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Experimental study of explosive emission cathodes for the formation of nanosecond electron beams

R.V. Tsygankov, O.P. Kutenkov, V.V. Rostov, A.S. Stepchenko*

Institute of High Current Electronics SB RAS, Tomsk, Russia
mincemeat@rambler.ru

Abstract. The article is devoted to describing the results of the experimental studies of two types of explosion-emission cathodes for high-current periodically-pulsed electron accelerators.

The operating characteristics of tubular explosion-emission cathodes based on carbon microfiber for electron beam formation in a coaxial diode with magnetic insulation are experimentally investigated. Attention was paid to their properties influencing for the generation of microwave radiation in a pulse-periodic mode. To study the properties of such cathodes, a moderately relativistic Backward Wave Oscillator (BWO) of the centimeter wavelength range was used, and a high-current pulse-periodic electron accelerator with a current and voltage pulse duration of 45 ns was used as a driver. The amplitude of the voltage pulse in the diode reached 450 kV, and the electron beam current was 4.5 kA. It was shown that the lifetime of carbon microfiber cathodes at operating in the pulse packet mode with a repetition rate of 500 Hz was more than 10^6.

A planar metal-dielectric cathode with a beam aperture of 170 cm^2 and an electron beam energy of up to 400 keV has been developed for radiation treatment of bulk substances. As a result of the computational optimization of the emission area of the cathode and the focusing electrode, an electron beam with the necessary energy characteristics and a uniform distribution of current density on the object was obtained.

Keywords: cathodes, carbon fiber, metal- dielectric cathodes, electron beam.

1. Introduction

Explosive emission cathodes are used to produce electron beams in high-power pulse technology. The main task of such cathodes is the formation of a high-current electron beam with specified and stable characteristics for various applications. Recently, electron beams with a continuous cross-section with an emission area of up to several hundred square centimeters, as well as thin-walled ones, have attracted increasing interest [1].

Cathodes with an area of several square centimeters are used as a source of nanosecond pulses of bremsstrahlung X-ray radiation for biomedical research [2]. They are also used in microwave generators and electron beam sterilizers with beam output into open space through foil [3]. Both types of devices are implemented on the basis of the SINUS nanosecond pulse generator [4]. In practice, when using such devices, the required cathode life should be 10^6 pulses.

Of practical interest is the pulse-periodic operating mode of such microwave radiation sources with a large number of pulses in a package of at least several hundred with a pulse repetition rate of several hundred Hertz.

High uniformity of current density at low field strength (150–200 kV/cm) is ensured by cathodes with a surface made of ordinary velvet or velor [5]. In particular, these cathodes were used in experiments on the generation of microwave radiation in vircators. It is due to the use of cathodes of this type in them that it was possible to increase the generation efficiency up to 15% [6]. For example, in a Cherenkov generator without a magnetic field, by replacing a composite metal-dielectric cathode with a velvet cathode, it was possible to increase the generation efficiency at an accelerating voltage of about 1 MV from 8% to 15%, and at a reduced accelerating voltage of 500 kV, the efficiency is 8% [7].

At the same time, when operating in a pulse-periodic mode, velvet cathodes quickly lose their properties. The service life of a velvet cathode is particularly shortened when the cathode surface is heated. In particular, this occurs when the electron beam passes through an uncooled wire mesh.

When operating at a high pulse repetition rate, the grid heats up to high temperatures due to the influence of electrons.

Metal-dielectric cathodes, consisting of a set of foil-textolite plates, also turned out to be suitable for generating beams. However, our research shows that when operating in a periodic pulse mode, they quite quickly, lose the properties of uniform density in the cross section.

A significant improvement in parameters is provided by the use of surface flashover-based cathodes. In this case, it is possible to use metal contacts to set local overvoltage points and long-lived ceramics. The results of using this type of cathode in practice are described in the second chapter of the article.

