Development of an Industrial Computed Tomography Designed with a Plastic Scintillator Position Sensitive Detector

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Abstract - An industrial computed tomography (CT) using the plastic scintillator (PS) as a detector sensitive to the radiation interaction position was proposed. Firstly, a code using Monte Carlo method was developed to study the effects of the plastic scintillator geometry in its gamma ray detection. The software simulates the results system designed with two photomultiplier-tubes set up in coincidence. Four simulations sets were performed to foresee the effect of the diameter (5-50cm) and length (1-128cm) of the detectors. The plastic scintillator was designed to be used for the industrial tomography system application. The Monte Carlo developed code was validated for its use to foresee the suitable dimension of the scintillator detector and some geometrical aspects.

I. Introduction

The attenuation of electromagnetic radiation, e.g., gamma or X-rays passing through matter, involves basically four interaction mechanisms: photoelectric effect, Rayleigh scattering (elastic interaction type), Compton scattering (inelastic interaction type) and pair production. In the photoelectric effect, the gamma (or X-rays) photon dissipates its entire energy by knocking out an electron from an atom. In the Compton scattering, the gamma (or X-rays) imparts some energy to an electron, but survives with a lower energy and a different direction. In the pair production, the gamma (or X-rays) photon is absorbed to create an electron-positron pair. For pair production to occur, the incident gamma (or X-rays) must have an energy equal to or greater than the rest mass of an electron-positron pair. This energy is 1.02 MeV, since the rest mass of each is 0.511 MeV. Finally, the Rayleigh scattering is a process by which photons are scattered by bound atomic electrons and in which the atom is neither ionized nor excited. This process occurs mostly at low energies and for high Z materials, in the same regions where electron biding effects influence the compton scattering cross sections. Although the Rayleigh scattering pratically does not dissipate energy, it should be considered in the detector design since the Rayleigh process is one of the most responsible factors for the photon scattering and consequently, it has an important role in the resolution of the tomography system [1,2,3].

The probability of each of these interaction mechanisms varies with the atomic number and the photon energy. The photoelectric and Rayleigh effects are more dominant at low photon energy and high atomic number. Compton scattering is dominant at energies around 1 MeV, especially for materials with a low atomic number. Pair production becomes dominant around 5 MeV for materials with a high atomic number (and at a somewhat higher energy for lighter elements) [1,4].

Scanners for transmission tomography employ radiation sources, such as an encapsulated gamma ray source, positioned on one side of the object to be scanned, and a set of collimated detectors arranged on the other side. Scanners of the second generation (parallel beam), an array of detectors, facing a single source, move around the object and provide a number of projections equal to the number of detectors. Generally, the objects analyzed in industrial tomography field have high density and large dimensions, such as the case of the diameters of the oil refining columns. Consequently, high energy radiation source is required in order to be capable to cross the material. A dense detector material or a large detector is necessary to absorb the photons from the source [5,6]. Commonly, detectors made with NaI(Tl) (3.8 g/cm^3), CsI(Tl) (4.3 g/cm^3) and BGO Bismuth-Germanium-Oxyde ($Bi_4Ge_3O_{12}$, 7.13 g/cm^3) are used in a multidetectors array (Fig. 1A). This system requires a complex hardware because each scintillator needs independent electronics, e.g., phototube, high voltage, preamplifier, amplifier and counter. On the other hand, for large objects several detectors are required to fit the object surface, making the system very expensive. An alternative is to use a unique bar of detector since it can be used as a position sensitive detector. Barouch and Marriete [3] developed a system using a CsI(Tl) bar (Fig. 1B).

