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Employing a Cerenkov detector for the thickness measurement of X-rays in a scattering background *

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Abstract The variation in environmental scattering background is a major source of systematic errors in X-ray inspection and measurement systems. As the energy of these photons consisting of environmental scattering background is much lower generally, the Cerenkov detectors having the detection threshold are likely insensitive to them and able to exclude their influence. A thickness measurement experiment is designed to verify the idea by employing a Cerenkov detector and an ionizing chamber for comparison. Furthermore, it is also found that the application of the Cerenkov detectors is helpful to exclude another systematic error from the variation of low energy components in the spectrum incident on the detector volume.

Key words X-ray, environmental scattering background, Cerenkov detector, thickness measurement

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1 Introduction

The variation in environmental scattering background is a major source of systematic errors in X-ray inspection and measurement systems, ranging from thickness measurement, radiation imaging, density measurement and HVL (half-value layer) measurement for calibrating the energy of linac electrons and so on, and it is often discussed and evaluated in practical operations, e.g., in Refs. [1–4]. The problem is more serious for the megavoltage X-ray beams with which the Compton Effect dominates the interaction between the X-ray photons and the materials. It is often tiresome to evaluate the influence of the environmental scattering background, because it is unstable and changes with the collimator system, the structure of the inspected material, the experiment layout and so on. For a liner scanning system of X-ray radiation imaging, the final images distorted by scattering factors may be discerned and not produce a serious problem, while for complex systems that require more complex computations, such as CT and material discriminations [5], these errors may produce bewildering results. The conventional method to minimize the scattering influence involves refining the collimator system and shielding around detectors with heavy metals, often together with Monte Carlo simulation for evaluation and optimization and so on. Because thickness measurements are actually the foundation of radiation imaging and other similar measurements with transmitting X-ray beams, they should share the same problems and solutions. In this paper, we attempt to explore the peculiar function of the Cerenkov detector in thickness measurements in varied environmental scattering backgrounds.

The energy of these photons consisting of environmental scattering backgrounds is much lower generally. For example, the pulse height spectra from gamma-ray detectors often show a peak (called the backscatter peak) in the vicinity of 0.2–0.25 MeV [6]. So we may employ a Cerenkov detector using its detection threshold as an inherent ability to exclude the influence from the scattering factors.

In one of our previous publications [7], a practical Cerenkov detector was designed with a CsI(Tl) detector to calibrate the energy variation of an electron

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linac, and this has a threshold of 0.5 MeV for X-ray photons. Fig. 1 shows the scattered photons' energy in different scattering angles, and we can see that the energy of the scattered photons with the scattering angle of 90° is no more than 0.5 MeV, no matter how much their original energy is.

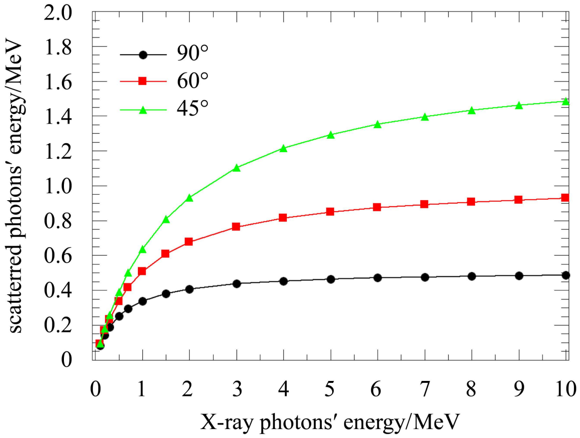


Fig. 1. The scattered photons' energy.

With the experiment layout in Fig. 2, the scattered photons incident in the detector active volume should have scattering angles larger than 90°, so in principle the Cerenkov detector can exclude these scattering influences.

