DIGITAL PULSED SYSTEM OF SHADOW IMAGES RECORDING FOR RADIOGRAPHY OF OBJECTS OF LARGE OPTICAL DENSITY

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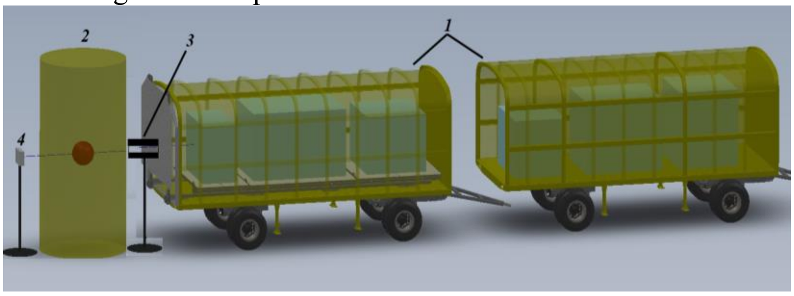
Abstract. The authors provide the development results of one channel of the digital multiframe recording system for the radiography of objects having large optical thicknesses. The recorder is created based on the modern CCD matrix and quick-acting unit that operates as an electron-optical shutter. Scintillators based on the monocrystal LYSO were used to transform the ionizing radiation into the visible spectrum. Spatio-time characteristics of the recording system were investigated in the laboratory; the system operability was also checked. It was shown that the recording system allows recording with time exposure ≥ 100 ns. The unit of the multiframe recording system was tested on the internal polygon of FSUE "RFNC-VNIIEF". Testing powering of the mobile cyclic accelerator (ironless pulsed betatron) was also performed. The X-ray patterns of the static test objects were obtained. The thickness of the X-rayed lead test object was ~90 mm at 4 m from the target at 11% contrast. The value of a capacitive storage of the pulsed powering system of the betatron electromagnet was C = 900 μF. The dimension of the tantalum target was 6×6 mm; the full width of the output gamma pulse at half maximum in a single frame mode was ~100 ns.

1. Introduction

Investigation of quick-acting processes such as forming and development of the cumulative jets, study of the state of substance in the conditions of the dynamic loading are very important and timely directions of the modern natural science. Characteristic velocities of these processes are from one up to several tens of km/s [1]. Pulsed radiography is one of the most informative techniques of such investigations.

Powerful sources of the ionizing radiation have been developed in FSUE "RFNC-VNIIEF" for many years. They allow performing the radiography of the dynamic objects with large optical thicknesses. The sources of such radiation are linear or cyclic electrons accelerators, particularly betatrons [2]. Such sources are large stationary complexes with complicated infrastructure. To reduce expenses and optimize the process of preparation and gas-dynamic experimentation, FSUE "RFNC-VNIIEF" began to apply the conception of using mobile radiographic complexes (MRC) [3]. They consist of mobile cyclic accelerators (MCA), an explosion-proof chamber (EPC) with a test object, system of X-rays collimation and shadow images recording system. Each of these sources allows getting from one up to three images of the test object with an interval from 0.5 up to 20 μs in an experiment.

Figure 1 presents one of the variants of the gas-dynamic experiment that allows obtaining up to three images in an experiment.



1 – mobile cyclic accelerator;
2 – EPC with a test object;
3 – X-rays collimation system;
4 – shadow images recording system

Figure 1. The experiment sketch with the usage of a single-beam three-frame mobile radiographic complex.

It is possible to increase the frames quantity and provide the small-angle tomography if to increase the MCA quantity [4].

