A Study of Operating Regimes of an Explosive-Emission Vacuum Diode as a Source of Pulsed X-Rays in the Subnanosecond Range

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Abstract – Operating regimes of an explosive-emission vacuum diode are studied when it operates as a source of pulsed X-rays in the subnanosecond range. Compact diodes with continuous pumping or of the sealed-off type are used in the experiments. X-rays forming upon the breakdown of vacuum diodes by high-voltage subnanosecond pulses are recorded. Experiments on determination of optimal configurations of the vacuum diode electrodes and the value of the interelectrode gap for maximizing the X-radiation dose at the longest lifetime of the diode are performed. The effect of the value and the shape of the voltage pulse applied to the diode on the dose is analyzed after different treatments of the electrode surface and in largely different vacuum conditions.

1. Introduction

The impulse electric strength of insulation elements of structures is improved considerably in the subnanosecond range, making it possible to design unique compact electrophysical devices, which cannot be developed even in the nanosecond range. One of such devices is a pulsed X-ray apparatus with a miniature radiator tube connected to a source of high-voltage pulses through a thin flexible coaxial cable. The idea of this apparatus was conceived in 1979 [1]. A miniature explosive emission vacuum diode was planned as the X-ray emitter. It was shown that short lengths of commercial radio-frequency cables could be used in principle for transmission of subnanosecond high-voltage pulses [2]. However, one of the main obstacles to development of working production prototypes of subnanosecond X-ray apparatus was the absence of commercial miniature (several millimeters in size) pulsed X-ray tubes. Available commercial nanosecond tubes type IMA are more than 38 mm in diameter and 40–130 mm long and do not suit the aforementioned applications because of their dimensions. The present paper deals with an experimental study of operating regimes of explosive emission vacuum diodes for use as sources of picosecond X-ray radiation.

2. Experimental technique

In [3], a small-size voltage pulse generator (PG) type RADAN-303 [4] was taken as the basis for development of a laboratory prototype of a subnanosecond X-ray apparatus with a radiator tube, which was connected to a source of high-voltage pulses through a thin flexible coaxial cable (PK50) rated at 50 Ohm. Explosive emission vacuum diodes were used as the X-ray emitter. This laboratory prototype was used to study the operating regimes of the explosive emission vacuum diodes. We did not pose ourselves the task to minimize the size of these diodes as much as possible. This is a purely engineering problem. However, our investigations showed that the limiting size of the diodes could be a few millimeters.

A subnanosecond pulser with high-pressure peaking and chopping nitrogen gaps [5] was installed at the generator output. The pulser supplied subnanosecond high-voltage pulses with smoothly adjustable parameters to the diode. The explosive emission diode had a nonlinear voltage-current characteristic, which changed during the pulse. Therefore, in the general form it could not be matched completely with the cable. The analysis [6] demonstrated that the diode and the cable could be matched by the proper selection of the shape of the voltage pulse applied to the diode. The optimal matching was achieved when high-voltage triangular pulses were fed to the explosive emission diode. In our experiment, the subnanosecond voltage pulse (Fig. 1) approached the required shape for matching.

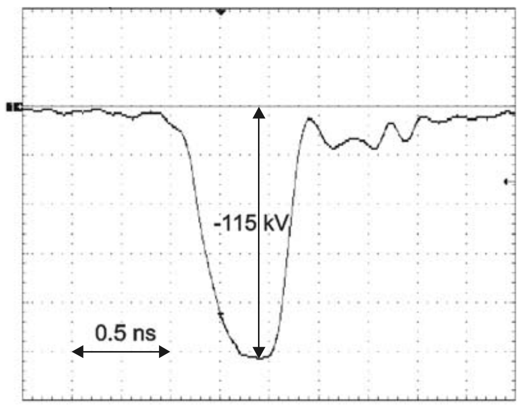

Fig. 1. High-voltage pulse measured with a Tektronics TDS6604 oscilloscope

As the X-ray radiator explosive emission vacuum diodes with continuous evacuation and of the sealed-off type (Fig. 2) were used. Most of the experiments were performed using continuous-evacuation diodes because they allowed a rapid redesign of the vacuum gap electrodes and the change of the interelectrode spacing. The outer diameter of the diode was 9 mm. A mechanical backing oil pump served for evacuation through a hole in the anode. The working vacuum was 1 Pa. No special measures were taken to preclude the ingress of oil vapor to the tube volume.

