

# Mobile Cyclic Accelerator Based on Ironless Pulsed Betatron. Results of Testing Powering

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**Abstract.** The authors describe the mobile cyclic accelerator based on the ironless pulsed betatron. The possibility of such accelerators application as a part of mobile radiographic complexes is illustrated. These complexes are intended for the radiography of dynamic objects with large optical thicknesses located in the explosion-proof chamber (EPC). Such complexes allow optimizing the radiography geometry in the hydrodynamic experiment at the expense of the possible location change of the radiator and recorder relative to the investigation object. The geometry optimization allows increasing the X-ray radiation intensity in the recorder plane at least twice if compare with the active Russian radiographic complexes. The authors provide the output parameters of the mobile cyclic accelerator at its testing powering on the test bench. The value of a capacitive storage of the pulsed powering system of the betatron electromagnet was  $C=900\ \mu\text{F}$  ( $C_{\text{max}}=1800\ \mu\text{F}$ ). The thickness of the lead test object examined with X-rays was  $\approx 100\ \text{mm}$  at 4 m from the tantalum target; the dimension of the target was  $6\times 6\ \text{mm}^2$ . The full width of the output gamma pulse at half maximum in a single frame mode was  $\approx 100\ \text{ns}$ . The dimension of the radiation source was  $\approx 6\times 3\ \text{mm}^2$ .

## 1. Introduction

Powerful sources of the pulsed radiation with the optimal spectral composition are required for the radiography of dynamic objects with large optical thicknesses. The generators of such radiation are either linear or cyclotron electron accelerators. There are several active radiographic complexes based on the linear accelerators in the world: the American complex DARHT [1], the Chinese complex DRAGON [1], the English complex HRF AWE [2], etc.

The ironless pulsed small-sized betatrons of the BIM type [3,4] have been applied in FSUE “RFNC-VNIIEF” and FSUE “RFNC-VNIITF” for a long time in radiographic complexes to provide hydrodynamic investigations, particularly, the investigations of the substance behavior in supercritical conditions [5].

Nowadays, the active radiographic complexes are stationary ones. Their development, creation and maintenance require a lot of finance and time resources. To reduce expenses and optimize the process of preparation and hydrodynamic experimentation, FSUE “RFNC-VNIIEF” began to apply the conception of using mobile radiographic complexes (MRC) [6]. They consist of mobile cyclic accelerators (MCA) [7], an explosion-proof chamber (EPC) with an investigation object, system of X-rays collimation and shadow images recording system. One EPC can be maintained by several MCAs.

The realization of this conception allows:



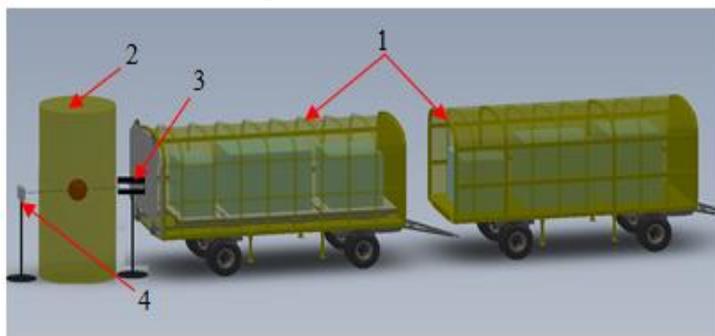
1) optimizing the experiment geometry at the expense of the position change of the radiation source and recorder relatively to the test object located in the EPC; this allows increasing the x-ray radiation intensity in the recorder plane twice as compared with active Russian complexes;

2) significantly decreasing the cost of radiographic complexes if not building heavy protective casemates; thus, decreasing the expenses for their infrastructure maintenance (it is possible to use cheap rapidly erected constructions);

3) creating an efficient environment protection system at the expense of localization of dangerous explosion products and hereby, a shock wave;

4) increasing the calendar time of hydrodynamic experiments (nowadays, the experiments are prohibited during summer time because of fire risks) due to the fire safety growth.