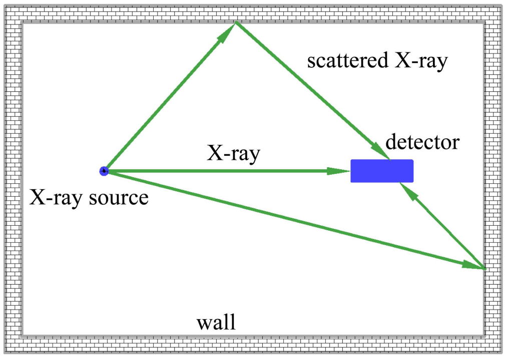


Fig. 2. Experiment layout with Cerenkov detector not suffering the scattering factor.

There is another systematic error from the variation of low energy components of bremsstrahlung spectra. Fig. 3 shows the spectra of an electron linac with the energy of 6 MeV and thick tungsten target simulated by Geant4. Despite their different magnitudes at different outgoing angles, they have the same character that the low energy component (i.e., below 0.5 MeV) contributes considerably to the whole spectrum, and the peaks are at about 0.4 MeV (beside the peak locating 0.511 MeV from the annihilation radiation). Moreover, these low-energy photons have a greater attenuation coefficient, so both the inspected materials and the detectors are sensitive to them. Meanwhile, it also changes with the tungsten target thickness and casing material for electron linacs, detectors and so on, and may lead to some errors in the measurement result. Fig. 3 gives a simulation result of the filtered spectrum with a 6 mm-thick steel board. A practical measurement, for example, HVL measurement for calibrating the energy of electron linac suffers these influences [3]. It is then a demanding task to evaluate the error both in practical measurements and in calculations.

In the following, we attempt to verify the advantages of employing Cerenkov detectors in an environmental scattering background through a carefully designed thickness measurement experiment. Another experiment on the influence from the filtered X-ray beam spectrum is also carried out to enhance the understanding of the particular function of Cerenkov detectors.

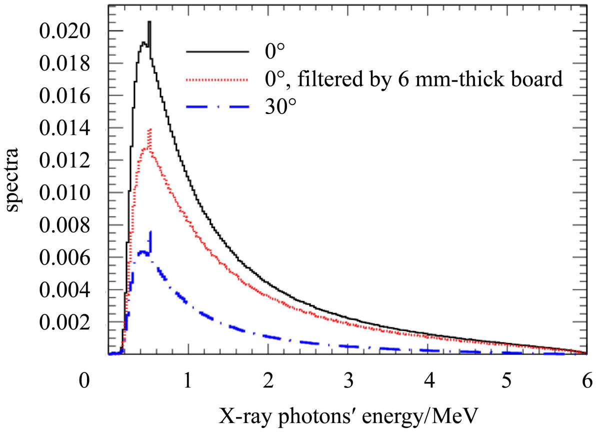
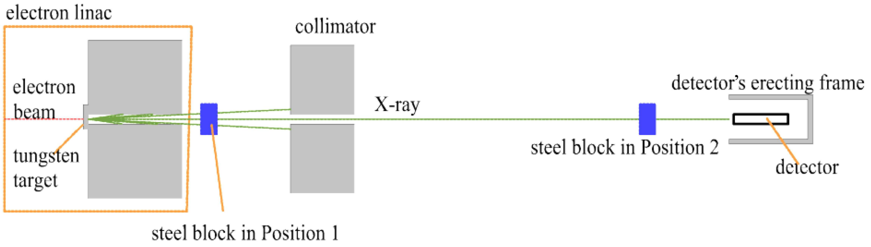


Fig. 3. The bremsstrahlung spectra of a 6 MeV electron linac simulated with Geant4. The uppermost curve is the spectrum at 0° angle between the outgoing X-ray beam and the linac's electron beam. The lowermost curve is that at 30° and the curve in between is that at 0° angle but filtered by a 6 mm-thick board.

