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Monte Carlo optimization of an industrial tomography system

A. Berdondini[a,*], M. Bettuzzi[a], D. Bianconi[a], R. Brancaccio[a], F. Casali[a], S. Cornacchia[a], A. Flisch[b], J. Hofmann[b], N. Lanconelli[a], M.P. Morigi[a], A. Pasini[a], A. Rossi[a], C. Sauerwein[c], M. Simon[c]

[a]*Department of Physics, University of Bologna and INFN, C. Berty Pichat 6-2, Bologna, Italy*
[b]*EMPA Materials Science and Technology, Department of Electronic/Metrology, Uberlandstrasse 129, Duebendorf, Switzerland*
[c]*Hans Wälischmiller GmbH, Klingleweg 8, Meersburg, Germany*

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Abstract

Computed tomography (CT) is a very useful non-destructive testing technique in the industrial field, since it permits the detection of small inner defects in a reliable and accurate way. In order to get very good performance, in terms of image contrast and spatial resolution, the configuration of the tomography system has to be optimized carefully. Monte Carlo simulations can be very helpful for choosing different conditions and selecting the best configurations of a CT system. In this paper, we present a preliminary optimization of an industrial CT apparatus, obtained by means of Monte Carlo simulations. The system is composed of an X-ray tube, filtering and collimation devices, and a detector made of a scintillator coupled to a CCD camera. We focus our attention on large aluminum objects, such as motor heads, and investigate the contribution of the scattered radiation. Some options have been simulated, for reducing the scattering photons, thus improving the overall image quality.

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Keywords: Computed tomography; Monte Carlo; Industrial CT

1. Introduction

In industrial tomography, the benefits of this technology are to audit product quality and improve process performance through identification of process end-points and optimization of process conditions. One of the aims of the physicist involved in tomography imaging research is to optimize the design of the imaging systems and to improve the quality and quantitative accuracy of the reconstructed images. The aim of this work is to investigate the optimal configuration of a tomography apparatus, made of an X-ray tube, filtering and collimation systems, and a detector composed of a scintillator coupled to a CCD camera. Detectors consisting of these main components have already been developed by our group and used for various applications [2,3]. Here, the focus is a system for industrial tomography of large aluminum objects, such as motor heads.

2. Materials

In this investigation, we used the Monte Carlo simulation code ITS-3, a powerful software package permitting state of the art solution of linear time independent-coupled photons/electrons radiation transport problems [1]. We simulated an entire industrial tomography system (Fig. 1 shows the simulated scenario).

The system consists of a 450 kVp X-ray tube, a detector composed by a scintillator and a CCD camera, two collimators (at the exit of the tube and before the scintillator, named pre-collimator and post-collimator, respectively), and various metal foils used for filtering the radiation. Since the system will be utilized for the analysis of motor heads, we simulated objects with similar characteristics (large aluminum objects with holes inside).

*Corresponding author. Tel.: +39 051 2095132; fax: +39 051 2095047.
E-mail address: andrea.berdo@libero.it (A. Berdondini).

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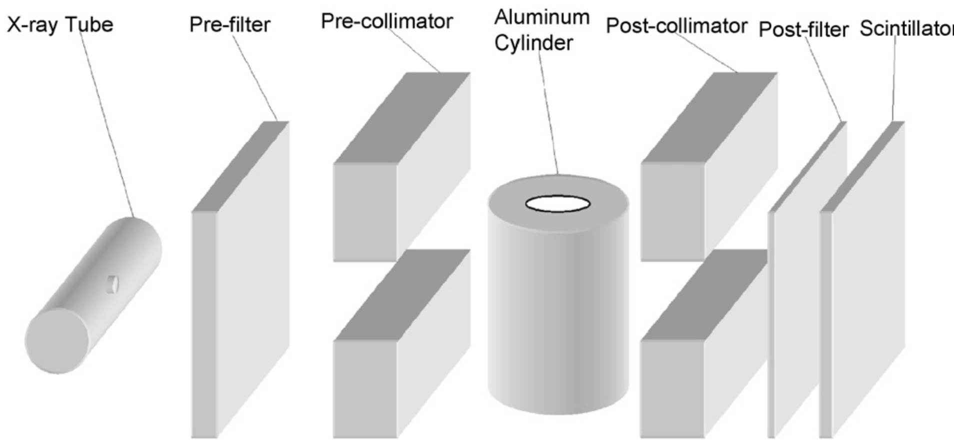

Fig. 1. Simulated scenario: the CT system is composed of an X-ray tube, some metal foils as pre- and post-filter, pre- and post-collimators, and the scintillator. The investigated object (Al cylinder with air holes) is also shown.

