RESEARCH OF THE WORK OF TECHNOLOGICAL COMPTON SCATTERING TOMOGRAPH ON THE PHOTON BEAM OF THE SOURCE ^{137}Cs

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The results of the works, which have been carried out in NSC KIPT, on creation of a stationary technological Compton scattering tomograph are submitted. Modeling physical processes under program GEANT 3 is carried out, the design of a tomograph for a case of use is determined as a source of photons of the accelerator Van de Graaf on energy 3 MeV. Tests results of a tomograph work on a photon beam of the source ^{137}Cs are submitted.

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1. INTRODUCTION

Application of the tomography based on Compton scattering measurement, for the purposes of nondestructive research of substance, materials and products properties is justified in that case when other traditional methods or cannot give necessary contrast and solution, either their application basically is impossible (as, for example, in case of a rentgenoscopic method when there is an access to a product only on the one side).

Physical basis of a technological Compton scattering tomograph's work is that phenomena, that in a first approximation the output of the Compton-scattered photons is proportional to a substance density on which scattering is carried out.

The Compton scattering differential cross-section of photons on electron for non-polarized photon beam is determined by an expression:

$$\frac{d\sigma}{d\Omega} = \frac{r_e^2\left(1+\cos^2\Theta\right)}{2\left[1+\gamma\left(1-\cos\Theta\right)\right]^2}\left\{1+\frac{\gamma^2\left(1-\cos\Theta\right)^2}{\left(1+\cos^2\Theta\right)\left[1+\gamma\left(1-\cos\Theta\right)\right]}\right\}, \quad (1)$$

where r_e - classical electron radius, θ - a photon scattering angle, $\gamma = E_\gamma / m_e c^2$ ($m_e c^2$-electron rest mass).

Energy of scattered photon is determined by the formula:

$$E_\gamma^{/} = \frac{E_\gamma}{1+\gamma\left(1-\cos\theta\right)}, \quad (2)$$

The quantity of scattered photons, in a direction of the detector is determined by the following formula:

$$n_{det.} \approx 0,5(d\sigma/d\Omega)\rho_A N_A \Delta L N_\gamma \Delta\Omega_d \times \exp(-\mu_1 x_1 - \mu_2 x_2), \quad (3)$$

where $(d\sigma/d\Omega)$ is a differential cross-section of the Compton scattering, N_γ is the number of γ-quanta getting into "investigated" volume from a source through the beam collimator, ΔL is the length of interaction determined by the size of the detector collimator, $\Delta\Omega_d$ is a solid angle determined by collimator detector, ρ_A is a density of researched substance, N_A is an Avogadro constant, coefficient 0,5 is the ratio of a charge to nuclear number for the majority of elements of the periodic system, μ_1 and μ_2 are linear coefficients of photons absorption, and x_1 and x_2 are traversed by a photon path in substance before and after scattering, accordingly.

Obviously, the number of detected photons linearly depends on the scatterer density ρ_A and exponentially on absorption coefficients.

In case of use nonmonoenergetic (for example, bremsstrahlung) photons it is necessary to carry out integration on spectra of primary and scattered photons.

Practically the tomograph represents a system of two collimators, specifying the sizes of a primary beam and scattered photons which crossing of images determines the size of "investigated" volume. Scattered in this area photons are registered after the second collimator by the protected in appropriate way detector on a basis scintillation crystal and the photo multiplier. Scanning of "investigated" volume of a sample is made by moving of one by positioner. Measurement of scattered photons intensity at moving "investigated" volume on sample volume gives the information on density change of a sample, that, in turn, enables to carry out wide area of investigations on defects detection inside a homogeneous material, quality definition of coverings and couplings of various materials, a condition definition and thickness measurement of walls of various vessels, access inside of which is closed, nondestructive definition of density of the details received by methods of powder metallurgy, etc.

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By now for various scientific and technical problems solution devices of similar type are already created or creating in several laboratories of the world: in the USA, in France, in Syria (collaboration - England, Syria, Pakistan), etc. [1-4]. Philips Corporation releases such type of tomographs of wide purpose in small lots (ComScan), and also the specialized tomographs for the airline baggage control [5].

As a sources of γ-quantums radioisotope sources ^{60}Co from 5 up to 370 Cu activity, ^{137}Cs activity up to 17 Cu, and also x-ray tubes with a voltage from 160 up to 320 kV and electron accelerators are usually used.

As detectors of scattered photons crystals NaJ (Tl) are usually used.