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

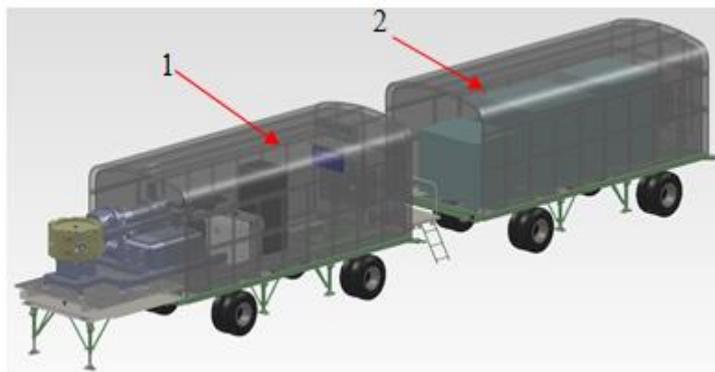


**Figure 1.** The experiment sketch with the usage of a single-beam three-frame mobile radiographic complex:

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

## 2. Mobile cyclic accelerator based on ironless pulsed betatron

Main parts of the MRC is the MCA. Figure 2 presents a sketch of a single-beam three-frame MCA based on the betatron of the BIM type that consists of two units: an accelerator unit (AU) and a unit of pulsed powering of the betatron electromagnet (UPPE).



**Figure 2.** The sketch of a single beam three-frame mobile cyclic accelerator:

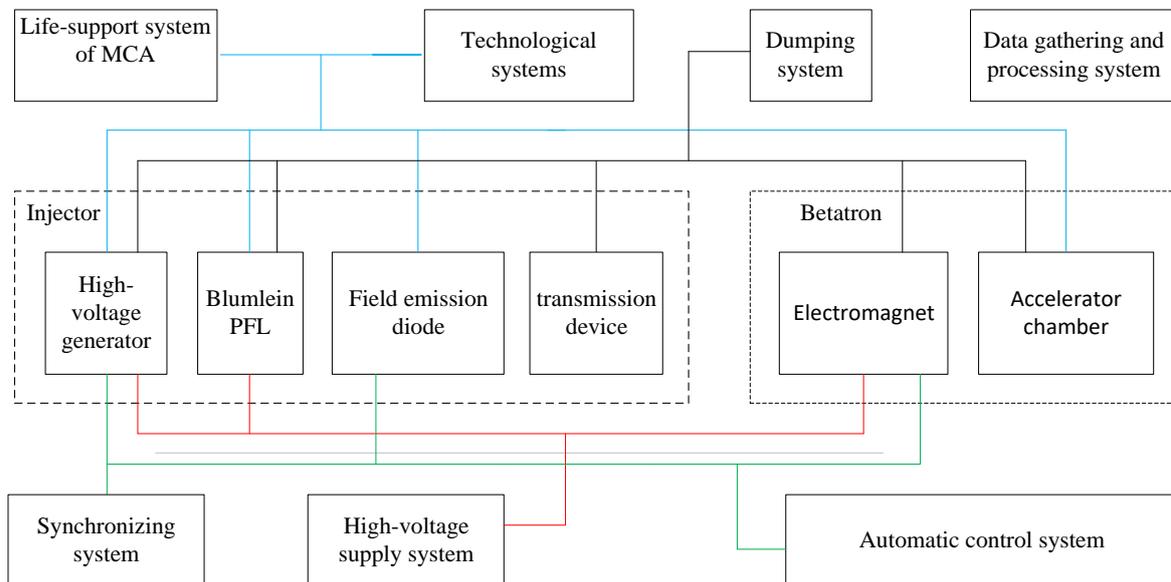
1– accelerating unit; 2– unit of pulsed powering of the betatron electromagnet .

Symbolically, there are the oscillator elements of the radiographic facility in the van of the accelerator unit (1). In the other van (2) there is a pulsed powering system of the betatron electromagnet and technological equipment. The connection between the units and external automated control system is performed with the use of cable and fiber-optic lines (these lines are not shown in the sketch of a mobile cyclic accelerator (Fig.2)).