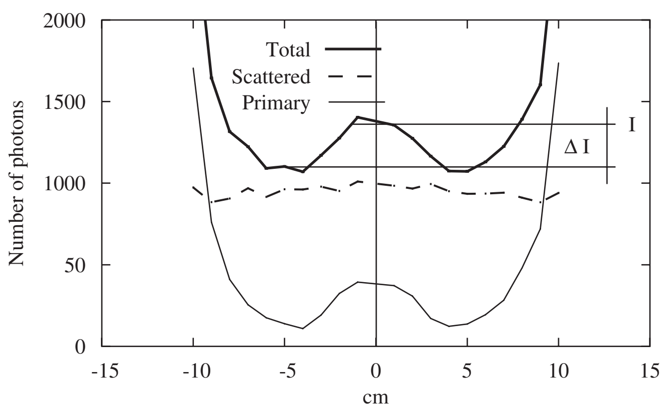

Fig. 2. Spatial distribution along the central strip of the detected photons: primary, scattered, and total. The origin of the *x*-axis coincides with the optical axis of the system which intersects the focal spot of the X-ray tube and the central axis of the cylinder.

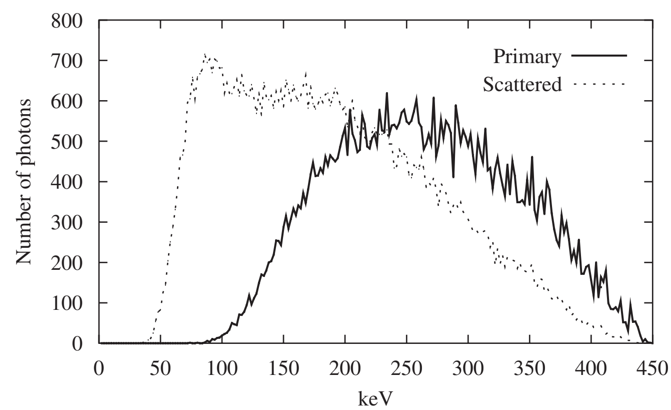

Fig. 3. Energy spectra for primary and scattered photons impinging the scintillator, for a configuration without collimators (6.4 mm Cu pre-filter).

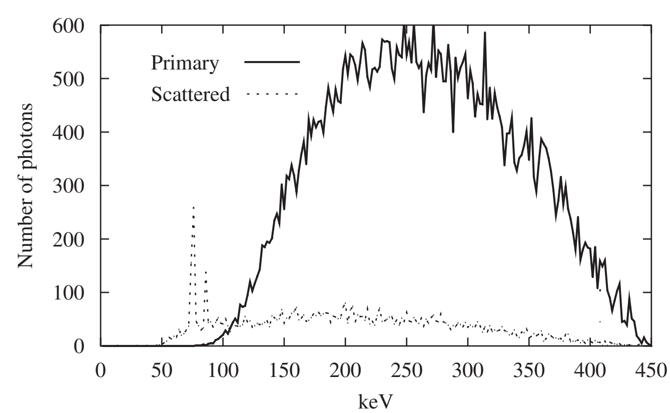

Fig. 4. Energy spectra of scattered and primary photons impinging the scintillator for a configuration with pre- and post-collimators (1 cm aperture), and 6.4 mm Cu pre-filter.

To this end, we simulated a cylinder made of aluminum with an air hole inside. The cylinder has a diameter equal to 20 cm, and the central air hole has a diameter equal to 5 cm. We simulated two different scintillators: the first one is a CsI screen (1 mm thick) and the second is a Fiber Optic Scintillating plate (FOS) with a thickness equal to 12 mm. The scintillator screen has a front area equal to $40\,cm \times 30\,cm$, but we focus our attention only on a central strip.