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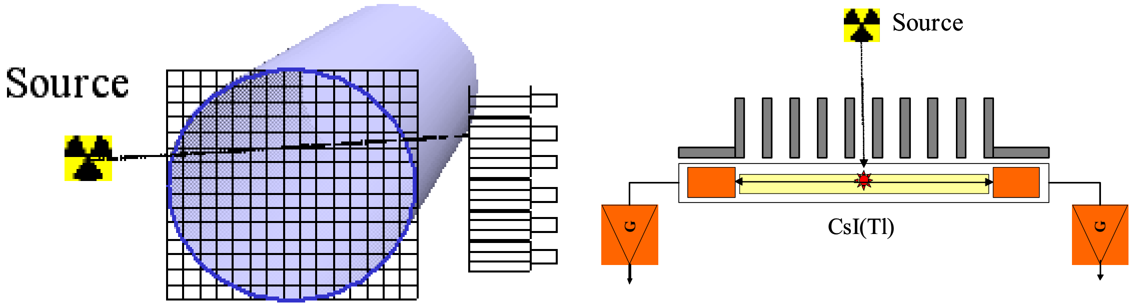


Fig.1- (A) Multidetector array and (B) position sensitive detector bar.

This kind of detector can be useful mainly in the case of industrial CT applications for large objects because it uses only two photomultiplier, thus requiring more simplified electronics, compared with those used in multiple detectors version. Besides, its cost is significantly cheaper.

This substitution has the advantage of being capable to involve large objects and exploring the faster response of the plastic scintillator (≅2.5 ns), what is necessary for fast image acquisitions, like the multiphase systems.

Plastic scintillators have low density (≅1 g/cm^3) and low Z materials [7]. These properties could be dissuading the use of the plastic for the tomography purpose. However these limitations can be overcome using a large dimension plastic scintillator taking in account its easy manufacturing in the dimension and shape required at a low cost. In this paper, a position sensitive detector is proposed and the use of a plastic scintillator cylinder is discussed, using the Monte Carlo simulation.

II. Methods

A code (software) was developed to simulate the history of gamma-ray photons within the scintillator detector like those used in the gamma spectral density using the Monte Carlo method. Much of the focus of this simulation is to obtain more information about the complex and dynamic structure of the nuclear detector tool response to be used as a guide to select the ideal detector dimensions. Although a large number of possible interaction mechanisms are known for gamma-ray photons in matter, only four types play an important role in the energy range of nuclear logging services: photoelectric absorption, Compton scattering, pair production and Rayleigh scattering. All these processes lead to the total or partial transfer of energy to electrons in the scintillator plastic, what results in important roles in the gamma-ray history.

In order to know the light auto-absorption (auto-quenching), a 100cm cylinder with 4cm diameter of PS made with PPO (0.5%w/v) and POPOP (0.05% w/v) in a polystyrene matrix was prepared. A photomultiplier was coupled to the cylinder extremity of the PS detector. A collimated ^{60}Co gamma source was positioned, step by step, on different positions of the PS cylinder. The pairs of X (cm) vs pulse height (volts) was fitted to a mono-exponential function:

$$PH(volts) = V_0 \times \exp(-\frac{X}{X_{37}}) \qquad (1)$$

where X is the distance in centimeters from the source to the PS extremity coupled to the photomultiplier, V_0 is a constant representing the maximal pulse height generated by the photomultiplier signal and X_{37} is the PS length which reduces the light level to V_0 x exp(-1) (~37%) from its original value. Consequently, the distance of the interaction point in relation to each photomultiplier can be estimated by the equation (2):

$$X(cm) = X_{37} \times \log_e(-\frac{PH}{V_0}) \qquad (2)$$

For two photomultipliers, the best estimate of the incidence position can be determined by the equation (3), as being the average, giving a more precise value:

$$\bar{X} = \frac{X_{PMT1} + (Detector_{Lenght} - X_{PMT2})}{2} \qquad (3)$$

The schematic drawing of the plastic scintillator tomography is showed in Fig. 2.

When the radiation interacts with the detector, the light photons scatter inside the detector and reach two detector extremities, generating two different signals (except for the middle detector position, which generates identical signals). Consequently, the farther the events occur from the photomultipler (RCA mod. HV supplied by Ortec mod. 556), lower signals are generated. In the sequence, the signal is pre-amplified (Ortec mod. 276) and amplified (Ortec mod. 460). For each signal, the maximum height value needs to be kept constant at least for 2 microseconds, due to the limitation of the ADC used (ADC0820). This circuit was projected and built in our laboratory.

