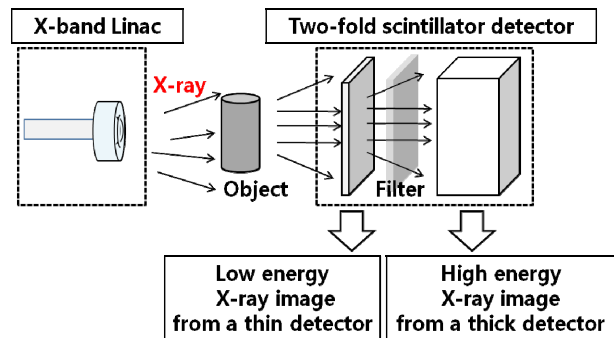_____
[#]kiwoo@nuclear.jp

Figure 1: Dual energy X-ray concept with two-fold scintillator detector.

We can obtain two images, low energy X-ray image and high energy X-ray image, from two scintillators during X-ray irradiation once. In this way, we do not need two times irradiations with dual energy X-ray. That leads to inspection time-saving and prevention of discordance between two images.

In the research, we set our goal to distinguish light metal such as Fe from heavy metal such as Pb. They cannot distinguish these metals up to atomic number 82 with established inspection system because they use X-ray tube as X-ray source which can generate X-ray energy up to 500 keV. X-rays below 500 keV cannot penetrate material target which is composed of high atomic number element in certain thickness range. Therefore we tried to overcome the restriction with higher X-ray in a range which cannot be distinguished with X-ray tube such as up to Pb; atomic number 82.

EXPERIMENT

We set the size of entire system to $50 \times 50 \times 50$ cm to place in an airport for custom inspection. It is realized by X-band Linac which is equipped with small size of accelerator and magnetron (Fig. 2, Table 1).

950 keV X-band Linac

Table 1: Specifications of 950 keV X-ray source

Resonant frequency	X-band 9.4 GHz
RF source	250 kW magnetron
Cavity type	On-axis coupling
Shunt impedance	~ 70 MW/m
Gun type	Thermionic, Diode, 20 keV
Tube length	~ 30 cm

One of the special features is the 250 kW magnetron; size is 0.1×0.2×0.2 m. The small size of power supply system is provided to supply electric power. Another feature is 950 keV accelerating energy. We do not concern to provide radiation safety manager on-site within 1 MeV X-ray energy [3].
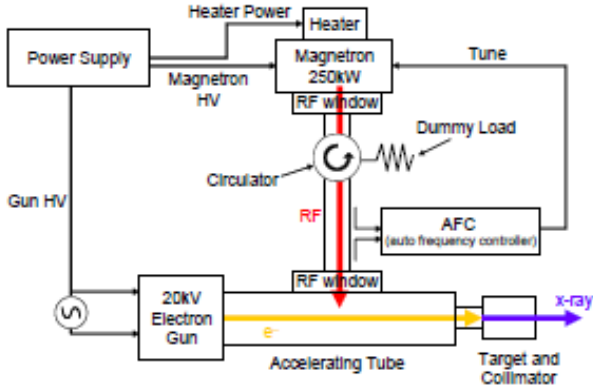

Figure 2: Schematic view of 950 keV X-band Linac.

Two-fold scintillator detector

We performed Monte carlo simulation to design two-fold scintillator, accelerating the electron bunch to generate bremsstrahlung X-ray from tungsten target. Accumulated energy in each scintillator was analyzed to decide the thickness of two scintillators, CsI and $CdWO_4$. Low energy X-ray is absorbed in CsI, thin scintillator, because high energy X-ray penetrates thin scintillator easily. High energy X-ray behind thin scintillator reaches thick scintillator and is absorbed in it. 500 μm for CsI, 15 mm for $CdWO_4$ are proposed to increase the ability of material recognition.

Target

Iron and lead, representing light and heavy metal, are introduced as targets (Fig. 3 a). These are placed in containers to conceal the target materials changing the thickness while we put small concealment in bigger one. Container materials are polyethylene and polyvinyl chloride which are normal material around us. Its thickness is 5 mm. Every time we put the small one in the bigger one, thickness of container is increased 10 mm each from 10 mm to 50 mm (Fig. 3 b).
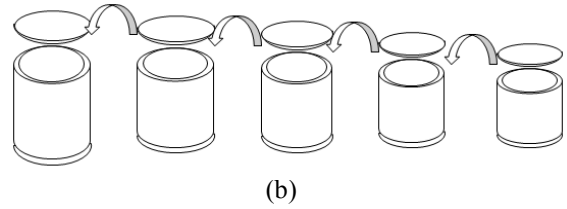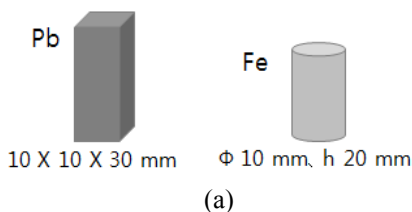

(a)

(b)

Figure 3: Samples (a) and concealment (b).

We placed the containers on the X-stage. While the container moves on the stage, two-fold scintillator takes the line image according to 10 pps frequencies.

