Optimization of the design of scattered radiation detectors

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Abstract. The article deals with the problem of implementing one-way object control with the help of X-ray radiation. Various geometries and materials of radiation detectors are considered. The efficiency of detection of scattered radiation by means of inorganic and organic scintillation detectors with various effective atomic numbers is estimated. Calculations and experiments to determine the signal-to-noise ratio for scanning systems with registration of the radiation beam reflected from the object were carried out taking into account dynamic blurring. Methods for manufacturing detectors that increase the collection efficiency of secondary low-energy quanta formed in the body of the scintillator and reduce the overall dimensions structure are considered. The conditions for achieving the maximum of the efficiency of detection of light photons are determined and the designs proposed for their practical realization.

Certain tasks that have arisen in industry and Russian law enforcement structures have required the creation of X-ray scanners on backscattered radiation – devices that provide information on the internal structure of a controlled object by X-ray radiation when the source and receiver are located on one side of it [1, 2]. When developing this device, recording back scattered radiation from the object of control, it was necessary to solve the following tasks: ensure the required reliability of the registration of the presence of inhomogeneities in the field of control; provide the minimum possible dose load, both to the object of control, and to the operator; provide high performance control.

The reliability of registration is determined both by the deterministic and stochastic parameters of the radiation detection system. Deterministic parameters include: density of the control object and its effective atomic number; density of the inclusion to be detected, its dimensions and the effective atomic number; energy of incident and reflected radiation beams; distance from the focus of the X-ray tube to the target; distance from the monitoring object to the entrance window of the backscattered radiation detector; area of the scanning radiation beam on the surface of the monitoring object; area of the entrance window of the scattered radiation detector; speed of the scanning beam’s movement along the object of control; albedo of the scanning beam from the object of the control; albedo of the scanning beam from the inclusion material to be detected.

The stochastic parameters for recording backscattered quanta include: number of quanta falling on the object of control; number of quanta reflected from the object of control; probability of interaction of incident quanta with the material of the object of control; efficiency of registration of reflected radiation by an X-ray detector. The probability of detecting a foreign inclusion in the object is determined by the signal-to-noise ratio.

\[ \frac{S}{N} = \frac{\Delta N}{\sqrt{N_1 + N_2}} \]

where \( \Delta N = |N_1 - N_2| \), \( N_1 \) and \( N_2 \) – the number of quanta recorded by the detection system from the monitoring object and the artifact (inclusion) to be detected, respectively. When detecting X-ray radiation reflected from an object, the signal-to-noise ratio is determined by the following expression:

\[ \frac{S}{N} = \frac{\Delta N}{\sqrt{N_1 + N_2}} \]


\[
\left( \frac{S}{N} \right)_{a} = 2.4 \cdot 10^{3} \cdot \exp \left[ - \left( \mu_{ob} + \mu_{ob}^{\prime} \right) d \right] \alpha_{s} - 2.4 \cdot \exp \frac{P_{o} \cdot i_{a} \cdot S_{s} \cdot S_{d} \cdot \Delta t \cdot \eta}{\alpha_{w} \cdot E \cdot \mu_{m}},
\]

(2)

where \( \mu_{ob} \) and \( \mu_{ob}^{\prime} \) – energy attenuation coefficients in the monitoring object for direct and back scattered radiation, respectively; \( d \) – depth of occurrence of the inclusion to be detected; \( \alpha_{s} \) and \( \alpha_{s} - \) albedo of the control object material and the inclusion material, respectively; \( F_{1} \) and \( F_{2} \) – distance from the focus of the tube to the object of control and from the object of control to the entrance window of the backscattered radiation detector; \( P_{o} \) – radiation yield of X-ray radiation; \( i_{a} \) – anode current of the X-ray tube; \( S_{a} \) – area of the scanning spot; \( S_{d} \) – area of the entrance window of the radiation detector; \( E \) – energy of the scanning radiation beam; \( \mu_{m} \) – mass coefficient of electron conversion of the energy of the scanning radiation beam in air; \( \Delta t \) – scanning time of a single quasi-pixel, determined by the area of the scanning beam and the scanning speed; \( \eta \) – detection efficiency of the backscattered X-ray beam by the detector.