Earlier [6] we have carried out an estimation of a creation opportunity of technological Compton scattering tomograph with on a source of accelerator Van de Graaf γ-quantums the on 3 MeV energy. By now more careful modeling and calculation of a tomograph is carried out, its construction is determined and the first tests of its work on a source of ^{137}Cs are carried out.

2. MODELLING AND CHOICE OF PARAMETERS OF THE BASIC ELEMENTS OF THE TOMOGRAPH

At creation of devices of similar type the main question is the coordination of many parameters, especial at work on a bremsstrahlung. Collimation degree of primary and scattered beams, speed of the account of the detector, radiation detector protection and etc. relates to such parameters.

To coordinate all these parameters it is possible at careful modeling of electromagnetic processes with a help of program GEANT 3 [7].

A large amount of calculations, which has allowed determining a final construction of tomograph elements is carried out. Below for an example there are some results.

First of all a bremsstrahlung radiation process modeling of electrons with energy 3 MeV was carried out and the purpose of a material choice and its optimal thickness was the receiving the maximal output of γ-quanta. Calculations are made for converters of materials W, Ta and Au, and they have shown, that the output maximum of photons for researched materials is at thickness about 0,3 mm that corresponds approximately 0,1 radiation length. Constructional tungsten plate with thickness of 0,3 mm placed into stainless box with a forward wall thickness of 0,08 mm and backward wall is 0,75 mm, on a gap thickness of 1,5 mm between a forward wall, the converter and a back wall cooling water runs that is especially important at work with the big currents. Behind a back wall the aluminum filter by thickness of 1,8 mm is established. Such converter has been made and showed its efficiency and reliability.

Such design of the converter provides high photon output and, the most important is that electronic component practically is absent in a beam. This result has allowed us to exclude clearing magnet from the installation scheme [6] offered before and to approach a tomograph closely to the converter that has enabled to reduce a current of the accelerator beam essentially (with 100 μA up to 0,2 μA). It has led to essential weight reduction of protection and the signal / background ratio has become more comprehensible.

Now the tomograph scheme became such as it is submitted on Fig. 1.

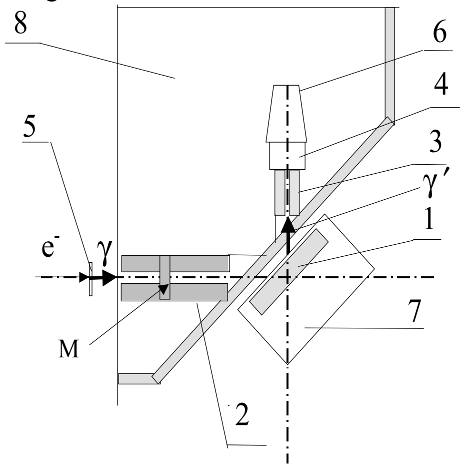

Fig 1. *The Compton scattering tomograph scheme: e⁻-an electron beam of accelerator ELIAS; γ and γ ' - primary and scattered photon beams; 1 - investigated object; 2 - a primary beam collimator; 3 - multislit collimator of the detector; 4 - BGO detector; 5 - the converter of the photons; 6 - the photo multiplier; 7 - the positioner; 8 - the detector protection; M - the beam monitor*

We shall notice that because of possible work instability of the accelerator a continuous beam monitoring is necessary. The beam monitor (collision chamber) is placed inside the beam collimator surrounded with protection of the detector that allows excluding practically an influence of an investigated sample on indications of the monitor.

At carrying out modeling of tomograph the problem was posed, first of all, to determine the highest possible account speed of the detector at minimally possible collimator sizes and an acceptable signal / background ratio. Eventually, the following collimator sizes have been determined: a beam collimator diameter of 3 mm, length of 20 cm; multislit (focusing) collimator of the detector (13 conic apertures in diameter 0,9×2,5 mm, directed at one point) with length of 5 cm. A collimator material is lead. These appeared optimum sizes are chosen from many variations of calculations. The results of these calculations, which have been carried out for a case when investigated elements are Fe, Al or C are submitted below.

First of all, there was determined the form of photon spectrums at each submergence of the "investigated" volume into an investigated sample.

The spectrum has an evident recession at small energies, caused by sharp absorption coefficient increase at these energies. The size of this recession is various at different immersions and brings the appreciable contribution to the account speed.