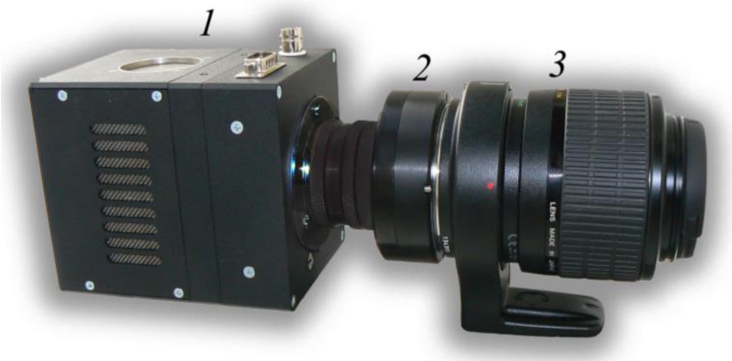
The recording system is an important part of any radiographic facility. The employees of FSUE "RFNC-VNIIEF" develop multiframe electron-optical recording systems to equip protongraphic and radiographic complexes. The usage of modern electron-optical devices together with the effective scintillation converters allows creating multiframe recording of the dynamic objects images. Hereby, it increases the information volume during the experiment.

2. Shadow images recording system as a part of the radiographic complex

An X-ray sensitive film has been applied in the radiography as a recorder for more than sixty years. Currently, luminescent storage screens (Imaging Plate) are also widely used. They have got improved characteristics and better velocity of the data extraction. Such recorders have got a high resolution and allow getting multiframe shooting of the dynamic process in some tasks. However, a complex internal structure and dimension of the test object often cannot allow taking several frames using one and the same X-ray film or luminescent screen. The usage of modern electron-optical devices together with effective scintillation converters allows solving the tasks of the multiframe recording.

Nowadays the sphere of digital recorders is being developed very well and the choice of digital optical cameras is very wide. However, the experiment conditions at the radiographic complexes provide strict requirements for the used devices. As a rule, in the experiments soft images are created in optically dense objects. The radiography is also characterized by a limited number of data light quanta. Thus, the digital recording unit should have an electron-optical shutter of the required exposure, image intensifier and high spatial resolution. As a rule, a CCD chamber is joined to the imaging intensifier that operates as an electron-optical shutter and image intensifier.

According to the task requirements the authors created one channel of the multiframe recording system; its photo is presented in Figure 2.



1 – digital camera,
2 – remote control unit of a diaphragm and focus,
3 –fast lens.

Figure 2. A channel of the multiframe recording system of the radiographic complex.

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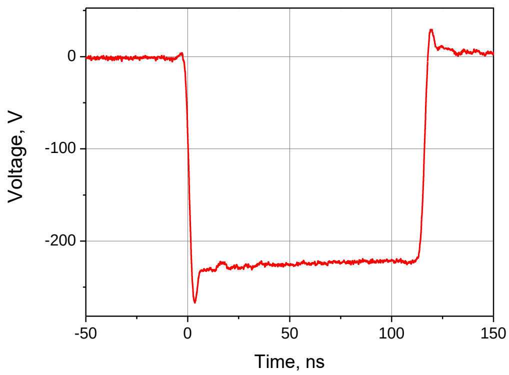
The recording channel consists of a gating digital camera, remote control unit of a diaphragm and focus, and fast lens [5].

The digital camera consists of an imaging intensifier with a self-made generator of gate pulses and TV CCD chamber. The components are joined by means of a fiber optic washer. A microchannel plate (MCP) is used as an amplifier that can amplify the signal 10^3 times. The CCD chamber is used for image sensing. The matrix dimension of the CCD chamber is 16.6 × 18.6 mm, the pixel dimension is 16 × 16 μm. The digital camera is totally controlled by the personal computer by means of fiber optic interface and can operate both in the trigger mode and in the mode of internal synchronization.