The decision to use carbon fiber cathodes stems from previous research at the Institute of High Current Electronics [7, 8], as well as from research from other large laboratories showing the advantage of using carbon to increase the estimated service life of the cathode surface [9–11]. Carbon has remarkable properties that have a positive effect on explosive electron emission. In addition, if the cathode is made of millions of filaments this leads to multiple local areas of electric field amplification. In this case, the cathode quickly “turns on”, and this leads to a decrease in the current front.

Another positive result is the uniform distribution of current density over the entire surface of the cathode during the pulse. The sublimation point of carbon fiber is at 3500 °C, allowing the cathode to withstand maximum transient temperatures of approximately 2500 °C. However, little destruction of the carbon fibers occurs during the emitter explosion process. However, as is the case with other cathodes, surface degradation occurs much more slowly (Fig. 2). Carbon fibers do not melt or form blunt ends, they break and splinter, creating additional sharp points that are areas of field enhancement. This effect does not lead to significant degradation of the cathode performance due to the overall field strength remaining at the base level.

2. Surface flashover-based cathodes testing

Finding the configuration of the cathode and the material from which it is made is a difficult task facing scientists who use high- power electron beams in their work [12]. It is quite difficult to predict changes in their characteristics over time. Those areas of the cathode where the electric field is strengthened are most susceptible to degradation. When solving the problem of focusing an electron beam from a large-area solid cathode, we encountered the problem of nonuniform distribution of current density across the cross section.

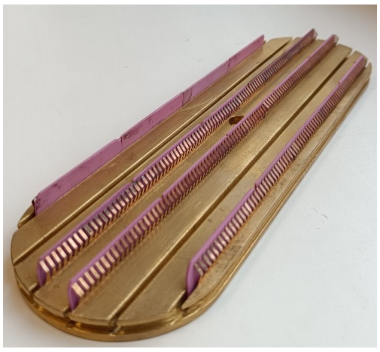

Fig. 1. The view of metal-dielectric cathode.

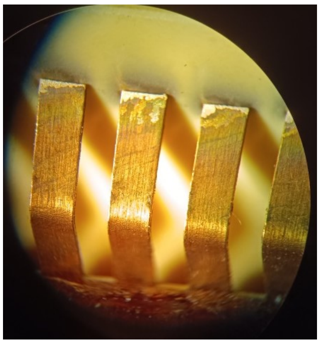

Fig. 2. The cathode contacts (enlarged photo).

This was controlled by the imprint of the electron beam, which was obtained after its deposition on the polymer film in the area of the anode walls. Using a focusing electrode covering the cathode along the perimeter, it was possible to reduce the spread of the electron beam and increase its density along the edges of the cathode. However, increasing the focusing electrode in the direction of beam motion has an optimum, after which the effect of screening of parts of the cathode located closer to the focusing electrode is observed, corresponding to a decrease in the current density along the edges of the cathode. In our previous studies, a rectangular cathode was used. When trying to uniformly increase the focusing electrode to obtain a uniform current density over the entire cross-section of the cathode, it was impossible to avoid the fact that in the corners of this rectangle the electric field turned out to be several times smaller. This problem was solved using numerical simulation by optimizing the rounding of the electrode sides. As a result, a rounded rectangle lies in the cross section of the cathode.

This type of metal- dielectric cathode consists of a set of ceramic plates with bronze contacts pressed to them (approximately 250 contacts). The ends directed towards the anode are made in the form of a comb (Fig. 1, 2). Electric signals from the probes were recorded with a Rigol MSO8204 high-speed digital oscilloscope.

At a maximum charging voltage of 460 kV, the amplitude of the high-voltage pulse reaches ≈ 420 kV, the peak value of the beam current is about 4.2 kA (see Fig. 3). The first peak in the current is capacitive due to the existing stray capacitance of the cathode holder on the vacuum diode body.