2 Experiment on scattering influence

The experiment layout is depicted in Fig. 4. The X-ray beams from the tungsten target of the electron linac flush out through the gap of the collimator and reach the detector at its erecting frame. According to the geometry, the width of the beam at the detector position is about 1 cm, the topmost spot in the detector erecting frame that the X-ray beam can reach lies at a distance about 2.5 m from the detectors, and that of the lowermost spot is about 0.8 m. The electron linac is produced in Nuctech with 6 MeV energy. The distance between the electron linac and the detectors is about 7 m, and that between the collimator and the electron linac is about 1.5 m. An iron block of 200 mm (height) × 100 mm (width) × 50 mm (thickness) is used as the inspected material. It is placed perpendicular to the X-ray beam. If the iron block is placed in Position 1 between the electron linac and the collimator, there will be fewer photons from the X-ray source arriving at the detector's erecting frame to produce a scattering background than in the case with a block in Position 2 about 1.5 m from the detector. However, if there are only X-ray photons from the tungsten target directly incident to the detector's volume, that is, without scattered photons, the detector will have two almost identical signals whether the iron block is in Position 1 or 2.

(a) top-sectional view



(b) front-sectional view

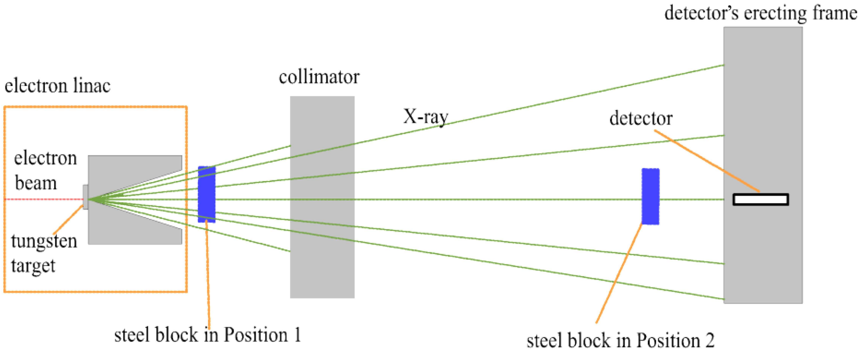


Fig. 4. Experimental layout for evaluating the influence of the environmental scattering background.

The electron linac is operated in 20 Hz with a 10 cGy/min dose rate. The average detector's output for one thousand pulses of incident X-ray beams is used as the detector's signal magnitude for further calculation.

The structure of the Cerenkov detector and its energy response can be found in Ref. [7]. An ionization chamber produced in the Nuctech of model NT/GD02 is used to compare the results with those from the Cerenkov detector. The detector is 21 cm long and has a 1 cm×1 cm cross section, and it is filled with 31atm xenon gas.

The scattered photons' spectra incident in the Cerenkov detector's active volume in different experiment conditions are simulated and plotted in Fig. 5. First, we can see that the main peaks of these spectra locate similarly at around 0.2 MeV (the annihilation peak is located at 0.511 MeV for all situations). Secondly, the magnitude exhibits an insignificant difference among the three spectra, indicating that the scattering background is not sensitively dependent on the thickness of the iron block at Position 2, which is

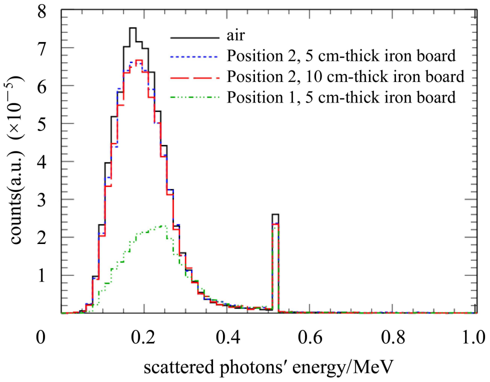


Fig. 5. Spectra of scattering photons incident in the Cerenkov detector.

close to the detector. The simulated spectra for the ionization chamber are similar and will not be presented here.