The base facility of the MCA BIM is a pulsed ironless betatron of a new generation. Its units have been worked out on the test bench since 2002; and the radiation parameters have been optimized. One of the main units of the facility is an injector. It is designed based on the small voltage multiplier [8] and Blumlein pulse forming line (PFL). This injector allowed significantly decreasing (2.5 times) mass-sized characteristics of the radiation source as compared with the sources of active Russian

complexes [9]. The facility dimensions are  $4.5 \times 2 \times 1.8 \text{ m}^3$ , the total weight is about 5 tons. The major units and systems of the oscillator are similar to those of earlier developed Russian complexes.

Figure 3 illustrates the structural scheme of the MCA BIM.



**Figure 3.** The structural scheme of the MCA BIM.

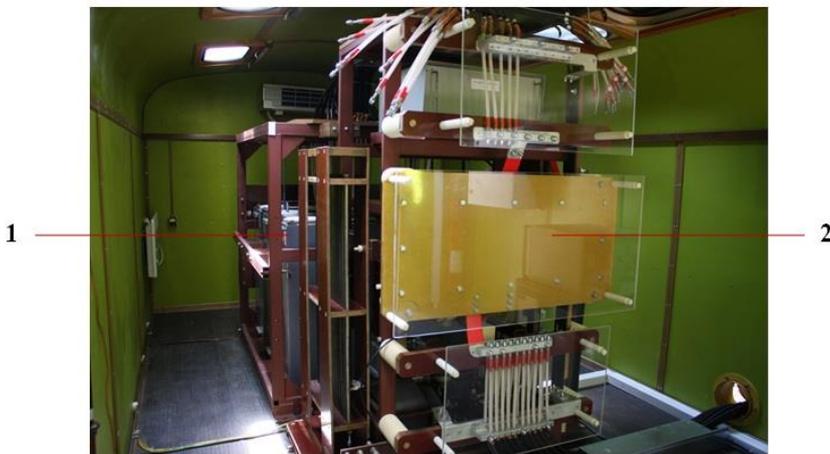
The MCA BIM consists of a betatron, injector, high-voltage supply system, synchronizing system (low-voltage and high-voltage), automated control system, data gathering and processing system (operate with the output parameters), dumping system (“low” and “fast” dumping), technological systems and other accessory life support systems of the MCA.

The electron acceleration in the betatron is realized by the vortex electrical field that appears because of a discharge of the capacitive storage through the electromagnet coils. Hereby, the magnetic field changes according to the sine law:  $B(t) = B_0 \sin(\Omega t)$ , where  $\Omega = 1/(LC)^{1/2}$  – circuit cyclic frequency ( $L$  and  $C$  – circuit inductance and capacity), and  $B_0 = KI_{max}$  – field on the orbit at the peak current of the electromagnet  $I_{max}$  ( $K$  – correction factor). Automatically, the magnetic field inductance is changed synchronically with the acceleration by the expense of the electromagnet coils geometry. It allows holding an electron beam on the orbit. The high-voltage electromagnet power unit is switched on firstly, forming the signal “0 field”. After this signal the powering time reading of some facility systems starts (Blumlein PFL, transmission device, high-voltage generator, etc.). The electron beam is generated and preliminary accelerates in the injector. In this case it is the accelerator of the direct action for  $E_{inj} = 1,5 \text{ MeV}$ . The injector operates in the following way. Blumlein PFL is charged at the high-voltage generator response. A machining voltage pulse is formed in the Blumlein PFL after a discharge arrester response. This pulse is transmitted through an intermediate discharge arrester to the field-emission diode, where an electron beam with a current amplitude of  $\approx 2 \text{ kA}$  and a pulse width at half maximum of  $\approx 10 \text{ ns}$  is generated. A beam injection into the betatron is performed with the use of the transmission device [10] at the moment  $t_{inj}$ , when the magnetic field on the orbit achieves the value that is defined by the ratio:  $B = B_0 \Omega t_{inj} = E(300R_0)^{-1}$ , here:  $R_0$  – radius of the equilibrium orbit,  $E$  – electron beam energy. Hereby, an injection moment  $t_{inj} \approx E(300B_0R_0\Omega)^{-1}$ . The conduction and focusing of the electron beam is performed with the use of two magnetic lenses that are symbolically called a solenoid and lens; they are powered by their high-voltage supply units. Electrons are accelerated up to highest possible energy by the vortex electrical field. Then the accelerated beam is dumped to the target using either ‘fast’ or ‘slow’ dumping units. Both units consist of windings which are assembled inside the electromagnet and individual high-voltage generators.

