Laboratory Prototype of Subnanosecond X-ray Apparatus with Flexible Cable Radiator Probe Based on Explosive Emission Diode

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Abstract - Small-size voltage pulse generators RADAN type served as the basis for development of laboratory prototypes of a subnanosecond X-ray apparatus with a miniature radiator tube, which was connected to a source of high-voltage pulses through a thin flexible coaxial cable (PK50) rated at 50 Ohm. Miniature explosive emission vacuum diodes were used as the X-ray emitter. The developed small-size X-ray apparatus with a flexible cable radiator probe may find application in medicine for close-focus intracavitary roentgenotherapy and stomatology, and also in industry for X-ray inspection of small intricate hollow parts since the X-ray tube can be brought immediately to spots, which are hard to irradiate from available X-ray apparatus.

1. Introduction

An ever-increasing interest is attached today to practical applications of picosecond power electronics. One of the promising leads of the use of short pulses is development of small-size high-voltage electrophysical devices. This is explained, in the first place, by a considerable increase in the electric pulse strength of various insulation elements of structures while the pulse length becomes shorter. As a result, it is possible to design unique compact electrophysical devices working in the subnanosecond range, which cannot be developed for operation already in the nanosecond range. One of such devices is a pulsed X-ray apparatus with a miniature X-ray tube, which is connected to a source of high-voltage pulses through a thin flexible coaxial cable. Main advantages of the subnanosecond X-ray apparatus with a flexible cable radiator probe include a small size and the possibility to bring the X-ray tube immediately to an object, which is hard to reach with available X-ray apparatus. These apparatus may prove to be useful in medicine for close-focus intracavitary roentgenotherapy and stomatology, and also in industry for X-ray inspection of small intricate hollow parts.

The idea of such apparatus was suggested 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, although the idea about a compact X-ray apparatus with a flexible feeder was suggested a quarter of a century ago, it could not be embodied so far. This situation was due to both difficulties involved in generation of subnanosecond high-voltage pulses and the absence of commercial miniature pulsed X-ray tubes. Available commercial nanosecond tubes type IMA (production of Russia) are more than 38 mm in diameter and 40-130 mm long and do not suit the aforementioned applications because of their dimensions. The recent small-size voltage pulse generators (PG) RADAN type, which form subnanosecond high-voltage pulses

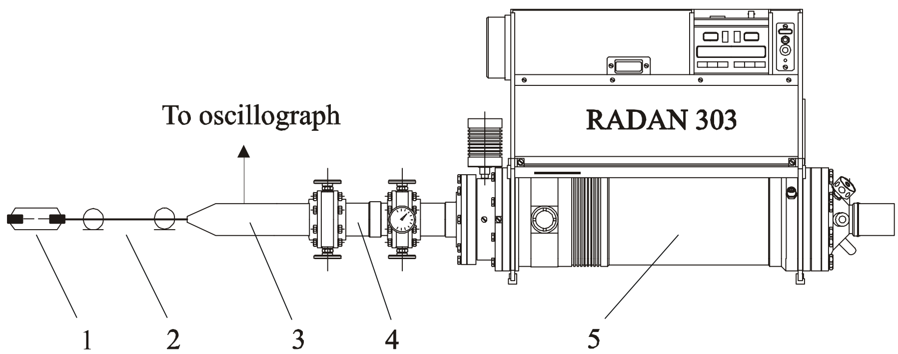

Fig. 1. Block diagram of the subnanosecond X-ray apparatus with a flexible cable radiator-probe: 1 – explosive emission diode; 2 – coaxial cable (1 m long); 3 – matching unit; 4 – subnanosecond pulse slicer; 5 – compact pulse generator RADAN

with smoothly adjustable parameters open up new opportunities for the use of subnanosecond range. These generators may serve as the core of various electrophysical devices including compact X-ray apparatus.