To compare the influence of the scattering factors on the two detectors, and the results between the experiment and calculations, we normalize the detectors' signal in different experimental conditions to the signal without any medium (e.g., iron block) between the electron linac and the detectors, i.e.,

$$R=\frac{S}{S_{\mathrm{Air}}}, \tag{1}$$

where S_{Air} is the average output signal magnitude from the circuits of the detector without any medium, and S is the value with a medium. In calculations, these signal magnitudes are represented by the quantity of Cerenkov photons for the Cerenkov detectors, and the electron-ion pairs for the ionization chamber, respectively. To compare the deviation of R value between Position 1 and Position 2, we define

$$D=\frac{R_2-R_1}{R_1}, \tag{2}$$

where R_2 and R_1 are the R value in Position 1 and Position 2 with identical thickness of iron block, respectively; D is the relative deviation and also is the quantity for evaluating the magnitude of scattering influence.

The calculation results by Geant4 are presented in Table 1 and Table 2 in comparison with the experimental measurements. The relative statistical uncertainty of the experimental data is smaller than 1%, while the uncertainty of the simulation is smaller than 0.5%. It is shown that the Cerenkov detector gives an insignificant difference between the two scattering backgrounds compared to that given by the ionization chamber. The results for the ionization chamber have about five times deviation higher than those for the Cerenkov detector.

Table 1. Results from the Cerenkov detector.

observable	iron block's mass thickness/(g/cm^2)			
	39.3		78.6	
	calculation	experiment	calculation	experiment
R_1	0.221	0.220	0.054	0.056
R_2	0.223	0.225	0.056	0.062
D	1.0%	2.3%	3.7%	10.7%

Table 2. Results from the ionization chamber.

observable	iron block's mass thickness/(g/cm^2)			
	39.3		78.6	
	calculation	experiment	calculation	experiment
R_1	0.133	0.140	0.030	0.037
R_2	0.144	0.158	0.041	0.056
D	7.8%	12.9%	36.7%	51.4%

3 Experiment on the influence of the variation of the low energy component on the energy distribution of X-ray photons

We apply a 6 mm-thick steel board next to the X-ray beam exit of the electron linac to filter the bremsstrahlung spectrum to impose a change on the outgoing X-ray energy distribution. The iron block is also placed in Position 1. The comparison of the normalized magnitude R in the two conditions with or without the steel board is shown in Table 3 for the Cerenkov detector and the ionization chamber. Without the filtering board, the normalized magnitude is calculated using Eq. (1), while with the filtering board,

$$R'=\frac{S'}{S'_{\mathrm{Air}}}, \tag{3}$$

where S' and S'_{air} are the same as those in Eq. (1), except that the filtering material is employed. Similarly, the deviation between R and R' is defined as

$$D'=\frac{R'-R}{R}. \tag{4}$$

The experimental results are shown in Table 3. The deviation in the normalized magnitude with or without the iron block is almost negligible for the Cerenkov detector, in contrast to an obvious difference for the ionization chamber.

Table 3. Experimental results with the filtering material and without.

observable	mass thickness/(g/cm^2)			
	Cerenkov detector		ionization chamber	
	39.3	78.6	39.3	78.6
R	0.220	0.056	0.140	0.037
R'	0.224	0.059	0.151	0.041
D'	1.8%	5.4%	7.9%	10.8%

4 Discussion and summary

In practice, there are two types of scattering source in the first experiment in Section 3: the forward-scattered photons from the iron block directly incident on the detector active volume and the multi-scattered photons that consist of an environmental scattering background. Because there is a distance between the iron block and the detectors, the former has a smaller quantity than the latter.

The simulation results by Geant4 show that the first source only a signal increase not more than 4% in the experiments.

For the two types of systematic errors from the environmental scattering background and variation of low energy component of spectra, the Cerenkov detector demonstrates an inherent ability to exclude their influence, which in turn makes thickness measurement more robust and adaptable. Given that conventional detectors such as scintillation detectors and ionization chambers have much higher sensitivity and are sophisticated in this field, Cerenkov detectors may only play the role as a reference at present. However, for the advantage and functions of Cerenkov detectors presented in this paper and our earlier publication [7], it may be worthwhile exploring new techniques to improve the usability of Cerenkov detectors in thickness measurement and radiation imaging.

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