In the created sample the exposure time of the registered image is varied in the diapason from 100 ns up to 5 μs by means of continuous adjustment. It is achieved by a noise-immune generator developed by the authors during this work. It should be noted that the provided normal generator of gate pulses had not got the claimed technical characteristics and had very weak magnetic pickup protection. At the generator development the inductive elements as well as digital and analog integrated circuits were excluded as much as possible from the electric circuit. The discrete semiconductor element circuit was used. The optimal design arrangement and electric circuit screening were performed. The generator provides the MCP gain control and a gate pulse formation. The generator control is performed from the remote panel by means of fiber optical lines with timing-tracking accuracy up to 1 ns. It also provides undisturbed operation of the recording system while measuring in the conditions of a higher level of the magnetic pickup. There is a photo of the gate pulse generator in Figure 3 (*a*) and a characteristic oscillogram of its output pulse (*b*).

a) Photo of a gate pulse generator.



b) Oscillogram of an output pulse of the gate pulse generator.

Figure 3. Photo and oscillogram of an output pulse of the gate pulse generator.

The gate pulse generator with the obtained characteristics excels the present analogs in several parameters and can be effectively applied in the images recording systems based on the electron-optical devices. The generator usage provides new possibilities for data gathering at the dynamic objects radiography and imaging of fast processes in the conditions of electromagnetic disturbance and scattered X-ray radiation during the experiments at the physical facilities.

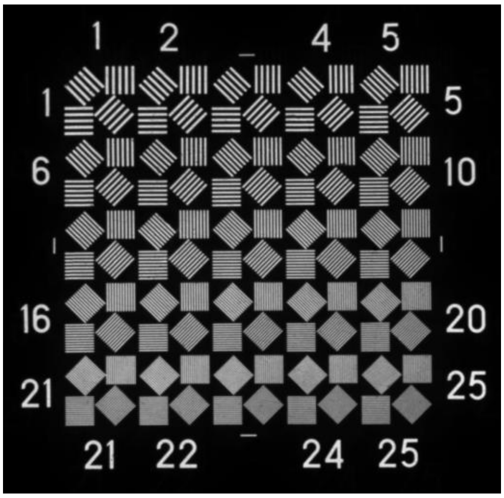
As component units are easily accessible and rather cheap, it is possible to use them in the multichannel digital systems of the images recording of the dynamic objects with minimal expenses.

The main characteristics of the recording channel are:

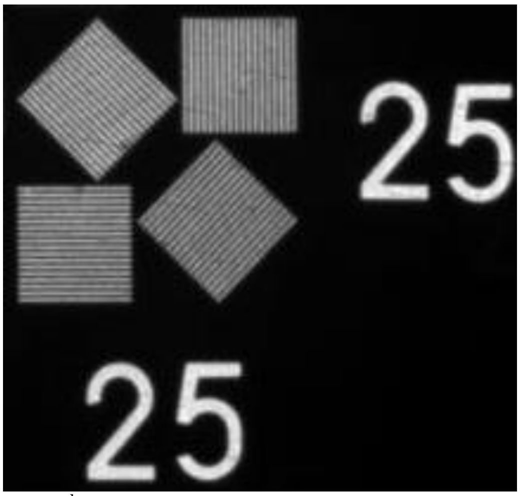
- quantum efficiency of imaging intensifier – at least 20%;
- spectral sensitivity from 350 up to 650 nm (sensitivity maximum is equal to the radiation spectrum of the used scintillator);
- spatial resolution of the photocathode – at least 25 lp/mm;
- number of pixels of the CCD matrix – > 10^6;
- dynamic diapason of the CCD chamber – 14 bit;

– amplifier diapason – $\leq 10^3$ times;
– exposure time – $\geq$100 ns;
– response accuracy – $\leq$ 5 ns;
– built-in high-speed series fiber-optic interface for synchronizing and system control, and data transmission into the computer.

The assembly and adjustment of the electron-optical recorder were performed in the laboratory. Spatial-time characteristics of the system were studied. It was defined that 25th field is resolved with at least 16% contrast with the use of an optical test pattern № 4 that has a limiting spatial frequency 25 lp/mm. The test pattern recording was fulfilled in the scale 1:1. There is a test pattern image (Fig. 4*a*), and its expanded 25th field (fig.4*b*).



a) Test pattern image.



b) 25th test pattern field.

Figure 4. Study of the spatial characteristics of the recording channel.