CALCULATION FOR IMAGE RECONSTRUCTION

Transparency

$$T(t,Z) = \frac{\int_0^E N(E)\exp(-\mu_Z t)EP_d(E)dE}{\int_0^E N(E)EP_d(E)dE} \quad (1)$$

$N(E):X-ray\ energy\ spectrum$

$P_d(E):The\ energy\ response\ function$

$\mu_Z:The\ mass\ attenuatio\ n\ coefficien\ t$

$t:The\ mass\ thickness\ of\ the\ irradiated$
$\quad material\ with\ atomic\ number\ Z$

Transparency is the ratio of X-ray intensity after penetrating the materials to the incident X-ray intensity (see Eq. 1). It depends on the cross section of X-ray in materials which contain the photoelectric effect, Compton scattering, pair production.
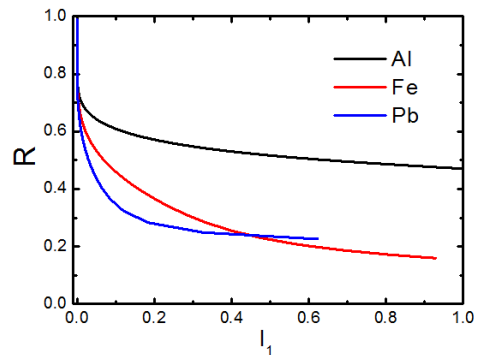

Figure 4: R and I_1 graph based on the attenuation calculation result.

With the transparency of each scintillator; I_2: natural log of transparency of high energy X-ray for $CdWO_4$, I_1: natural log of transparency of low energy X-ray for CsI, we define $R = I_2 / I_1$.

The relation between R and I_1 shows certain pattern according to atomic number [4]. It is very useful as reference data covering all of elements to find out the composed material of target (Fig. 4).

RESULTS AND CONCLUSION

Fig. 5 shows the reconstructed image by numerical calculation of Fe and Pb inside of each container using R and I_1 data. In the polyethylene container, Fe and Pb show in the atomic number difference between experimental value and theoretical value of 3 ~ 10 for Fe, 2 ~ 5 for Pb. In the polyvinyl chloride container, Fe and Pb have the difference of 9 ~ 12 atomic number for Fe, 1 ~ 3 for Pb. The difference between experimental value and theoretical value is getting bigger as the thickness of container is thicker and density of composed material is higher (Table 2).

One thing we have to concern is the size of photodiode $15 \times 15 \times 2$ mm because point images are so big that noise looks big when it appears in an image. As the baggage inspection in an airport, pixel size should be smaller than 1 mm. Another is the collimator to suppress scattered X-ray. Scattered X-ray increased by high energy X-ray induces incorrect transparency. The spatial resolution is also affected by scattered X-ray. Therefore collimator has a key role to refrain clear image from scattered X-ray.

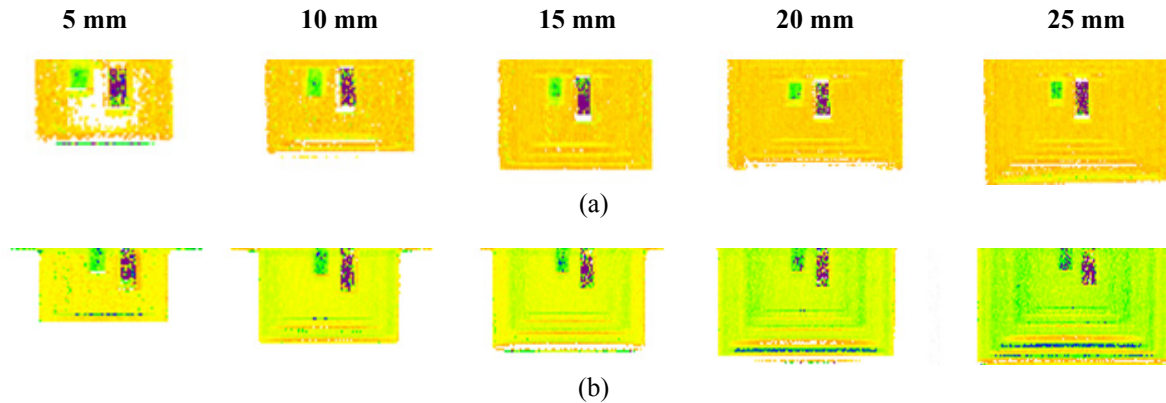| 5 mm | 10 mm | 15 mm | 20 mm | 25 mm |

(a)

(b)

Figure 5: Image reconstruction of Fe (light green) and Pb (plum) in polyethylene (a) and polyvinyl chloride (b) container.

Table 2: Atomic number difference between experimental values with theoretical value for each container

Polyethylene container

Thickness of container	Fe (26)	Pb (82)
5	3.41	2.35
10	4.76	2.58
15	4.06	3.22
20	7.02	3.31
25	9.99	4.34

Polyvinyl chloride container

Thickness of container	Fe (26)	Pb (82)
5	9.09	2.86
10	11.53	2.71
15	9.64	1.58
20	9.33	1.86
25	10.7	2.14

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