In the sequence, this signal goes through the three pathways: the first one will be used for spectrometric purpose, the second to certify the signal coincidence in two photomultipliers and the third will be used for threshold control. With this procedure, the random noise from each photomultiplier can be eliminated, and in the third pathway the signal is processed by a PC computer.

In the first pathway, the signals are summed and evaluated by threshold (cut off) criterion. Next, these three signals are converted to TTL signals (5V). When these three signals reach simultaneously the three inputs of the

AND gate, the acquisition board is ready to receive thespectral signal which is delayed until this process finishes.

After that, the analog signal is converted to an 8 bit digital signal (ADC0820) and buffered in a RAM memory until be acquired by PC computer.

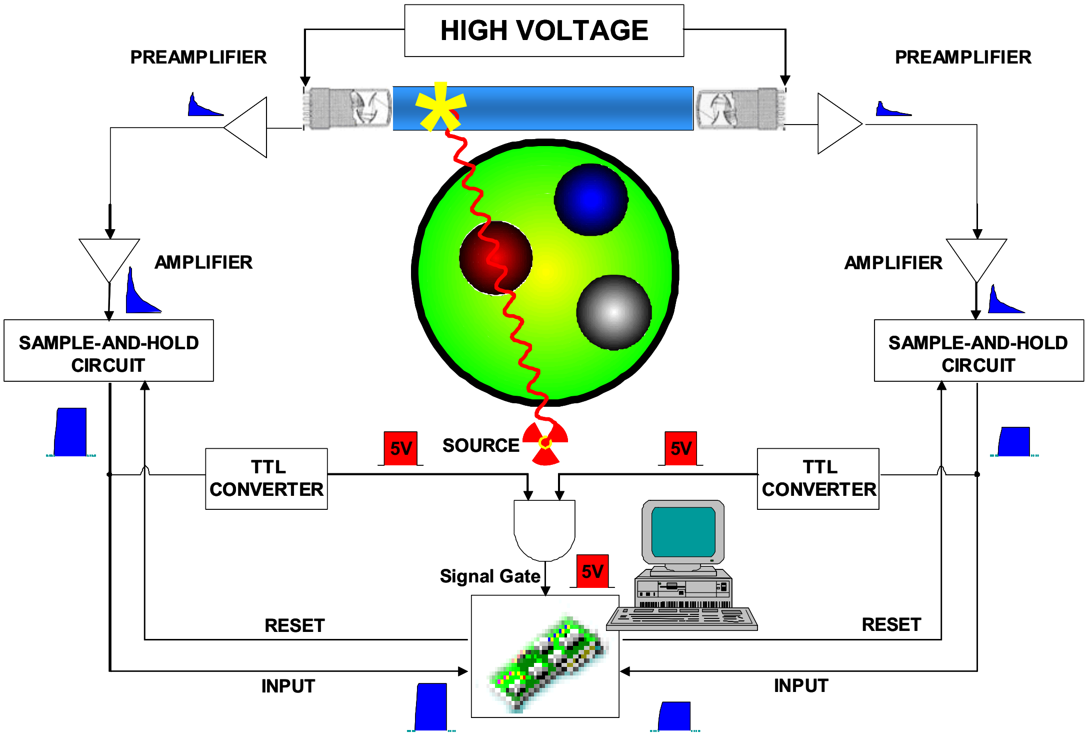


Fig. 2 – Scheme of the CT system using the plastic scintillators as position sensitive detector.

III. Results and Discussion.

Fig. 3 shows the light attenuation curve in the plastic scintillator studied in function of its distance from the photomultiplier. According to this study, the position of the incidence radiation can be predicted by the equation (3). As it can be observed in Fig. 3, the plastic scintillator cylinder can be used up to 65 cm in order to work suitably as a position sensitive detector.

The use of two photomultipliers can improve the plastic scintillator low energy resolution. On the other hand, this arrangement allows a better definition of the position of photon gamma interaction in the plastic scintillator cylinder, as it can be inferred from equation (3). In other words, the use of two phototubes can be considered an important rule in the proposed project.