The optical diagnostic system based on the pulsed laser was used to check time characteristics of the recording channel. As opposed to the technique based on the electric signal control on the photocathode imaging intensifier, this diagnostic system allows obtaining correct visual information. The pulse duration of the probe radiation is less than 10 ns. The typical dynamics of the recording channel operation is presented in Figure 5.

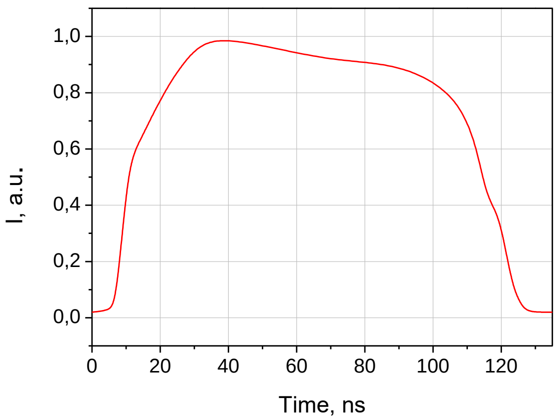


Figure 5. Dynamics of the recording channel operation.

The essential part of any recording system of the radiographic complex is the existence of an X-ray sensitive element, that is a converter of the X-ray radiation into the light one. In the presented recording system a scintillation crystal LYSO is chosen as a converter (lutetia – yttrium orthosilicate). This crystal has got high effective atom number (Z > 60) and density (ρ ~ 7 g/sm^3), that allows providing the required recording of high energy particles. The light output is in the frames from 27 000 photons/MeV up to 32 000 photons/MeV, the fall time constant is not more than 47 ns. At the same time, the crystal is not hygroscopic and is easily treated up to the thickness of 0.3 mm and even less. The distinguished properties make it rather attractive in the tasks of the pulsed radiography; with the use of this crystal it is possible to achieve rather high time resolution, required sensitivity and high spatial resolution of 2-D images.

Scintillation crystals of 78 mm diameter were used during the testing of the recording system. The scintillator photo is presented in Figure 6.

Density (g/sm^2)	7,1
Hygroscopicity	0
Absence of internal defects of the diameter more than (mm)	0,1
Radiation resistance (Grey)	10^6
Refractive index	1.81
Radiation spectrum maximum (nm)	420
Fall time (ns)	41
Specific light yield (photons/MeV)	32 000

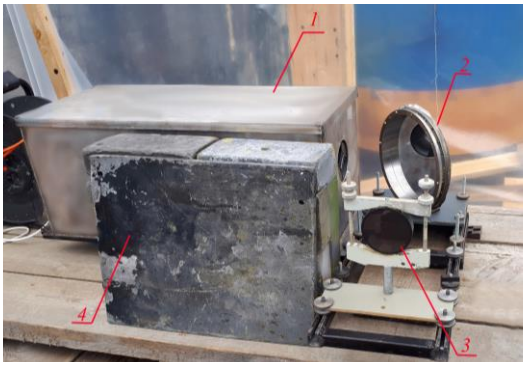
Figure 6. Scintillation monocrystal LYSO Ø78 mm.

Preliminary, a recording channel was studied on the test bench in the laboratory aimed to compare the quality of images that are obtained at the usage of different lens and scintillation converters. The growth of noise immunity of the electron circuits in the conditions of strong magnetic pickup had to be also studied. The obtained results showed that it is possible to increase the coefficient of the optical system acquisition in the conditions of low light flux if to use faster lens; and hereby, the ratio signal/noise of the recording system will be also increased.