The automated control system [11] according to the time algorithm provides the charging of the capacitive storage of the functional units and their parameters control during the operation time of the MCA BIM. The control of the facility output parameters is performed by the data gathering and processing system. The technological systems provide: creation of the necessary working vacuum in the betatron accelerating chamber and in the area of the field-emission diode, water-cooling of the vacuum pumps, filling of the gas-filled discharge arresters by the working composition, and filling of the high-voltage devices of the facility by the liquid dielectric. The MCA BIM is also equipped by the vision-based inspection system, light and sound alarm, firefighting, audio and climate control systems, and load lifting mechanism.

The solution to create the MCA BIM was made in 2013. The construction design of the accelerator van was being performed since 2013 up to 2015. The oscillator equipment of this van was worked out. The assembly work and commissioning were also carried out.

The oscillator testing with its electromagnet powering from the pulsed system located on the test bench was performed in 2015. All the oscillator systems located in the accelerator unit operated in the normal mode. We finished the development of the van construction of the UPPE. There is a capacitive storage for the energy of  $\approx 0.5$  MJ (6 capacitors per  $300\ \mu\text{F}$ ,  $24\text{kV}$ ) and a high-voltage power source 25-15 (PS25-15). The switch box adjustment was finished on the test bench; the switch box transmits the energy from the capacitive storage to the electromagnet. At the beginning of 2016 the switch box and some part of the technological equipment were assembled in the UPPE. The test powering of the pulsed powering system of the electromagnet was carried out. The load was the electromagnet located in the accelerating unit. The dimensions of the capacitive storage with the switch box were  $2.6 \times 1.4 \times 1.8$  m; the weight was  $\approx 2$  t. There is a photo (Fig. 4) of the capacitive storage with the switch box located in the UPPE.



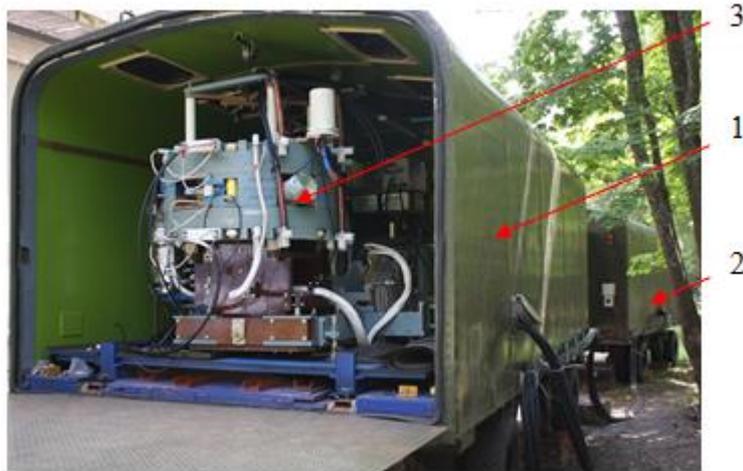
**Figure 4.** The photo of the unit of pulsed powering of the betatron electromagnet:

1 – capacitive storage; 2 – switch box

The MCA was moved to the internal polygon of FSUE “RFNC-VNIIEF” in September 2016. The testing powering was carried out. All the systems of the MCA BIM operated in the normal mode. The value of the capacitive storage of the pulsed powering system of the electromagnet was  $C=300\ \mu\text{F}$ .