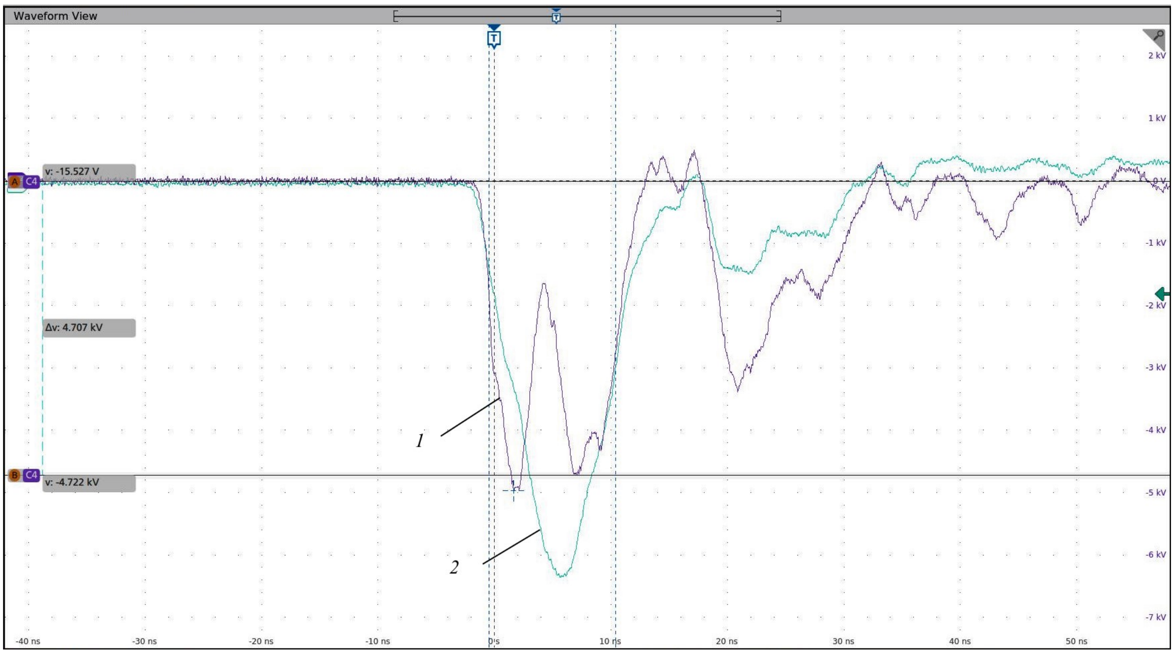

Fig. 3. Oscilloscope signals. *1* – Current signal (1 kA/div), *2* – Voltage signal (65 kV/div), time scale 10 ns/div.

This cathode option is preferable not only because of the local field enhancement near the “metal-dielectric-vacuum” triple points, but also causes an anomalously high speed of plasma propagation along the dielectric surface [13, 14]. This speed (~$2 \cdot 10^7$ cm/s) is an order of magnitude higher than the speed of cluster expansion in a vacuum from conventional microemitters.

For those shown in Fig. 3 oscillograms, the cathode-anode distance is slightly 4 cm.

The cathode was located in a planar diode; the role of the anode was played by thin aluminum foil, located against the edge of cathode. The continuous electron beam generated by the cathode passes through the foil and is interacting with air into the air space, deposited on the conveyor belt. Bulk substances are fed onto a moving conveyor belt, which, as they move, pass through the electron beam. Due to the effects of interaction of high-energy electrons with the surrounding space and with the bulk substance, decontamination of the product occurs on the conveyor. In this case, a uniform electron flux density ensures high-quality irradiation of the product. Energy of electron beam in this case have a value about 300 keV on the target.

3. Carbon fiber cathode testing

Recently, more and more attention has been paid to cathodes made of graphite fiber. Indeed, in our experiments, such a cathode showed the ability to simulate an electron beam with a very short current rise up to a few nanoseconds, as well as provide a stable voltage in the diode throughout the entire pulse duration.