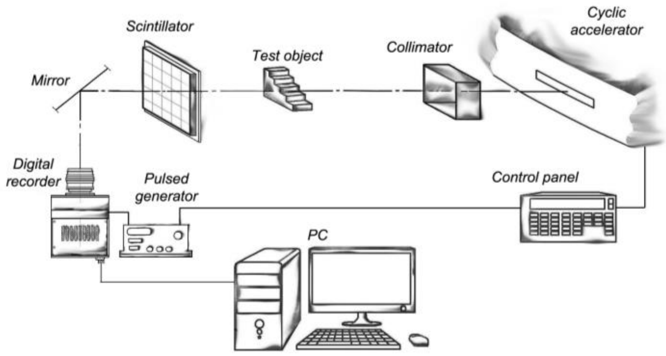
3. Testing of the recording system and its results.

The first full-scale test of the developed recording system was carried out during the testing powering of the mobile cyclic accelerator in September 2016. The value of the capacitive storage of the pulsed powering system of the electromagnet was C=300 μF.

The MCA BIM was moved to the internal polygon of FSUE "RFNC-VNIIEF" in June 2017. The testing powering was carried out. The value of the capacitive storage of the pulsed powering system of the electromagnet was C=900 μF. The dimension of the tantalum target was 6×6 mm. The full width of the output gamma pulse at half maximum in a single frame mode was ~120 ns. The recording was carried out with the use of the Imaging Plate system as well as with the use of the digital recording system. The photo of the recording channel and structure chart of the X-ray picture creation are presented in Fig.7.



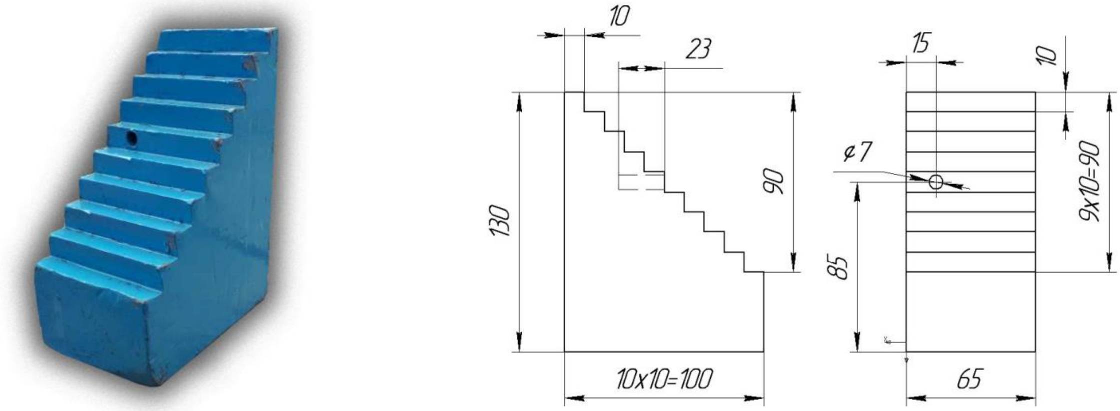
a) Photo of the recording channel



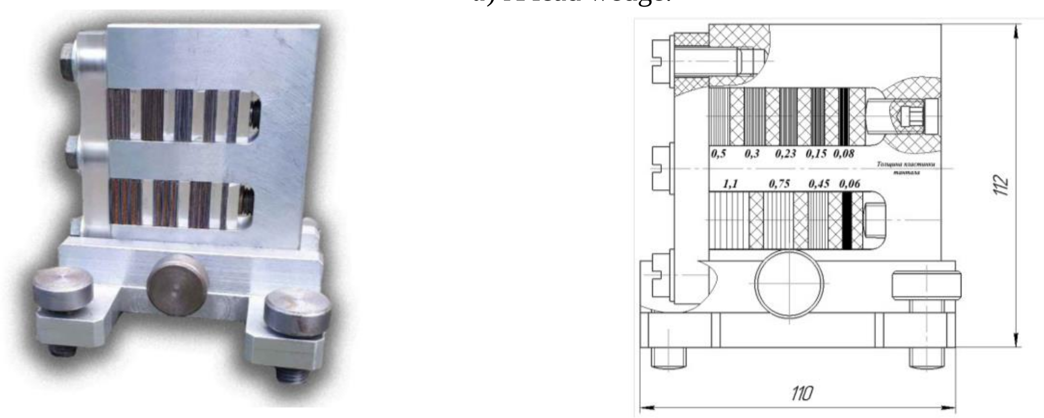
b) Structure chart

Figure 7. Photo of the recording channel (*a*): 1 – recording channel in the screening can, 2 – sweep mirror, 3 – scintillator, 4 – ionizing radiation protection; structure chart of the test performance (*b*).