### 3. Results of testing powering of MCA BIM

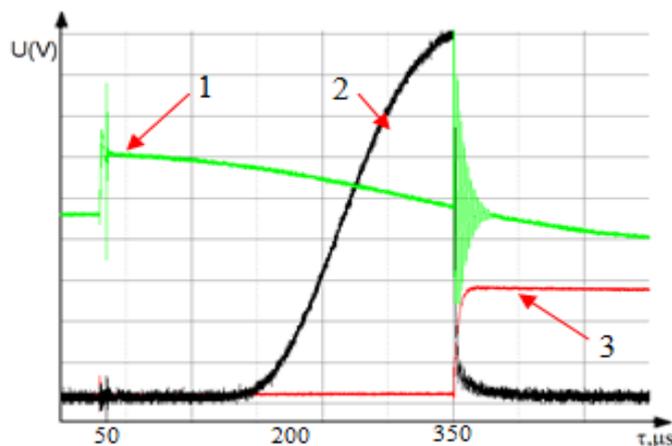
The MCA was moved to the internal polygon of FSUE “RFNC-VNIIEF” in June 2017. The testing powering was carried out. The value of the capacitive storage of the pulsed powering system of the electromagnet was  $C=900\ \mu\text{F}$ . Figure 5 illustrates the MCA BIM on the test bench.



**Figure 5.** The photo of a single-beam three-frame mobile cyclic accelerator:

1 – accelerating unit; 2 – unit of pulsed powering of the betatron electromagnet; 3 – betatron of BIM type.

All the accelerator systems operated in the normal mode during the testing powering of the MCA BIM. The typical oscillograms of the signals from the betatron detectors are illustrated in Figure 6; the signals are recorded during the testing powering.

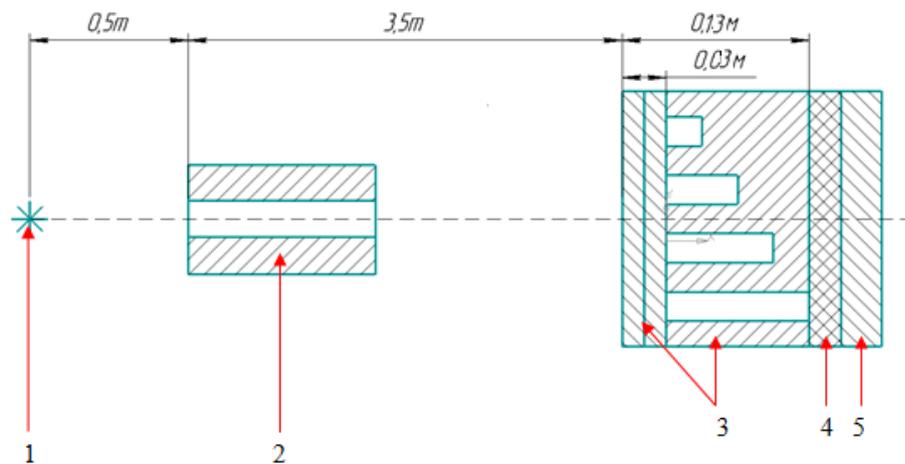


**Figure 6.** Oscillograms of the signals from the betatron detectors recorded during the testing powering:

line 1 – signal from the detector «0 field»; line 2 – signal from an optical detector of the synchrotron radiation; line 3 – intensity level of the bremsstrahlung.

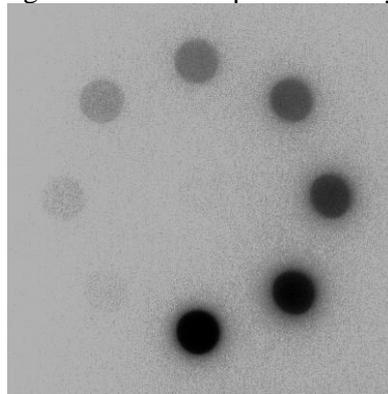
Diagram 1 in Figure 6 is a signal from the detector «0 field» (response process of the betatron electromagnet). High-frequency oscillations appear in the diagram at 350  $\mu\text{s}$ . They are caused by the operation of the electron beam dumping system. Diagram 2 is a signal from the optical detector of the electron beam synchrotron radiation in the betatron chamber. It appears after the electrons achieve some energy. Diagram 3 is a signal from the detector of the intensity level of the bremsstrahlung (detector of semi-conductor type, operates in the integration). All the provided oscillograms correspond to one powering. The charging voltage of the oscillator systems of the capacitive storage has the standard value.