The impedance in the diode remains constant during the pulse. Our experiments were carried out on a pulsed high-current accelerator SINUS- 450. Thanks to a controlled gas switch, the voltage and current in the diode can be varied. The diode voltage can be varied in the range plus or minus 50 kV. The experiment used an average voltage value of about 400 kV. The corresponding electron beam current at this voltage was equal to 4.2 kA (Fig. 4). In this mode, the cathode was investigated for its service life. More than 10^6 pulses were applied (Fig. 5). In this case, the quality of the cathode operation was assessed by the characteristics of the microwave pulse generated by the backward wave oscillator, through the slow-wave structure of which the electron beam was transported. One of the indicative characteristics of a microwave pulse is the time of the transition process - the time of buildup of microwave oscillations in the backward wave oscillator from zero up to maximum amplitude. It was this characteristic, the pulse duration (Fig. 6), as well as the microwave pulse amplitude, that we recorded when studying the cathode’s service life. Throughout the experiment, the pulse amplitude remained almost constant. Its variation is associated with some instability of the spark gap work and is less than 0.5%.

In the accelerator operating mode, 500 pulses for 2 second followed by a 1-minute break were applied using a carbon fiber cathode of 10^6 pulses. An oscillogram after overcoming 10^6 pulses shows that the cathode is working stably; no spread in the amplitude of the pulses is observed. It is also characteristic that the duration of the front of the detected microwave pulse is also stable and is within 10 nanoseconds. The duration of the microwave pulse itself was reduced slightly, by only 5–7 ns.

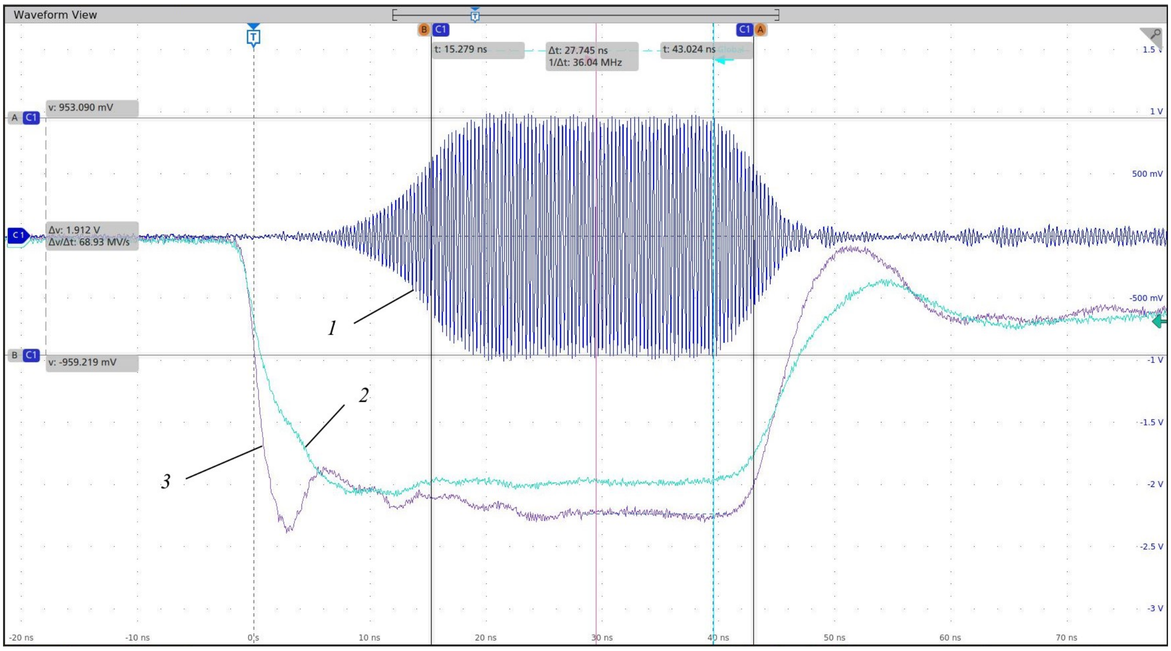

Fig. 4. Oscilloscope signals. *1* – Microwave signal, *2* – Voltage signal (100 kV/div), time scale 10 ns/div, *3* – Current signal (1 kA/div).