To estimate the parameters of the MCA BIM and recording system operation, the X-ray radiography of some test objects was carried out. The test objects were a lead step wedge and typesetting tantalum test pattern. The photos and sketches of these objects are presented in Figure 8. These objects allow obtaining a limiting spatial resolution and defining the X-ray ability, contrast sensitivity, and total system operability in general.



a) A lead wedge.



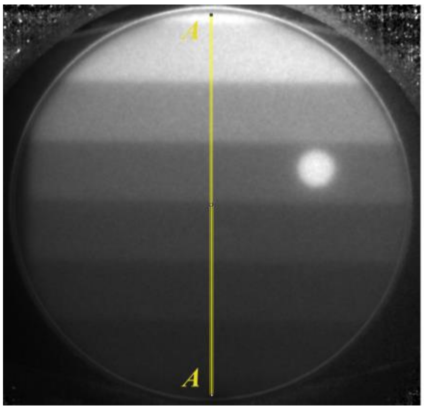
b) A typesetting test pattern.

Figure 8. Photos and sketches of the test-objects.

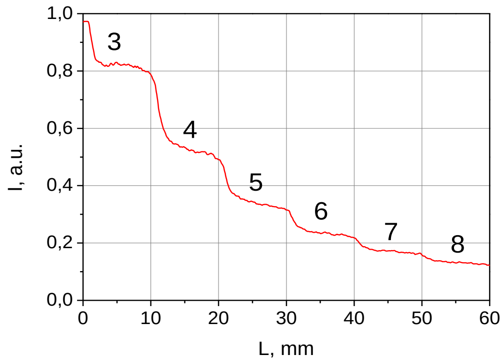
The recording of shadow images was carried out in the following geometry: the distance from the betatron target to the investigated test object was $L_1 \approx 400$ cm, from the object to the scintillator was

$L_2 \approx 50$ cm. Hereby, the geometrical factor was $K = 1.125$ and the optical system magnification was M = 0.189 (or 5.3).

The lead step wedge (Fig. 8*a*) was used to define a limiting the X-ray ability. The lead plate of 20 mm thickness was fixed before the test object to increase the optical thickness. The wedge is surrounded by the collimator made of the lead bricks. Figure 9 presents an X-ray picture and signal intensity profile along the vertical section of the wedge.



a) X-ray picture of the lead wedge.

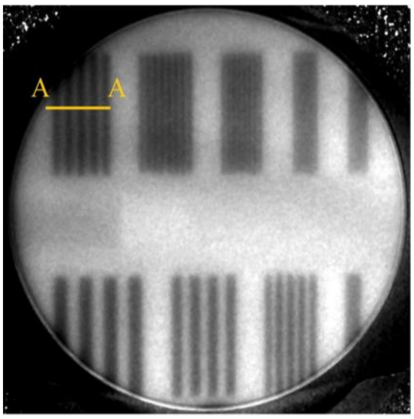


b) Profile of the signal intensity along A-A

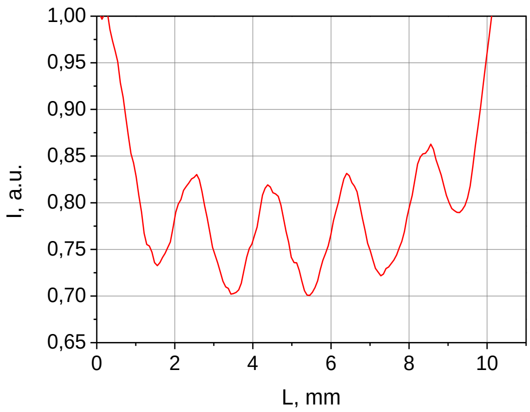
Figure 9. Results of the data processing of the X-ray picture of the lead wedge.