On Fig. 2 a dependence of background reading speed on thickness of lead detector protection (crystal BGO Ø40×40 mm size) for a beam current 0,2 μA is submitted.

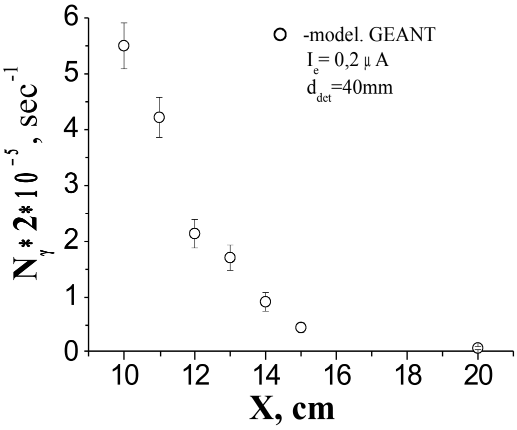

Fig. 2. *Dependence of background read speed on thickness of lead protection at a beam current of electrons 0,2 μA*

It is clear, that at 20 cm thickness of protection the background essentially decrease, and consequently we have chosen this thickness of protection in a converter of photons direction. In other directions as calculations can show, it is possible to be limited to size of protection 5…7 cm since the energy of photons from lateral directions is much lower.

A calculation of dependence of the account speed of wanted and background signals on energy of accelerated electrons for a beam current 0,2 μA was carried out. With reduction of electrons energy account speed of wanted signal falls essentially more slowly, than account speed of a background signal because of what the ratio the signal / background improves. This result is submitted on Fig. 3.

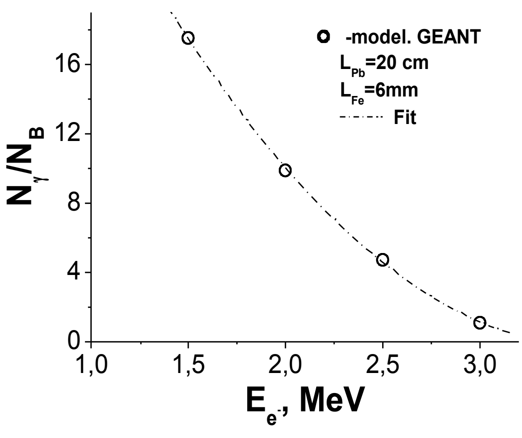

Fig. 3. *Dependence of a signal/background ratio from accelerated electrons energy for depth of immersing in iron on 6 mm at thickness of protection 20 cm*

It is clear, that a signal/background ratio at energy decrease from 3 up to 2 MeV increases in 10 times. At the same time mean energy of photons in beam is reduced insignificantly (from 0,560 up to 0,453 MeV).

The primary calculation results of the account speed and time of data set definition for statistical accuracy receiving of 0,1 % for two materials at different submersions of the "investigated" volume center are submitted in the concluding table.

The account speed of the detector for Fe and C

Material	x, mm	$N_{\gamma\ det}\times10^{-4}$, I_e= 0,2 μA	$t_{0,1}$,sec
^{56}**Fe** ρ=7,8 g/sm^3	4	8,48	11,8
	6	2,76	36,2
	8	2,12	47,1
	10	1,53	65,2
^{12}**C** ρ=2,3 g/cm^3	4	3,21	31,1
	6	2,99	33,3
	8	2,76	36,1
	10	2,53	39,4

The table data show, that a dependence of investigated samples density exists only at submersing of the "investigated" volume on a small depth. At the further submersing the account speeds for heavy and light substances are practically compared.

At tomograms decoding, evidently, it is necessary, except of integrated measurement of readout number, to measure spectra of scattered photons in addition. This variant we have modeled for iron and carbon at submersing of the "investigated" volume on depth of 6 mm at the same accelerator current. The result is submitted on Fig. 4.

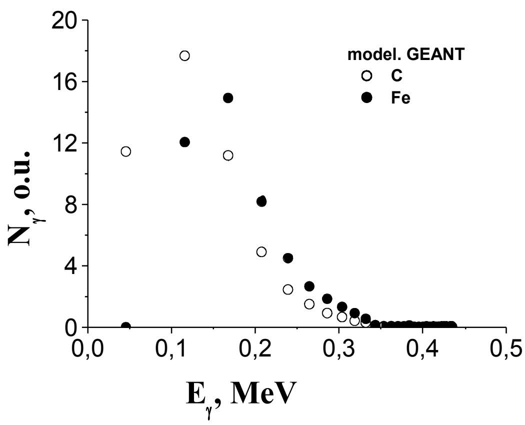

Fig. *4. The contribution of various scattered photons spectrum parts into integrated account speed Fe () and C ()*

It is clear, that spectra for Fe and C are strongly differ, especially in low-energy part, and probably, that registration and the energy spectra analysis of scattered photons at work on bremsstrahlung can help in many respects with decoding tomograms.