Visual inspection of the cathode after the experiments revealed irregularities and burnout on the edge. This is probably due to the presence of dielectric inclusions in the carbon fiber, which led to local field enhancement and fiber burnout. Despite this, the cathode continued to operate with a slight decrease in its initial characteristics. Probably, due to the burnout of the cathode edge, the electron beam was no longer as uniform as at first, however, we observed the generation of a symmetrical wave from the TM_{01} circular waveguide.

Fig. 5. The view of carbon-fiber cathode.

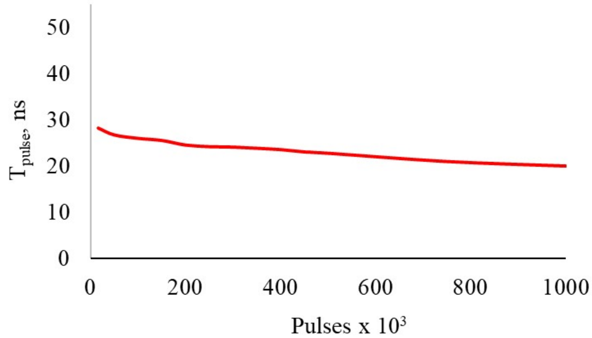

Fig. 6. The time of microwave pulse duration T_{pulse} in dependence of quantity of pulses.

It should be noted that under these conditions, a cathode made of solid graphite did not provide the required quality of the electron beam for generating microwave radiation. As a result, we observed, firstly, a long transient process of about 20 ns and a short duration of the microwave pulse with a reduced amplitude. The use of a graphite fiber cathode makes it possible to generate microwave pulses with an amplitude of about 800 MW and a duration of about 30 ns. The generation efficiency, estimated from the pulsed radiation power, was about 45%.

4. Conclusion

The cathodes studied in experiments have high reliability, long service life (more than 10^6 pulses) and repeatability of the parameters of the electron beam and electron energy.

Fixed sampling of emission centers and selection of the correct material for the metal-dielectric cathode (ceramics 22HS and bronze) made it possible to obtain an electron beam with a uniform distribution of current density over the entire cross section of the electron beam. This made it possible to use electron beams formed by cathodes of this type for disinfecting bulk food products.

It has been shown that carbon fiber cathodes have not only a short start time of explosive electron emission, but also a stable impedance that is maintained throughout the entire pulse. The configuration of the described cathodes determines the front of the current pulse and the uniformity of the beam, and, as a consequence, the duration of the microwave pulse.

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5. References

[1] A.V. Gunin, V.F. Landl, S.D. Korovin, G.A. Mesyats, V.V. Rostov, Long-lived explosive-emission cathode for high-power microwave radiation generators, *Technical Physics Letters*, vol. **25**(11), 922, 1999, doi: 10.1134/1.1262685

[2] M.A. Buldakov, A.I. Klimov, N.V. Litvyakov, et al., Explosive Emission Cathode Based on a Carbon Fiber for Long-Term Pulsed-Periodic Mode of Operation and its Application in a High-Power Microwave Pulse Generator Without External Magnetic Field, *Eur. J. Cancer*, vol. **47(**1), 197, 2011, doi: 10.1016/S0959-8049(11)70989-3

[3] G.A. Mesyats, S.D. Korovin, A.V. Gunin, et al., Repetitively pulsed high-current accelerators with transformer charging of forming lines, *Laser Particle Beams*, vol. **21**(2), 197, 2003, doi:10.1017/S0263034603212076