The X-ray radiography of the lead test object was carried out to estimate the radiography ability of the oscillator. The test object was a lead parallelepiped with holes. The minimum thickness of the lead was 30 mm with further growing of the thickness every 10 mm. The geometry scheme of this experiment is illustrated in Figure 7.



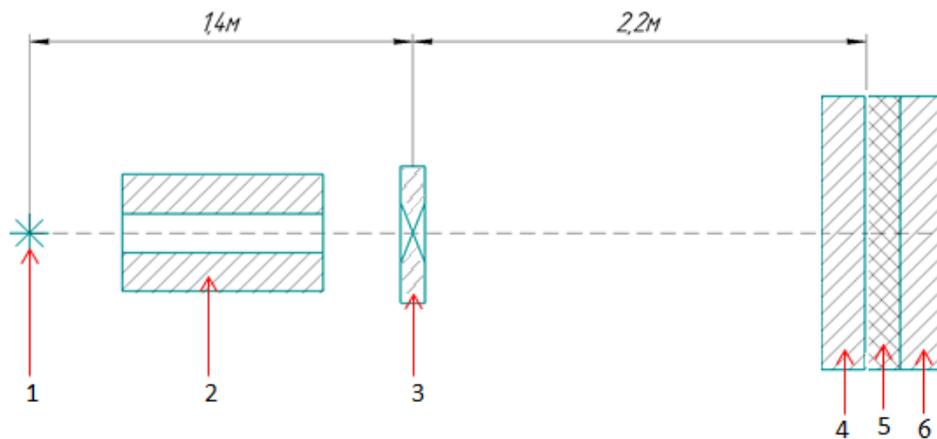
**Figure 7.** The experiment geometry scheme of the X-ray radiography of the lead test object: 1 – oscillator, 2 – collimation system of X-rays, 3 – lead test object, 4 - radiographic film, 5 – lead protective screen.

The recording of the lead test object shadowgraph and radiation source was carried out with the use of the system Imaging Plate. The maximum thickness of the X-rayed lead test at 4 m from the betatron tantalum target was  $\approx 100$  mm at the value of the capacitive storage of the pulsed powering system of the betatron electromagnet with  $C=900 \mu\text{F}$ . The X-ray picture of this test object is in Figure 8.



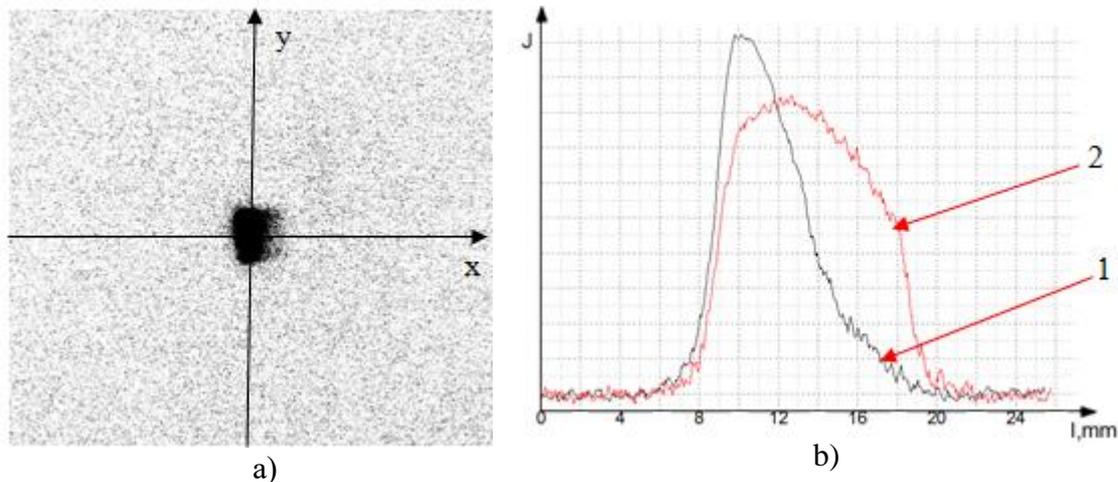
**Figure 8.** The X-ray picture of the lead test object.