Fig. 2. Appearance of X-ray emitters with continuous evacuation and of the sealed-off type

In the first part of experiments, the explosive emission diode received a voltage pulse having the amplitude of 115 kV, half-amplitude length of 0.4–0.5 ns, and rise time (relative to 0.1–0.9 of the amplitude) of 0.2–0.25 ns (Fig. 1). The voltage rise rate was (4.6–5.8) $\cdot 10^{14}$ V/s. The aim of these experiments was the determination of the optimal configurations of the vacuum diode electrodes and interelectrode spacing providing the maximum dose of the X-ray radiation and the longest lifetime of the tube. The cathode and the anode were made of tungsten. X-ray radiation doses were measured with the following configurations of the cathode-anode system: rod (dia 0.8 mm) – rod (dia 0.8 mm); rod (dia 0.8) – plate; pipe rolled up of a foil – rod (dia 0.8 mm); pipe rolled up of a foil – plate.

The interelectrode spacing was adjusted at 0.08 to 1–2 mm. The subnanosecond X-ray radiation, which resulted from the breakdown of the vacuum diodes, was recorded. The measurements were made using a 541R capacitor dosimeter ("The Victoreen Instrument Co", USA) and a thermoluminescent dosimeter type DTL (production of Russia). The cathode (rod) – anode (plate) system provided the most stable doses of the X-ray radiation. Fig. 3 presents the dependence of the X-ray radiation dose on the interelectrode spacing in this system. This dependence was measured using the capacitor dosimeter. The dosimeters were installed at the side of the cathode-anode gap at a distance of 20 mm from the discharge gap. Maximum radiation doses of 8–9 mR per pulse were obtained using vacuum diodes with the interelectrode spacing of 0.22 mm. Values measured with the DTL thermoluminescent dosimeter were different: 27–30 mR per pulse. Probable explanations for these metrological discrepancies are, firstly, the absence of universally accepted standards for measurement of subnanosecond X-ray radiation and, secondly, the possible attenuation of radiation by the metal casing of the capacitor dosimeter.

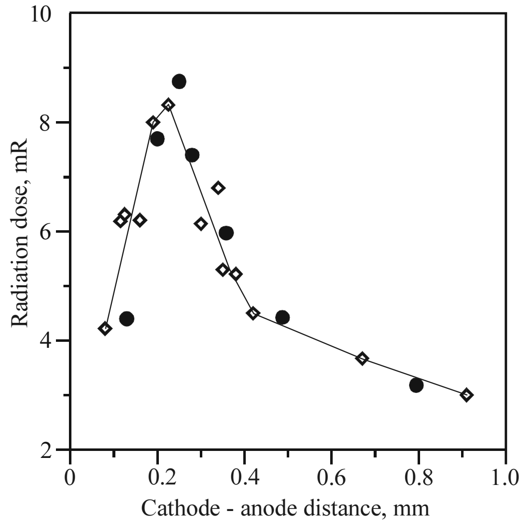

Fig. 3. Dependence of the X-ray radiation dose on the interelectrode spacing of the tube. Rhombus – X-ray tube with continuous evacuation. Circle – sealed-off X-ray tube

The radiation dose decreased if the cathode-to-anode distance diminished. The radiation dose became increasingly unstable from pulse to pulse when the distance was 0.08–0.12 mm. The material of the cathode was heavily sputtered, leading to considerable plating of the internal surface of the tube casing. A thin bridge (up to 0.4 mm in diameter) having the resistance of about 10 MOhm (as measured by an F4101 megohmmeter) was formed between the electrodes after 100–150 high-voltage pulses were applied to the diode. When the bridge was formed, the gap was ruptured on the bridge surface and the radiation dose decreased to 0.9–1.3 mR per pulse (in 5–10 times). Thus, the X-ray radiation was also generated during the subnanosecond vacuum breakdown on the dielectric surface. When the interelectrode gap was larger than 0.2 mm, the cathode sputtering was insignificant and not influenced the performance of the tube.

The cable and the tubes withstood at least 3000 pulses and this lifetime is quite sufficient for practical applications. It was found also that the electron beam burns a hole approximately equal to the cathode diameter in the explosive emission tubes with a flat anode (tungsten foil 0.1 mm thick) and the interelectrode gap less than 0.25 mm. As the hole is formed, the irradiation dose becomes unstable from pulse to pulse, but regains stability upon completion of the hole. Still, it is advisable to make the anode of foil 0.3 mm thick and more or increase the interelectrode gap up to 0.3 mm.