[4] R.J. Adler, G.F. Kiuttu, B.E. Simpkins, et al. Improved electron emission by use of a cloth fiber cathode, *Rev. Sci. Instrum*., vol. **56**, 766, 1985, doi: 10.1063/1.1138169

[5] E.M. Totmeninov, A.I. Klimov, and V.V. Rostov, Relativistic Cherenkov Microwave Oscillator Without a Guiding Magnetic Field for the Electron-Beam Energy of 0.5 MeV, *IEEE Trans. Plasma Sci*., vol. **38**(10) (Part 2), 2944, 2010, doi: 10.1109/TPS.2010.2060212

[6] B.M. Kovalchuk, S.D. Polevin, R.V. Tsygankov and A.A. Zherlitsyn, S-Band Coaxial Vircator With Electron Beam Premodulation Based on Compact Linear Transformer Driver, *IEEE Trans. on Plasma Sci.*, vol. **38**(10), 2819, 2010, doi: 10.1109/TPS.2010.2060367.

[7] N.M. Bykov, V.P. Gubanov, A.V. Gunin, S.D. Korovin, O.P. Kutenkov, V.F. Landl, G.A. Mesyats, S.D. Polevin, V.V. Rostov, F.Ya Zagulov, Development of Long Lifetime Cold Cathode, *10th Int. Pulsed Power Conf.*, Albuquerque, New Mexico, 71, July 1995, doi: 10.1109/PPC.1995.596457

[8] O.P. Kutenkov, I.V. Pegel, E.M. Totmeninov, Explosive Emission Cathode Based on a Carbon Fiber for Long-Term Pulsed-Periodic Mode of Operation and its Application in a High-Power Microwave Pulse Generator Without External Magnetic Field, *Russian Physics Journal*, **57**(5), 565, 2014, doi:10.1007/s11182-014-0277-8

[9] T. Buntin, M. Abide, A. Neuber, J. Dickens, R. Joshi and J. Mankowski, Evaluation of Explosive Emission Carbon Fiber Cathodes for High-Power Microwave Devices, *IEEE Transactions on Plasma Science*, vol. **50**(10), 3459, 2022, doi: 10.1109/TPS.2022.3202884

[10] Y.E. Krasik, A. Dunaevsky and J. Felsteiner, Operation of a carbon fiber cathode, *ICOPS 2000. 27th IEEE International Conference on Plasma Science*, New Orleans, LA, USA, 279, June 2000, doi: 10.1109/PLASMA.2000.855155.

[11] B.W. Hoff, S. Beeson, D. Simon, W. Tang, R. Smith, S.C. Exelby, et. al., Brazed carbon fiber fabric field emission cathode. *Review of Scientific Instruments*, **91**(6), 064702, 2020, doi:10.1063/5.0006371

[12] Y.E. Krasik, A. Dunaevsky, A. Krohmal, J. Felsteiner, A.V. Gunin, I.V. Pegel, S.D. Korovin, Emission properties of different cathodes at E < 10^5 V/cm, *Journal of Applied Physics*, vol. **89**(4), 2379, 2001, doi: 10.1063/1.1337924

[13] K.V. Afanas'ev, O.P. Kutenkov, I.V. Pegel, V.V. Rostov, M.I. Vagner, G.A. Pribytkov, V.P. Tarakanov, Current characteristics of quasi-planar vacuum diodes with explosive-emission cathodes made of various materials at a high-voltage pulse duration of a few nanoseconds, *Russian Physics Journal*, vol. **55**(7), P. 772, 2012, doi: 10.1007/s11182-012-9880-8

[14] G. Shafir, M. Kreif, J. Z. Gleizer, S. Gleizer, Y.E. Krasik, A.V. Gunin, O.P. Kutenkov, I.V. Pegel, V.V. Rostov, Experimental research of different plasma cathodes for generation of high-current electron beams, *Journal of Applied Physics*, vol. **118**(19), 193302, 2015, doi: 10.1063/1.4935880