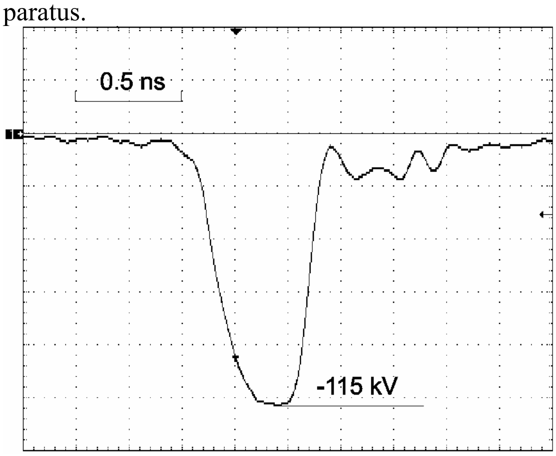

Fig. 2. High-voltage pulse measured with a Tektronics TDS6604 oscilloscope

2. Experimental Technique

The laboratory prototype of the X-ray apparatus (Fig. 1) is based on a small-size PG RADAN-303 [3]. A subnanosecond pulse slicer with high-pressure peaking and chopping nitrogen gaps [4] was installed at the generator output. In our experiments the explosive emission diode received a voltage pulse having the amplitude of 115 kV, the half-amplitude length of 0.4-0.5 ns, and the rise time (relative to 0.1-0.9 of the amplitude) of 0.2-0.25 ns (Fig. 2). The voltage rise rate was $(4.6\text{-}5.8)\times10^{14}$ V/s. 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 [5] 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 approached the required shape for matching. The magnitude and the shape of the voltage pulse applied to the vacuum emitting diode were controlled by means of a capacitive voltage dividers built into the coaxial line of the short 50-Ohm oil-filled transmission line, which was part of the unit responsible for matching of the pulse generator and the coaxial cable.

As the X-ray radiator miniature explosive emission vacuum diodes with continuous evacuation (Fig. 3) and of the sealed-off type (Fig. 5) were used. The tubes were connected to the PG through the commercial cable type PK50 (PK50-11-11, PK50-9-11 or PK50-7-11) having the outer diameter of 14, 12 and 10 mm respectively and the length of 1 m. 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 design of the continuous-evacuation diode is shown in Fig. 3. 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.

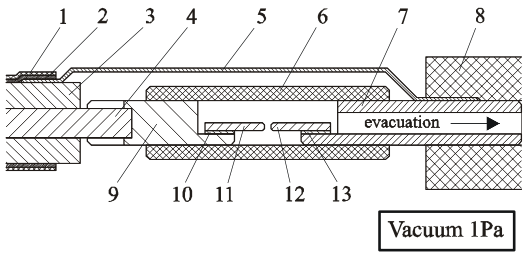

Fig. 3a. X-ray emitter with continuous evacuation. Coaxial cable (1 – external insulation, 2 – braiding, 3 – internal insulation, 4 – conductor); 5 – grounding busbar; 8 – vacuum-rubber hose; explosive emission diode (6 – glass body; 7 – tubular anode; 9 – plunger contact cathode; 11, 12 – tungsten electrodes made of wire 0.8 mm across; 10, 13 – nickel foil). Parts 7, 9-13 were made using contact welding. Parts 6, 7 and 9 were fixed with an epoxy adhesive

Some experiments were aimed at determination of the optimal configurations of the vacuum diode electrodes and interelectrode spacings 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;
rod (dia 0.8 mm) – rod (dia 0.8 mm), the breakdown occurred on the surface of the dielectric link between the anode and the cathode.

In these experiments 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. Figure 4 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.

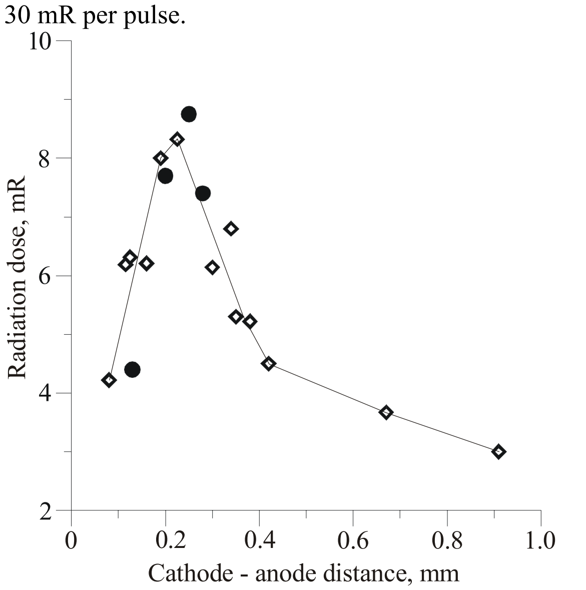

Fig. 4. Dependence of the X-ray radiation dose on the interelectrode spacing of the tube. Rhombus – X-ray tube with continuous evacuation. Circle - sealed-off X-ray tube

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. Thus, the X-ray radiation was also generated during the subnanosecond vacuum breakdown on the dielectric surface.