The experiments were performed using a variety of vacuum conditions. The X-ray radiation dose

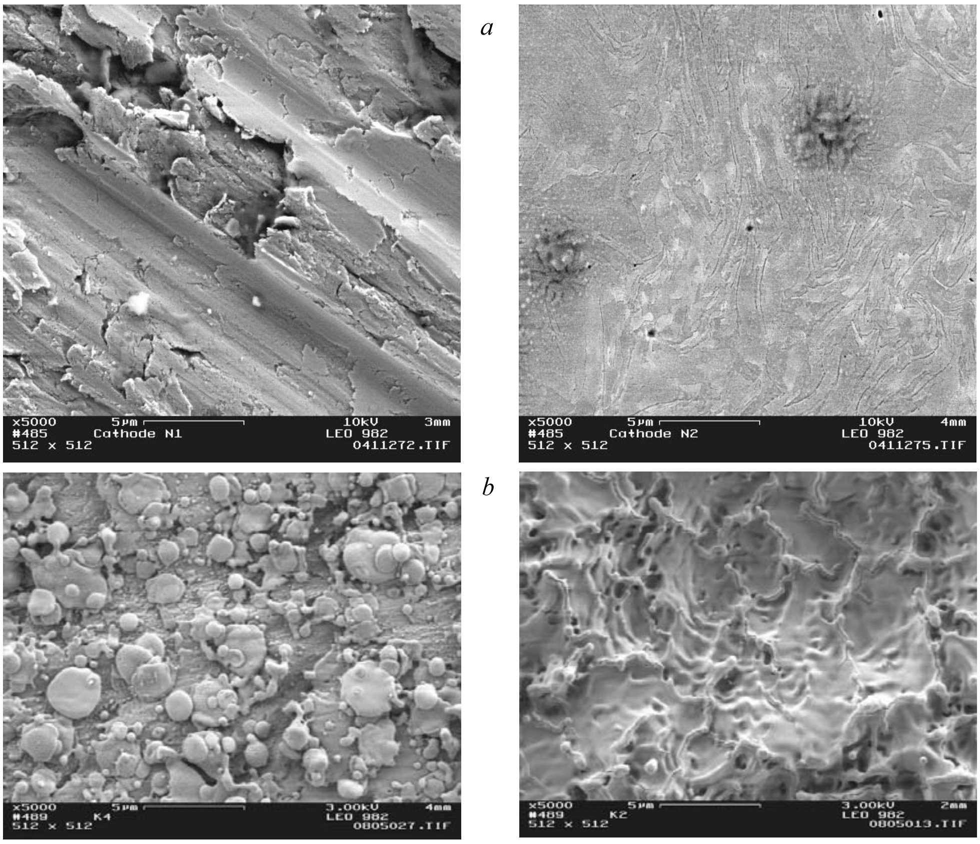

Fig. 4. Photographs of the surface of the cathodes: *a* – after machining; *c* – after electropolishing. The surface of the machined (*b*) and electropolished (*d*) cathodes after aging by 1000 high-voltage pulses

decreased at the residual pressure of the tube higher than 1 Pa. Compact sealed-off explosive emission X-ray tubes (the residual vacuum of 10^{-5} Pa) (Fig. 2) were made. The sealed-off and continuously evacuated explosive emission tubes had similar parameters during tests. The X-ray radiation dose did not increase in a higher vacuum. This is one of the most interesting results of the study considering that X-ray tubes, which would provide stable operation in conditions of a technical oil vacuum, are unavailable today.

The configuration of the electrode system, in which the cathode and the anode were shaped as rods 0.8 mm in diameter, also proved to be promising for practical applications. The stability of the irradiation dose was impaired a little from pulse to pulse in this electrode configuration. However, it provides the maximum miniaturization of the diode.