With a signal-to-noise ratio \( > 3 \), the probability of recording the foreign inclusion is \( P \geq 99.6 \% \). The efficiency of registration when scanning an object of control will be determined not only by the efficiency of absorption of radiation quanta and the efficiency of conversion of quanta into an electrical signal, but also by the speed of the recording system [3].

Expressions (1) and (2) that determine the signal-to-noise ratio do not take into account the dynamics of the registration process when scanning an object of control. In order to take into account the influence of the time for the movement of a narrow X-ray beam on the object of monitoring and the response of the detector signal, we introduce into the expression (2) an additional term determining the dynamic blurriness of the image of the scanning object – \( K_{d} \), and also determine its effect on the signal-to-noise ratio at the output of the registration system.

\[
K_{d} = \exp \left( \frac{\tau}{\Delta t} \right),
\]

(3)

where \( \tau \) – inertia of the detection system in seconds; \( \Delta t \) – scan time of one quasi-pixel per second.

\[
\Delta t = \frac{S}{V},
\]

(4)

where \( S \) – area of one quasi-pixel, determined by the aperture of the scanning beam and the distance from the emitter to the scanning object in \( \text{cm}^{2} \); \( V \) – velocity of the scanning beam in the plane of the scanning object in \( \text{cm/s} \). Taking into account expression (4), the expression for dynamic blur becomes:

\[
K_{d} = \exp \left( V \cdot \frac{\tau}{\sqrt{S}} \right).
\]

(5)

For the convenience of analyzing expression (5), we expand the exponential function in a series and consider the first two terms of this series:

\[
K_{d} = 1 + V \cdot \frac{\tau}{\sqrt{S}}.
\]

(6)

The task of maintaining a high signal-to-noise ratio when scanning a monitoring object will be performed at \( K_{d} \rightarrow 1 \), that is, when \( V \cdot \tau \sqrt{S} \rightarrow 0 \).

Given that the scanning speed \( V \) is set and determined by the performance of the monitoring system, it is desirable to have the maximum possible speed, while maintaining the specified image quality. Increase the area of the scanning beam \( S \) is also undesirable, since this leads to a deterioration in the resolving power of the scanner.

There remains one choice – to ensure the maximum speed of the detector, that is, for \( \tau \rightarrow 0 \), \( K_{d} \rightarrow 1 \). This condition meets the requirement of maintaining a given signal-to-noise ratio at high resolution and a given control performance.

Taking into account the dynamic blurriness, the signal-to-noise ratio for scanning systems with registration of the radiation beam reflected from the object takes the form:

\[
\left( \frac{S}{N} \right)_{a} = \exp \left( V \cdot \frac{\tau}{\sqrt{S}} \right)^{-1} \left( \frac{S}{N} \right)_{a},
\]

(7)
where \((S/N)_{st}\) – value obtained for the static model by expression (2).

Thus, we were faced with the task of developing a detector with high speed and a high efficiency of detecting X-ray quanta reflected from the object of scanning. When choosing the material of the scintillator conjugated with the photoelectric multiplier (PMT), it was first of all necessary to ensure its high speed. This requirement is best met by organic scintillators: stilbene and anthracene (table 1).

**Table 1.** The main parameters of organic scintillators.

| Scintillator | Density, g/cm³ | Effective atomic number \(Z_{eff}\) | Decay time \(\tau\), s | Wavelength of the spectrum, nm |
|--------------|----------------|-----------------------------------|---------------------|-------------------------------|
| Anthracene   | 1.25           | 5.8                               | \(2.5 \times 10^{-9}\) | 445                           |
| Stilben      | 1.16           | 5.7                               | \(7 \times 10^{-9}\)  | 410                           |

However, their low density and small effective atomic number do not provide high registration efficiency. While inorganic scintillators (table 2) such as ZnS(Ag) or CaWO₄ provide high registration efficiency due to high density and high effective atomic number \(Z_{eff}\).

**Table 2.** The main parameters of inorganic scintillators.

| Scintillator | Density, g/cm³ | Effective atomic number \(Z_{eff}\) | Decay time \(\tau\), s | Wavelength of the spectrum, nm |
|--------------|----------------|-----------------------------------|---------------------|-------------------------------|
| ZnS(Ag)      | 4.1            | 27                                | \(>10^6\)           | 450                           |
| CaWO₄        | 6.06           | 59                                | \(>10^6\)           | 430                           |
| NaJ(Tl)      | 3.67           | 50                                | \(2.5 \times 10^{-7}\) | 410                           |

The widely used inorganic scintillators NaJ(Te) and CsJ(Te) have a decay time of 250 ns and 700 ns, respectively. Which is also significantly more than anthracene and stilbene.