3. THE RESEARCH OF THE WORK THE TOMOGRAPH ON PHOTON BEAM OF THE SOURCE ^{137}Cs

Based on results of calculations, we have made a laboratorial variant of a technological Compton tomograph designed for work on an accelerator ELIAS beam. The tomograph is made under the scheme submitted on Fig. 1. Beam and the detector collimators are built in lead detector protection of weight about 500 kg. Some removable complete sets of the collimators are made, which allow working at different resolutions from 1 up to 5 mm. A number of apertures in the detector collimator from 13 up to 121 depending on the resolution. A Work on making collimators with the resolution less than 1 mm is carrying out. A beam collimator length is 200 mm, the detector collimator is 50 mm. Thickness of the detector protection on the part of a beam is 200 mm, and from other directions is 70 mm.

The researched sample is placed on the positioner that has an opportunity to move a sample along the X - and Y - directions on ± 200 mm. An object scanning is carried out discretely with the help of stepping motors, a step of scanning is $1{,}1\times10^{-2}$ mm. Accuracy of a plant at positioner movement on 100 mm is not worse than ± 0,02 mm. A placing of a sample along Z direction, and also its rotation are carried out while manually.

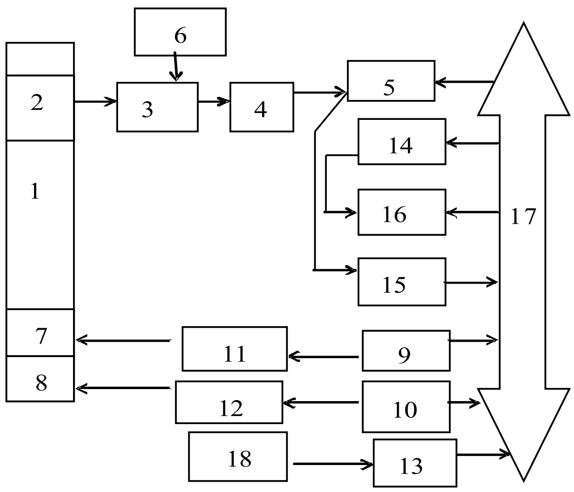

Fig 5 The flow block of tomograph management . 1 - a tomograph, 2 - BGO detector, 3 - phototube, 4 - the amplifier, 5 - the discriminator - creator, 6 - a high-voltage power unit , 7,8 - step motor, 9,10 - the step motor management module, 11,12 - the power amplifier, 13 - the crate controller CC-077, 14 - clock generator, 15 - the four-channel counter, 16 - the indication counter , 17 - CAMAC, 18 - a personal computer.

As the detector crystal BGO in size Ø40×40 mm with photomultiplier and a spectrometer preamplifier is used.

Full weight of the tomograph is about 700 kg.

A work management of stepping motors, gathering and primary information processing is carried out automatically with the help of a personal computer and a set of electronic blocks in system CAMAC.

The flow block of tomograph work management is shown on Fig. 5.The computer program of a tomograph work management also allows representing measured values in a graphic form in online mode;to archive the results of measurements as, necessary for work with standard graphic packages, mode; the program has the convenient user interface for work in an interactive mode.

For the beginning, some laboratory researches of a tomograph work on a photon beam of an isotope source ^{137}Cs by activity $7{,}5\times10^{7}$ Bk carried out, placed on a the monitor of a beam space (see Fig. 1). A beam and the detector collimators diameters are increased in size up to 5 mm because of a small activity of a source. A number of the detector collimator apertures is 31, a total solid angle is $9{,}5\times10^{-2}$ sr.With the purpose of increasing the ratio a signal / background for registration only the impulses, located in the field of a peak of scattered photons, were selected with the help of the differential discriminator. Scattered photons with energy 0,288 MeV and background spectra are shown on Fig 6.