For each photon, we registered both the energy deposited in the scintillator and the coordinates (x, y) where the energy has been released. In addition, we marked the photons that scatter inside the object (cylinder). In this way, we can separate the detected primary (unscattered) photons from the scattered ones. For each simulation, we calculated the fraction of primary and scattered photons, the total number of detected photons, the total normalized energy deposited in the scintillator, and the energy spectra for primary and scattered photons. Furthermore, we computed the spatial distribution along the strip of the detected photons; it allows us to estimate the contrast of the central hole, with respect to background of the Al cylinder. The contrast is then defined as the ratio $\Delta I/I$, where I and ΔI have the meaning illustrated in Fig. 2.

Table 1
Results of some simulated configurations, in terms of scattering fraction, image contrast, and light photons produced on the scintillator

Parameter of the simulations	Scattered radiation fraction		Contrast		Photon light production (a. u.)	
	CsI	FOS	CsI	FOS	CsI	FOS
No collimators Pre-filter: 6.4 mm Cu No post-filter	74%	66%	16%	20%	2.2	0.7
Pre- and post-collimator: 1 cm aperture Pre-filter: 6.4 mm Cu No post-filter	18%	13%	48%	51%	0.9	0.3
Pre- and post-collimator: 1 cm aperture Pre-filter: 0.5 mm W Post-filter: 0.2 mm W + 0.8 mm Ag	10%	9%	52%	52%	0.6	0.2

3. Method

One of the main problems in applying tomography on large metal objects is the production of scattered radiation. Indeed, when the photon beam passes through the aluminum object, photons undergo a strong scattering, giving rise to two different components reaching the detector: the primary (unscattered) radiation, and the scattered component. The primary radiation is characterized by a higher average energy and gives useful information to image formation, while scattered photons have lower energy and do not contribute to useful signal.

In Fig. 3, we depict an example of the energy spectra of the scattered (noise) and primary (information) radiation that arrived on the scintillators screen, when no filtering and no collimation is used. We can note that the scattered radiation is an important fraction of the detected radiation.

We also studied the spatial distribution of these two kinds of radiation on the scintillator. As seen above, Fig. 2 shows a typical example of the spatial distribution of the scattered and primary detected photons. It is worth noting that, as expected for homogeneous objects, the scattered photons are distributed nearly uniformly over the entire scintillator screen. On the other hand, primary photons permit the observation of the cylinder's profile with the hole inside. This means that the effect of the scattering is a nearly uniform background added to the image (at least for uniform objects). As a consequence, a higher fraction will add a higher background. In other words, higher scattering will decrease the contrast of the image. In order to reduce the scattered radiation, we consider two options: the first one consists to put pre- and post-filters, whereas the second one consists in using pre- and post-collimators, as shown in Fig. 1.

4. Results

By analyzing the simulation results, it is possible to deduce some considerations about the elements of the tomography system.

Filters must absorb the low-energy photons (scattered radiation) but they must limit their influence to high-energy photons (primary radiation). Materials with a high atomic number fulfill this requirement. On the other hand, they have as a negative side effect a major fluorescence production. For this reason, post-filter that is close to scintillator shall be composed of two different layers: first, a heavy element layer and then a light element one able to reduce the fluorescence emission of the first layer.

Collimators are the most important elements for reducing the scattered radiation. A narrow aperture can reduce scattering, but on the other hand the scanning time can become very high. Fig. 4 shows the energy spectra of the photons impinging the scintillator in a configuration with pre- and post-collimators with an aperture of 1 cm. It is worth noting the great improvement, in terms of scattering fraction, of the spectra, compared to the case where no collimation was used (Fig. 3).

Scintillators: FOS detects a smaller scattering fraction than CsI, thanks to its greater thickness. That allows a better contrast on the image. On the other hand, although the deposited energy is always greater for FOS, CsI produces more light photons, for this reason the exposure time needed for getting the same gray level is always longer for FOS than that necessary for CsI.

Table 1 summarizes the value of the three calculated parameters relative to some simulations. As a general rule, the effectiveness of filtering and collimation in reducing the scattering fraction has been demostrated, thus improving image contrast. On the other hand, the exposure time will increase. A good compromise could be a collimator with an aperture of at most 2 cm, and a post-filter composed of two different materials (W and Ag), which has a good stopping power for the scattered radiation, and does not allow many fluorescence photons to reach the detector.

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