In order to confirm the validity of the developed code, a cylinder of 50x10 (length and diameter) was built and coupled to two photomultipliers and the spectra measurements were carried out according to the diagram shown in Fig. 2. A simulation by Monte Carlo method was performed to validate the computer code. Fig. 6 shows this comparison. Both results present spectra fairly similar, validating the code developed. The difference observed in low energy range could be explained by gamma photon backscattering. However, it is not relevant in this application because it is far from the signal interest region.

In the present work, the tomography system was tested using a phantom placed between the detector system and a collimated ^{60}Co source. The phantom is designed with three little cylinders of different materials (steel, aluminum and air) into another cylinder filled with water. The reconstruction algorithm used was the filtered back projection technique and was developed with MATLAB system [8]. The obtained image is shown in Fig.6.

Compton scattering is the most important interactions. Its contribution decreases in function of the detector dimensions, as shown in Fig. 4. This may be the main cause of the low energy resolution of a plastic scintillator in combination with its light auto-absorption (Fig. 3).

Fig. 5 shows simulated spectra for plastic scintillator of ten cm diameter at different lengths.

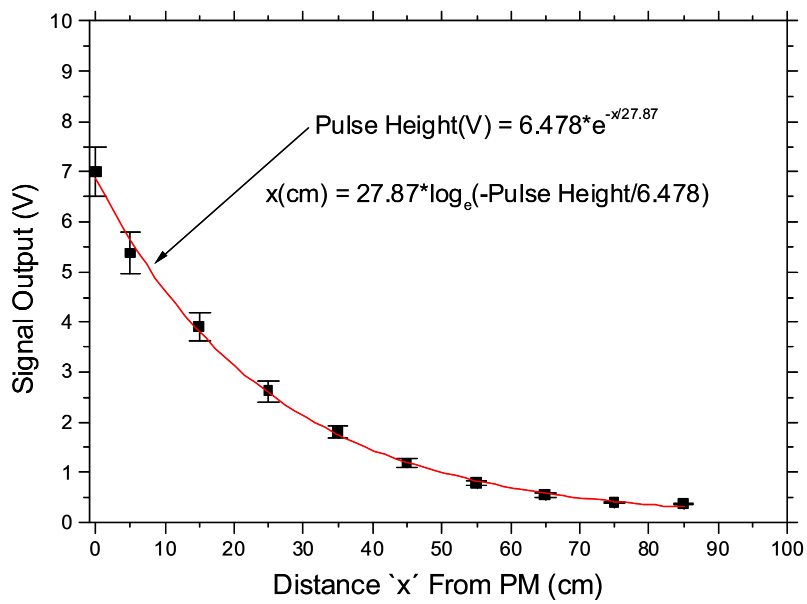


Fig. 3 – Light attenuation curve for the plastic scintillator used in this work.