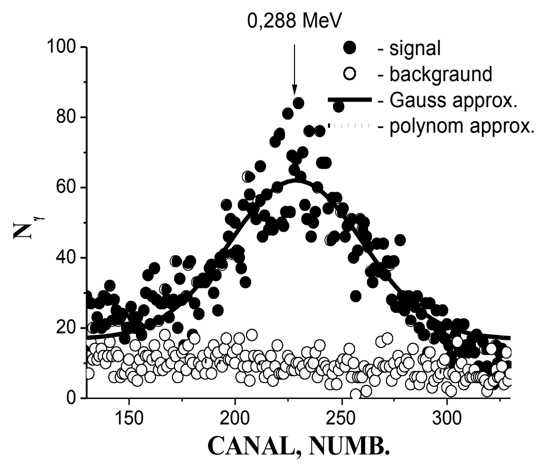

***Fig. 6**. Scattered photons registered by the detector and background spectra: ● - signal, ○ - background*

We have carried out a whole series of experiments on thickness measurement of steel, aluminium and graphite plates of various thickness, and also on measurement of assemblages consisting of two 4 mm plates divided by an air 5 mm interval.

For aluminium assembly where peaks for the first and second plates are divided neatly, modeling is carried out with the purpose of the real resolution definition received in experiment and how the experimental result will look at resolution of 1 mm.

This result is submitted on Fig. 7.

The submitted result shows, that, first, the resolution materially reached in this experiment is about 9 mm, and, second, at the resolution of 1 mm it is possible to measure an investigated object rather reliable.

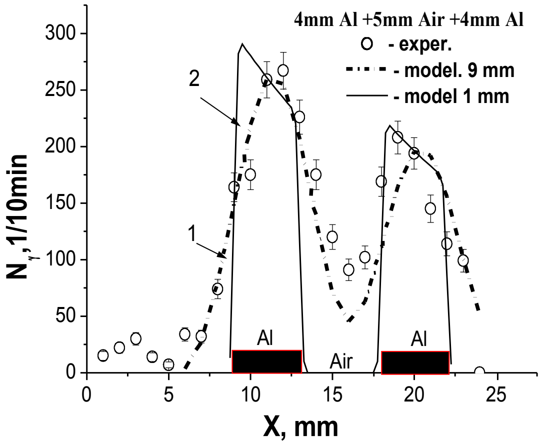

***Fig.** 7. A number of the detector readout dependence on submersing depth of an "investigated" volume into a product. Black areas are the location of an object. Experiment for Al - (○); modeling: 1 - for the 9 mm resolution, 2 - for the 1 mm resolution*

4. CONCLUSION

In summary it is necessary to note, that created by our calculations technological Compton scattering tomograph is quite efficient, and at enough high intensity of a photon beam on it is possible to carry out the broad band of researches. The system of automated management of a tomograph has shown high efficiency, a positioner works reliably. In the near future it is planned to use as a source of photons either a x-ray tube, or the electron accelerator ELIAS.

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ИССЛЕДОВАНИЕ РАБОТЫ ТЕХНОЛОГИЧЕСКОГО КОМПТОНОВСКОГО ТОМОГРАФА НА ПУЧКЕ ФОТОНОВ ИСТОЧНИКА ^{137}Cs

Ю.М. Аркатов, С.Н. Афанасьев, М.С. Глазнев, Д.В. Гущин, Ю.В. Жебровский, В.Ф. Попов

Представлены разультаты выполненных в ННЦ ХФТИ работ по созданию стационарного технологического комптоновского томографа. Проведено моделирование физических процессов по программе GEANT 3, определена конструкция томографа для случая использования в качестве источника фотонов ускорителя Ван де Граафа на энергию 3 МэВ. Представлены результаты испытания работы томографа на пучке фотонов источника ^{137}Cs.

ДОСЛІДЖЕННЯ РОБОТИ ТЕХНОЛОГІЧНОГО КОМПТОНІВСЬКОГО ТОМОГРАФА НА ПУЧКУ ФОТОНІВ ДЖЕРЕЛА ^{137}Cs

Ю.М. Аркатов, С.М. Афанасьєв, М.С. Глазнєв, Д.В. Гущин, Ю.В. Жебровський, В.П. Попов

Представлено результати виконаних у ННЦ ХФТІ робіт по створенню стаціонарного технологічного комптонівського томографа. Проведено моделювання фізичних процесів по програмі GEANT 3, визначено конструкцію томографа для випадку використання як джерело фотонів прискорювача Ван де Граафа на енергію 3 МеВ. Представлено результати випробування роботи томографа на пучку фотонів джерела ^{137}Cs.