It was studied experimentally how the performance of the explosive emission diode depends on the method used for treatment of the cathode surface. In these experiments, the cathode was made of lengths of tungsten wire 0.8 mm in diameter. In one lot of the diodes the cathode surface was machined using a fine-dispersed diamond wheel, while in the other lot of the diodes the cathode was machined and then underwent electropolishing. The anode was made of tungsten foil. Given the same interelectrode gaps and designs of the diodes, the irradiation dose of the diodes with the machined cathode was nearly twice as high as that of the diodes with the electropolished cathode during the first voltage pulses. The irradiation dose of the diodes with the polished cathode increased and almost equaled the dose at the unpolished cathodes with the working time. Fragments of the cathode surface before and after aging are shown in Fig. 4, *a–d*. It is seen that the size and the structure of micropoints on the surface of the cathodes are different. Numerous droplets of the molten metal with the characteristic size of tenth fractions of a micrometer to 2 μm are observed on the machined surface (Fig. 4, *b*). The surface of the electropolished cathode is fused almost uniformly and has a big number of a practically uniformly distributed microtips with the summit radius equal to tenth fractions of a micrometer. A fragment of the anode surface is shown in Fig. 5.

Dependences of the irradiation dose on the pulse amplitude were established. In this experiment, the vacuum diode received voltage pulses with the rise time of 0.18–0.22 ns and FWHM equal to 0.25–0.4 ns. The experimental results are summarized in the Table. It is seen that at the voltage pulse amplitude of 70 kV the irradiation dose was about 2 mR per pulse. In other words, in the frequency pulse repetition regime it is possible to develop small-size X-ray apparatus with a flexible cable radiator probe on the basis of compact PGs providing the output voltage of about 70 kV.

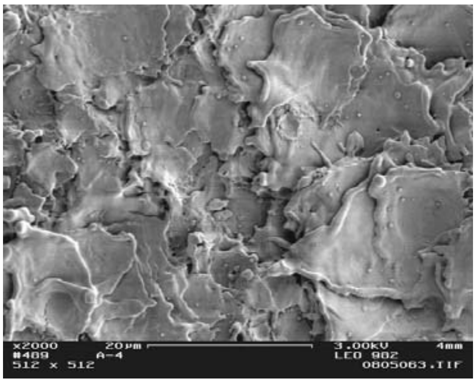

Fig. 5. Photograph of the fragment of the surface of anode

Table. Dependence of the irradiation dose on the pulse amplitude. The experiment was performed using a diode with a rod-like cathode (0.8 mm in diameter) and a flat anode. The interelectrode gap was 0.38 mm

V, kV	58	69.6	92	120.6
D, mR per pulse	0.6–0.9	1.4–2.2	2.8–3.2	5–5.5

The effective energy of photons was estimated by the method of foils (copper, nickel). The curves in Fig. 6 show the attenuation of the irradiation dose in copper. Calculations of the effective energy of photons demonstrated that 80% of the X-ray dose accumulated due to photons having the energy less than 60 keV. The rest of the dose corresponded to the effective dose of photons equal to 120–130 keV.

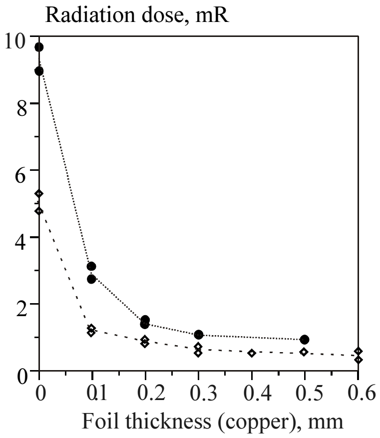

Fig. 6. Attenuation of the irradiation dose in copper for X-ray tube with 0.38 mm (rhombus) and 0.22 mm (circle) interelectrode distance

3. Conclusion

It was shown that explosive emission vacuum diodes could be used as sources of subnanosecond pulsed X-ray radiation over a wide interval of supply voltages and vacuum conditions, down to a technical oil vacuum (1 Pa). X-ray doses of a few tens of milli-Roentgen per pulse were obtained, making it possible to accumulate irradiation doses necessary for practical applications in the frequency pulse repetition regime.

Acknowledgements

The authors wish to thank G.A. Mesyats for support of this work; V.L. Kuznetsov, A.L. Filatov, and V.V. Uvarin for their help in making sealed-off explosive emission X-ray tubes; M.I. Yalandin and S.A. Shunailov for the RADAN generators used in the experiments; K.A. Sharypov for his assistance in the experiments; O.R. Timoshenkova and A.M. Murzakaev for the photos in scanning electron microscope; S.Yu. Sokovnin for his useful advice.

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