However, for scanning systems, the use of inorganic scintillators leads to image blurring. Therefore, for scanner systems, practically inertial scintillators of anthracene or stilbene type (\(\tau \sim 10^{-8}\) s, table 1), should be used. The disadvantage of organic scintillators is their relatively low efficiency of converting the energy of X-ray quanta into light. This is due to their relatively low density, as well as an insignificant effective atomic number (table 1) compared to inorganic scintillators (table 2). In order to increase the efficiency of the conversion of organic scintillators, the technologies for manufacturing scintillator materials with additions of high-atomic metals, for example, tin, have been used [2]. This made it possible to substantially increase the efficiency of recording inorganic scintillators without impairing their speed. Organic scintillators based on polystyrene and polyvinyltoluene with tin additives have a maximum of light output in the ranges 380–425 nm and 370–500 nm, respectively and comparatively high refractive index \(n_1 = 1.52\) and \(n_2 = 1.58\), respectively, which allows a good collection of light photons at comparatively long scintillation blocks, since they become light guides for formed in them photons of light.

Light photons are formed in the scintillator and propagate in a solid angle of \(4\pi\), from which they can either directly enter the photocathode of the photomultiplier, or undergo a complete internal reflection from the faces of the scintillator once or repeatedly. Figure 1 shows a simplified scheme of this process, with the formation of scintillations on the front face and the condition of their total internal reflection, where \(n -\) refractive index of the scintillator; \(\alpha -\) angle of incidence of the light photon on the opposite face of the scintillator; \(\beta -\) solid angle, within which the formed light photons do not undergo complete internal reflection.

Let us determine the value of the critical angle \(\alpha\), at which the total internal reflection of light photons is achieved: \(\alpha = \arcsin(n_2/n_1)\), where \(n_1 -\) refractive index of light in the scintillator material; \(n_2 -\) refractive index of light in the material surrounding the scintillator. The condition of total internal reflection is achieved for \(n_1 > n_2\). For the case when the scintillator is in contact with air, \(n_2 \sim 1\) and the
Condition of total internal reflection is reached when \( \alpha \geq \arcsin\left(\frac{1}{n}\right) \). For scintillators based on polyvinyltoluene \( n = 1.58 \), \( \alpha = 39.3^\circ \). At the same time, the dead angle \( \beta = 2\alpha = 78.5^\circ \).

**Figure 1.** Simplified scheme of the process.

**Figure 2.** Way to increase the light collection.

In order to increase the light collection of the photon scintillator reflected from the faces, a scintillator configuration with a slope of its faces in the direction of the photomultiplier of the photomultiplier at the angle \( \theta \) (figure 2) was proposed, which allows to reduce the dead zone \( \beta \) by the values of the slope angle \( \theta \) and to provide an increase in the light-gathering photon, where \( \theta \) – angle of inclination of the reflecting face of the scintillator; \( \alpha \) – angle of the bevel of the end of the scintillator opposite to the photomultiplier, equal to the critical angle. At \( \theta \geq \arcsin(1/n) \), all photons will be reflected from the opposite face of the scintillator by the condition of total internal reflection. The probability of reflection is given by

\[
\eta_o = 1 - 2\arcsin\left(\frac{1}{n}\right)/180^\circ.
\]  

Expression (8) does not take into account the transparency of the scintillator to its own radiation. The condition \( \theta \geq \arcsin(1/n) \) practically limits the length of the scintillator, contradicts the requirement of the maximum area of its surface \( S_{\theta} \), on which the X-ray beam falls (2).