The coaxial cable withstood several thousand voltage pulses without the insulation breakdown and the radiation dose could be easily accumulated with the PG operating in the frequency regime. If the insulation of the transmission cable was punctured, the flexible R-ray radiator probe remained serviceable. The breakdown channel, which was formed in the cable insulation, worked as a chopping gap, leading to the decrease in the amplitude of the voltage pulse at the diode and, hence, the radiation dose. Some decrease in the X-ray radiation dose per pulse could be easily compensated by increasing the number of pulses. Repeated measurements, which were made several days later, showed that the punctured insulation of the cable fully healed. The cable withstood over 600 pulses until another breakdown. The capillary effect caused soaking of the copper braiding of the cable with transformer oil from the "cable – pulse generator" matching unit. As a result, the punctured insulation of the cable was restored.

Compact sealed-off explosive emission X-ray tubes (the residual vacuum of 10^{-5} Pa) with adjustable (Fig. 5a) and a fixed (Fig. 5b) interelectrode gap were made. The sealed-off and continuously evacuated explosive emission tubes had similar parameters during tests (see fig.4).

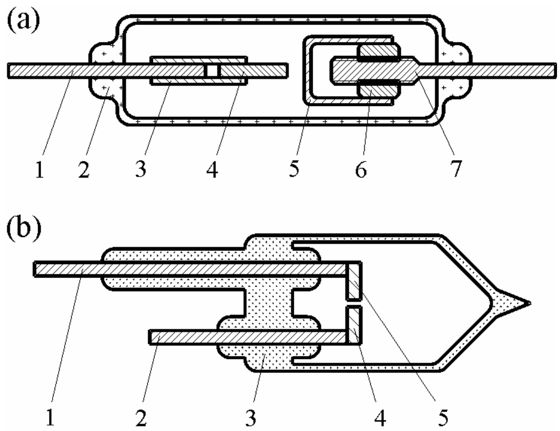

Fig. 5. Sealed-off X-ray emitters with an adjustable by means of an external magnet or by knocking on the diode body (a) and fixed (b) interelectrode gap.
At the fig 4a: 1,7 – kovar leads-in; 2 - glass body; 3 – nickel tube; 4 – tungsten cathode; 5 – tungsten anode (foil); 6 – iron screw. Parts 1, 3-6 were made using contact welding. At the fig 4b: 1,2 – kovar leads-in; 3 - glass body; 4 – tungsten cathode; 5 – tungsten anode. Parts 1, 5 and 2, 4 were made using contact welding

3. Conclusion

Small-size voltage pulse generators RADAN type served as the basis for development of laboratory prototypes of a subnanosecond X-ray apparatus with a miniature radiator tube, which was connected to a source of high-voltage pulses through a commercial thin flexible coaxial cable (PK50) rated at 50 Ohm. Explosive emission vacuum diodes were used as the X-ray emitter. Doses of subnanosecond X-ray radiation as high as several tens of milliRoentgens per pulse were generated. RADAN generators operate at the pulse repetition frequency of up to 100 Hz providing accumulation of X-ray radiation doses sufficient for practical applications. It was shown that the explosive emission diode functioned reliably as the X-ray emitter over a broad interval of vacuum conditions including those of the technical vacuum (1 Pa).

The compact subnanosecond X-ray apparatus with the flexible sealed-off radiator-probe may be useful in different spheres since the X-ray tube can be brought immediately to an object, which is hard to reach with existing X-ray apparatus.

Acknowledgements

The authors wish to thank V.L. Kuznetsov, A.L. Filatov and V.V. Uvarin for their help in making of sealed-off explosive emission X-ray tubes, M.I. Yalandin and S.A. Shunailov for the RADAN generators used in the experiments, and K.A. Sharypov for his assistance in the experiments.

The study was supported by the Russian Fund for Basic Research grant No. 04-02-08038.

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