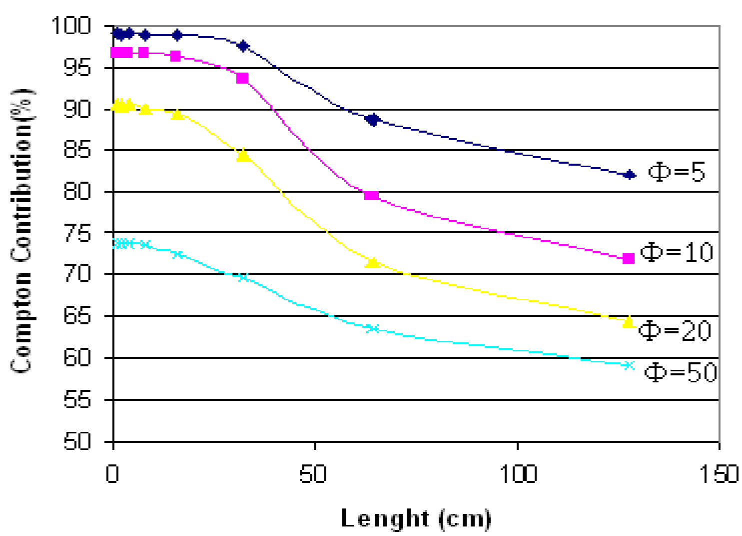
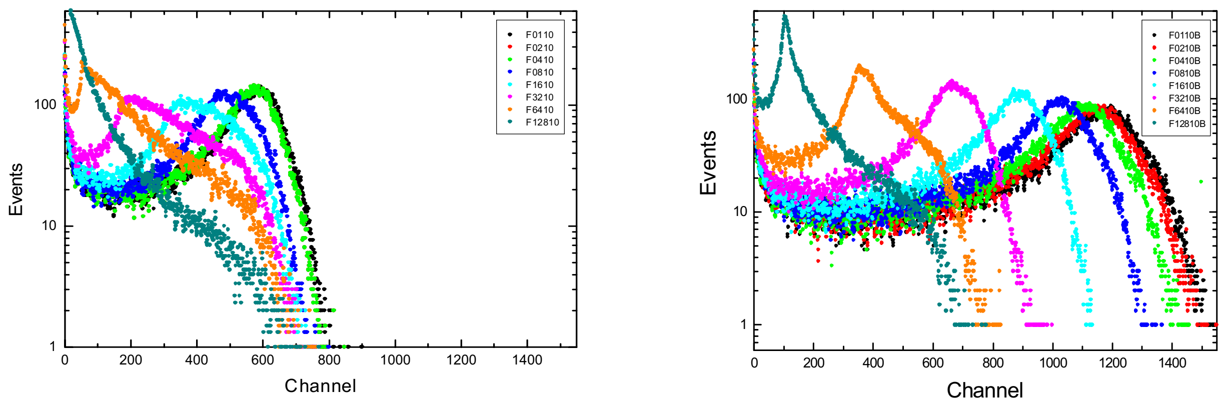
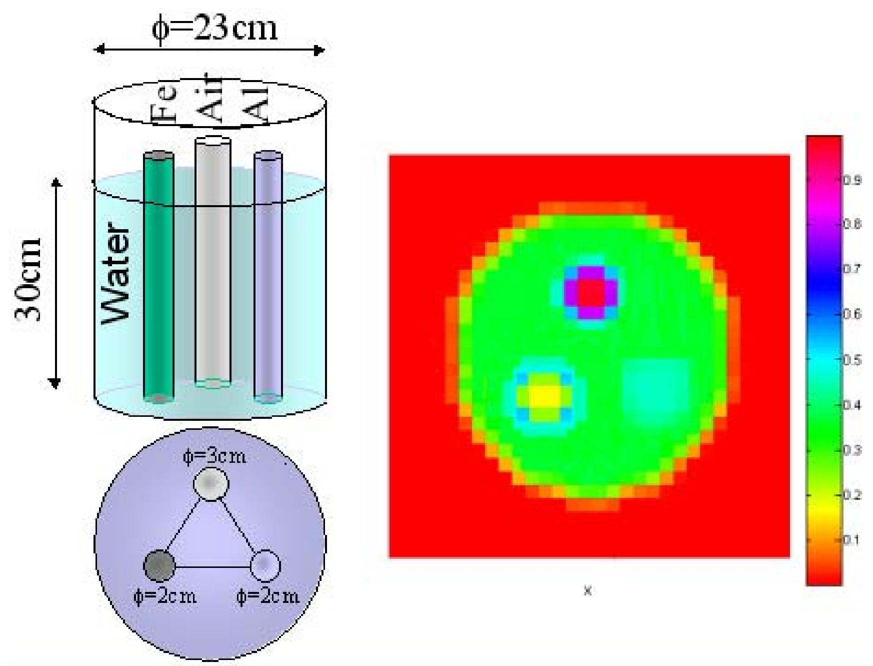


Fig. 4 – The Compton contribution in function of the detector dimensions.



(A) (B)

Fig. 5 – Energy spectra obtained with (A) one phototube and (B) two phototubes.



(A) (B)

Fig. 6 – (A) Diagram of the Phantom used to test de tomography system and (B) the respective image reconstructed.

Concluding, the plastic scintillator can be used for the industrial tomography system application. The Monte Carlo developed code was adequate for its use to foresee the suitable dimension of the scintillator detector.

IV. References

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