Taking into account the fact that in order to reach the photocathode plane of the photomultiplier, the reflected photons have to undergo multiple reflection from opposite sides of the scintillator, and at each reflection losses take place, taking into account which expression (8) takes the form

\[
\eta_i = C^{X_{sc}} \cdot \left(S_{nk}/S_{tsc}\right) \cdot \eta_o,
\]

where \( C \) – reflection coefficient, taking into account the quality of polishing of the faces of the scintillator (~0.9); \( S_{nk} \) – photocathode area of the photomultiplier; \( S_{tsc} \) – area of the end face of the scintillator, conjugate with the photomultiplier; \( K_{otr} \) – number of reflections before the PEM photocathode hits the plane. Thus, for the critical angle determined by the refractive index of the scintillator and triple reflection with a reflection coefficient of 0.9, the efficiency \( \eta_i \) is

\[
\eta_i = 0.9^4(1-(2\arcsin(1/1.58))/180^\circ)\cdot100\% = 41\% \text{ to } \left(S_{nk}/S_{tsc}\right) = 1.
\]

At the end position of the photomultiplier to the scintillation unit (figure 3), in addition to the reflected photons reaching the photocathode plane, photons of direct visibility also fall on its surface.

**Figure 3.** Simplified scheme of the process.

The efficiency of direct entry of photons onto the photocathode of a photomultiplier is determined by the following expression

\[
\eta_{\text{mas}} = S_{nk}/4\pi X^2 \cdot \exp(-X/L_{\alpha}),
\]

where \( S_{nk} \) – photocathode area of the photomultiplier; \( X \) – distance from the photocathode plane to the site of scintillation formation; \( L_{\alpha} \) – relaxation length, which determines the attenuation of the number of scintillation photons by a factor of “e” in the scintillator material.

The total efficiency of collecting photons formed in the scintillator, taking into account both the reflected photons trapped in the photocathode plane and the line-of-sight photons, is described by the following expression

\[
\eta_i = C^{X_{sc}} \cdot \left(S_{nk}/S_{tsc}\right) \left(1-2\arcsin(1/n)/180^\circ\right) + \left(S_{nk}/4\pi X^2\right).
\]
The expression (11) does not take into account the self-absorption of photons in the scintillator material, determined by the path length of the photons to the PEM photocathode and the relaxation length $L_\text{e}$ (10). Expression (11) takes into account only the entry of photons onto the entrance surface of the photocathode, without taking into account the absorption and reflection of photons from the input window of the photomultiplier and without taking into account the coefficient of spectral matching of the scintillator photon spectrum and the spectral distribution of the photocathode sensitivity. Let us determine the number of light photons formed in the scintillator in recording X-ray quanta (phot/s)

$$N_{\text{ph}} = \left(10^3 \cdot N_{\text{ph}} \cdot E \cdot S \cdot \left[1 - \exp\left(-\mu_l \cdot d\right)\right]/W\right) \cdot \left(\mu_e/\mu_l\right),$$  \hspace{0.5cm} (12)

where $N_{\text{ph}}$ – number of X-ray quanta incident on the scintillation detector (kv/cm^2-s); $E$ – quantum energy (keV). The energy of the backscattered quantum at $U_a = 100$ kV corresponds to 30 keV; $S$ – area of the input surface of the scintillation detector (cm^2); $\mu_l$ – coefficient of linear attenuation of the scintillator for energy $E$ (cm^{-1}); $\mu_k$ – coefficient of electron energy conversion in the scintillator material, (cm^{-1}); $d$ – thickness of the scintillator in the direction of the X-ray flux (cm); $W$ – energy expended by the electron formed in the scintillator material to form a single photon (eV). For organic scintillators, $W \sim 32$ eV.

When scanning a control object with a narrow beam of radiation with the beam area at the object input $\Delta S$ (cm^2) and the scan rate $V$ (cm/s), the time of irradiation of the scintillator with quanta reflected from one quasi-pixel $\Delta t$ is determined by the following expression (s): $\Delta t = \sqrt{\Delta S}/V$, $\Delta t$ can also be set by the clock frequency of the pulse counter at the PMT output. In this case, the number of photons produced in the scintillator during the time $\Delta t$ is defined as:

$$N_{\text{ph}(\Delta S)} = N_{\text{ph}} \cdot \Delta t,$$  \hspace{0.5cm} (13)

where $N_{\text{ph}}$ is determined from expression (11). The next task is the transmission of light photons to the photocathode photomultiplier.

$$N_{\text{lk}} = \left(N_{\text{ph}} \cdot S_{\text{lk}}/4\pi\right) \cdot \exp\left(-l/L_\text{e}\right),$$  \hspace{0.5cm} (14)

where $S_{\text{lk}}$ – photocathode area of the photomultiplier; $l$ – length of the scintillator; $L_\text{e}$ – relaxation length of photons in the scintillator, at which the attenuation of photons occurs “e” times. The length of relaxation depends not only on the scattering and absorption of scintillation photons in the scintillator material, but also on the geometric dimensions, the quality of the polishing of the scintillator faces and the reflection coefficient from the scintillator faces and their number. Expression (14) refers to the case when one photomultiplier is used, located at the end of the scintillator.