The camera obscura was used to estimate the value of the slowing-down radiation source. Figure 9 illustrates the geometry scheme of the experiment that defines the radiation source dimension.



**Figure 9.** The geometry scheme of the experiment that defines the radiation source dimension: 1 – radiation source, 2 – collimation system of X-rays, 3 – camera obscura, 4 – lead protective screen, 5 – radiographic film, 6 – lead protective screen.

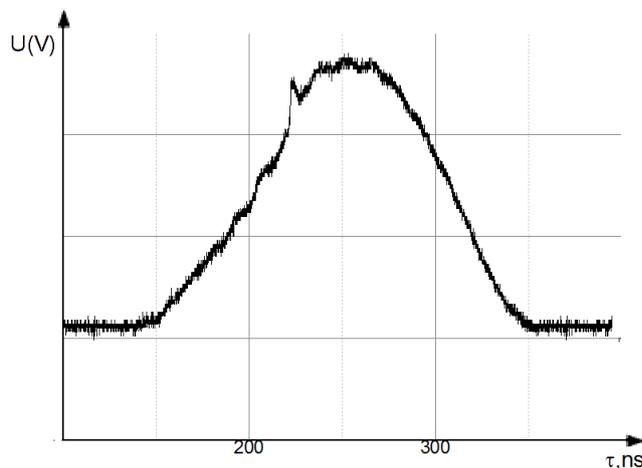
Figure 10 illustrates X-ray photograph of the radiation source and its densitogram.



**Figure 10.** a) - X-ray photograph of the radiation source, b) - densitogram of the radiation source: diagram 1 – on the axis X, diagram 2 – on the axis Y.

The results analysis showed that in the geometry experiment the radiation source dimension is  $6 \times 3$  mm (full width at half maximum of the densitogram diagrams) with the dimension of the tantalum target  $6 \times 6$  mm. It is necessary to point out that the betatron chamber design allows changing the tantalum target dimension according to the experiment tasks. And according to the previous investigations, if the target dimension is reduced twice, the output radiation intensity is down 15-20%

A stilbene scintillator detector was used to measure the length of the slowing-down radiation pulse. Figure 11 presents a typical oscillogram of the  $\gamma$ -pulse signal from the scintillator detector recorded during the testing powering.



**Figure 11.** Signal oscillogram from the  $\gamma$ -radiation detector.

The oscillogram analysis showed that the length of the  $\gamma$ -pulse in a single frame mode at full width at half maximum was  $\approx 100$  ns. It corresponds to the normal parameters of this X-ray facility.

The MCA BIM testing is going to be continued in 2018. There are plans to achieve working parameters in a three-frame mode at the value of the battery capacity of the pulsed powering system of the electromagnet equal to  $C=1800$   $\mu\text{F}$ . Besides, it is necessary to create and assemble some equipment of the technological system in the UPPE; develop and perform assembly work and

commissioning of the mobile control system. In this case we will get a fully autonomic mobile cyclic accelerator for the radiography of dynamic objects with large optical thicknesses.

#### 4. Conclusion

The testing powering of the MCA BIM showed that the thickness of the lead test object examined with X-rays at 4 m from the tantalum target with the dimension of  $6 \times 6 \text{ mm}^2$  was  $\approx 100 \text{ mm}$  at the value of a capacitive storage of the pulsed powering system of the betatron electromagnet equal to  $C=900 \mu\text{F}$ . The full width of the output gamma pulse at half maximum in a single frame mode was  $\approx 100 \text{ ns}$ . The dimension of the radiation source was  $\approx 6 \times 3 \text{ mm}^2$ .

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