While creating the intensity profile in the section A-A, the steps from the second one up to the eighth one were appearing. The seventh step relative to the eighth one is resolved with 11 % contrast. The thickness (along the beam) of the seventh step was 70 mm, 80 mm of the sixth step. Thus, with these parameters of the mobile complex at the usage of the proposed digital recorder ~ 90 mm of the lead was X-rayed with 11% contrast at 4 m from the target with a capacitive storage equal to C = 900 μF. It was done with the use of the fixed lead plate of 20 mm thickness.

A typesetting tantalum test pattern was used to perform the assessment of the radiographic complex resolution together with a recording channel. The photo of the test pattern is presented in Figure 8*b*. The X-ray picture of the test pattern and the densitogram of the field with the resolution of 0.5 lp/mm are provided in Fig. 10.



a) X-ray picture of the lead test pattern.



b) Profile of the signal intensity along the section A-A.

Figure 10. Results of the data processing of the X-ray picture of the lead test pattern.

Analysis of the profile of the section A-A reveals that the test pattern area with the spatial frequency of 0.5 lp/mm is resolved with a ~8% contrast; and the area with less spatial frequency (0.9 lp/mm) is resolved with a contrast less than 3%.

According to the provided X-ray pictures and diagrams, it is evident that the boundaries of the thicknesses transition have got a blurring. The easiest explanation is not an exact positioning of a beam. One more reason can be the influence of the scattered radiation. It can be also mentioned that the fixed target in the betatron had not got optimal geometric dimensions (6×6 mm). Thus, it could lead to the additional blurring of the X-ray pictures.

In general, the experiments results are considered to be positive. The developed recording channel showed its operability and can be considered as a base of the multiframe recording system for small-angle X-ray radiography. The proposed recording channel of the multiframe recording system allows shooting of the dynamic objects in the multi-angle and multiframe mode. The experiments results showed a good correspondence with the previous images obtained on the radiographic film and can be compared with the results obtained in the Imaging Plate system.

4. Conclusion

The efficiency of the multi-angle radiography can be essentially increased using the multiframe recording system (at the operation of one or several betatrons in the mode of several pulses). In the frames of this task the authors developed the recording channel based on the digital camera and scintillation converter. The generator of gate pulses was created to control an electron-optical camera. This channel was previously tested on the test-bench and was used during the MCA BIM adjustment, and during the testing powering of the mobile X-ray radiographic complex on the internal polygon of FSUE “RFNC-VNIIEF” as well. The static test-objects (a lead wedge and typesetting tantalum test pattern) were used to estimate a limiting spatial resolution, transparent ability and contrast sensitivity.

At the usage of the digital recorder, ~ 90 mm of the lead was X-rayed with 11% contrast at 4 m from the tantalum target of the betatron. The value of a capacitive storage of the pulsed powering system of the betatron electromagnet was C = 900 μF. The dimension of the tantalum target was 6×6 mm; the full width of the output gamma pulse at half maximum in a single frame mode was ~100 ns.

In spite of the fact that the own resolution of the recording channel was at least 25 lp./mm, the resolution of the radiographic complex together with the recording channel was 0.5 lp./mm. in the performed experiment. Low index of the spatial resolution is explained by several reasons: non-optimized dimensions of the betatron target (6×6 mm) that lead to the additional blurring of the obtained shadow images, absence of the precise alignment platform for test objects.

In general, the results of the optical-dense objects investigation should be considered positive. The proposed digital recording channel showed its operability and can be used as a base at the creation of the multiframe recording system for small- angle X-ray radiography. At the same time the authors would like to note that they are always in the process of searching new fast acting electron optical devices and charge-coupled devices to improve the recording system and quality of experiment results.

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