Expression (14) determines the number of light photons formed in the scintillator and trapped on the photocathode when the photomultiplier is placed at one end of the scintillation block.

The total number of light photons reaching the photocathode photomultiplier is determined by the following expression

$$\sum N_{\text{lk}} = \left(N_{\text{ph}} \cdot S_{\text{lk}}/4\pi\right) \int_0^l \exp\left(-x/L\right)dx,$$  \hspace{0.5cm} (15)

where $l$ – length of the scintillator. Expression (15) corresponds to the requirements of an ideal light guide with complete internal reflection from the faces of the scintillator and photons incident on the photocathode.

For practical calculations, by expression (15), we can replace the integral from “0” to “l” by a sum of discrete values with a given step along the length of the scintillator. Moreover, the expression (15) without taking into account the constant term $(N_{\text{ph}} \cdot S_{\text{lk}})/4\pi$ takes the form

$$\sum_{n=1}^n N_{\text{lk}} = (N_1 + N_2 + \ldots + N_n),$$  \hspace{0.5cm} (16)

where $N_1 = N_{\text{ph}} \cdot \exp(-\Delta l/L)$, $N_2 = N_{\text{ph}} \cdot \exp(-2\Delta l/L)$, $\ldots$, $N_n = N_{\text{ph}} \cdot \exp(-n\Delta l/L)$, $n = l/\Delta l$. 

5
The collection of light photons by conjugation of a scintillation crystal with a photomultiplier is optimal under the condition that \( S_{fk} = S_{ttsc} \) when the photocathode area of the photomultiplier is equal to the cross-sectional area of the scintillator.

As an example, figure 4 shows a sensitivity diagram of a scintillator with a width of 200 mm and a length of 650 mm, depending on the location of the gamma source along its length.

![Figure 4. The sensitivity of the scintillator, depending on the location of the gamma source along its length.](image)

For the purpose of registering radiation with a scanning X-ray beam, in order to reduce the dynamic blur, it is necessary to fulfill the condition: \( \tau \ll \sqrt{S/V} \).

The efficiency of registration reaches its highest value, provided that: \( (\text{photocathode area})/(\text{area of the cross section of the scintillator}) \to 1 \). In this case, if possible, a photomultiplier with a maximum photocathode diameter should be used.

In order to increase the collection of light photons, it is possible to skew the opposite end face of the scintillator to a critical angle \( \alpha \), and also to use the bevel of the scintillator at an angle \( \theta \) in the photocathode photocathode direction.

To smooth out the response function of signals from the photomultiplier when scanning with a narrow scintillator beam, three or more photomultipliers should be used to select photons from the dead band formed by the angle \( \beta \). The results of measurements are presented in table 3.

### Table 3. The results of measurements.

| Area of the input surface, cm\(^2\) | Thickness, cm | Length, cm | Width, cm | Sensitivity, Nm/cm\(^2\) | Efficiency \( \eta \), % |
|-------------------------------------|---------------|------------|-----------|------------------------|------------------------|
| 1270                                | 3.5           | 63.5       | 20        | 0.3                    | 5                      |
| 825.5                               | 3.5           | 62         | 14        | 0.36                   | 6                      |
| 23.4                                | 3.5           | 27.5       | 8.5       | 0.6                    | 10                     |
| 42.3                                | 3.5           | 27.5       | 16        | 0.58                   | 9.6                    |

Also, the dose rate of backscattered X-ray radiation in the plane of the scintillation block input window was measured with the help of the DKS-AT1123 dosimeter. The dose rate at \( U_s = 100 \text{ kV} \) and \( i_s = 3 \text{ mA} \) was 45 \( \mu \text{Sv/h} \). At a scattered photon energy of \( \sim 30 \text{ keV} \), the measured dose rate corresponds to 6 ph/cm\(^2\) during the time \( \Delta t = 64 \mu\text{s} \).

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