Experimental Study of Explosive-Emissive Graphite Cathodes in the Pulsed-Periodic Operating Regime[1]

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Abstract – Emission properties of a graphite cathode supplied by voltage pulses with an amplitude of ~300 kV, a pulse width of ~10^{-9} s and a pulse repetition frequency of up to 3.5 kHz have been studied. The electron beam had a peak power of 0.6 GW and an average power of up to 3 kW. A single current pulse had an energy of ~1 J. Delay dynamics of the current emission in correlation with the charge transferred by the beam has been analyzed. The cathode surface morphology was checked in a scanning electron microscope. The results have been compared with the data obtained earlier for emission of high-current beams with a pulse energy of ~50 J. Temperature dynamics of the cathode in the pulsed periodic regime has been estimated. The effect of changes in the electron beam parameters on the microwave generation of Ka-band relativistic BWO has been exemplified.

1. Introduction

The growing interest to sources of high-current electron beams, which operate in pulsed periodic regimes at pulse repetition frequencies (PRF) of tens and hundreds of hertz or more, is explained by their practical use in some studies and applications. On the other hand, it is supported by latest achievements in the technology concerned with formation of stable nanosecond accelerating pulses.

Most stringent requirements on high-current nanosecond accelerators are imposed in HPM generation, which is a domain where beam injectors should have stable characteristics and a long lifetime. For example, in experiments [1] an explosive emission cathode of a nanosecond accelerator was tested using up to 10^8 operations at a PRF of 150 Hz while parameters of microwave pulses of 10-GHz relativistic BWO were measured simultaneously.

Ka-band relativistic BWO [2] employed for the first time a high-current accelerator based on a hybrid modulator [3] and a magnetic system of beam focusing, which ensured operation in 1-s burst at PRF of up to 3500 Hz. Although the "energy content" of the accelerator beam [2] was much smaller than in the case of more powerful injector [1] (see Table I), new data about the cathode performance could be obtained due to a higher PRF.

Table I. Comparative characteristics of injectors with tubular graphite cathodes

Parameter	Ref. [1]	Ref. [2]
Cathode voltage, kV / pulsewidth, ns	500 / 20	290 / 1.5
Operating regime of accelerator	150 Hz, continuously	1000 Hz, 1-s bursts
Cathode's edge area: S, cm^2	0.3	0.04
e-beam current pulse amplitude: I_1, kA	5	2
Current density at cathode edge: $j_1 = I_1 / S$, kA/cm^2	15	50
e-beam charge emitted at single pulse: q_1, °C	160	3.3
Normalized charge of $N \approx 10^4$ pulses: $q_{NS} = q_1 N / S$, C/cm^2	5	1
Delay of N-th current pulse at "0.8" of amplitude: t_N, ps	1300 ÷ 1500	250
Normalized delay of current pulse : $\tau_{NS} = t_N / q_{NS}$, ps (cm^2/C)	260–300	250

2. Experimental Setup

Accelerating voltage pulses of the hybrid modulator had a trapezoidal shape, a rise time of ~200 ps, a characteristic plateau of ~900 ps and FWHM of ~1500 ps. When the impedance of the magnetically isolated electron diode was ~140 Ohm, the cathode voltage amplitude was as high as (270–290) kV. Thus, at a maximum PRF equal to 3500 Hz the accelerator injected an electron beam with a peak power of ~600 MW and a burst average power of ~3 kW.

Accelerating pulses were monitored by a calibrated capacitive voltage divider with the transient characteristic of less than 150 ps. Since the voltage pulse amplitude was highly stable (the mean-square deviation was within 1%), it was possible to use a Tek-TDS820 digital sampling oscilloscope with a 6-GHz bandwidth. Recording of a single oscillogram required 512 consecutive samples. Therefore, if the time base was 500 ps/div, the sampling period of 10 ps actu

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ally determined the measurement accuracy of time characteristics of voltage pulses. The same accuracy was typical in the measurements of parameters of ~2-kA e-beam current pulses. The latter measurements were made by a wide-band current probe, which was installed in the drift chamber of the accelerator instead of the BWO slow-wave system. The probe represented a Faraday cup mounted on the end face of a 3-Ohm coaxial transmitting line, whose output was matched with a strip line (the voltage divider). The absolute calibration accuracy of the probe amplitude response was ~5% and its transient characteristic was 200 ps or better. It should be noted that currents were measured using the automatic oscillogram integration function of the oscilloscope, which allowed measuring the electron beam charge.

The design of the electron injector and the beam current probe is shown in Fig. 1. The coaxial magnetically isolated diode of the accelerator had a sharp-edge tubular cathode 8.6 mm in diameter made of graphite grade MPG-6 (Fig. 2a). The radial size of the emitting ring was 150 μm. The cathode was placed in a homogeneous axial magnetic field of 2 T generated by a DC solenoid. The current density at the emitter surface was as high as 50 kA/cm^2. Fig. 2b presents a beam reprint on a polymer film installed instead of collector of the Faraday cup.

3. Beam Current Measurements

Several sets of measurements of the beam current were made at a PRF of 1000 Hz using identical virgin graphite cathodes. Each time the accelerator was switched on, a turbomolecular pump evacuated the vacuum diode to a residual pressure of ~10^{-5} Torr. Similarly to the situation observed in [1], the beam charge dropped and the current length shortened already at $N = 10^3$ pulses (in our case, one pulse burst). Photographs in Fig. 3 show the cathode edge in the process of training. It is seen that the surface structure of the emitter changed, i.e. the edge rounded off. In our opinion, the degree, to which the microrelief of cathodes made of the same material change, is determined by the density of the total beam charge emitted from the edge. Really, if we introduce the parameter τ_{NS} (see Table I) as the ratio between the current emission delay time and the density of the full charge, these parameters prove to be similar in experiments [1, 2] at the reference number of pulses $N \sim 10^4$, although other conditions are largely different.

Within certain limits, the current delay dynamics should be independent of the PRF. The presented experiment provided an opportunity to analyze variation of properties of the explosive emission cathode at high PRF.

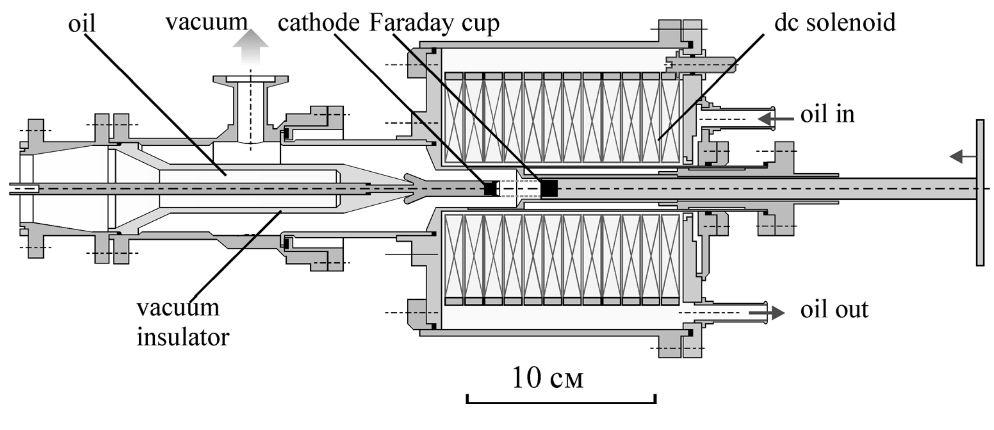
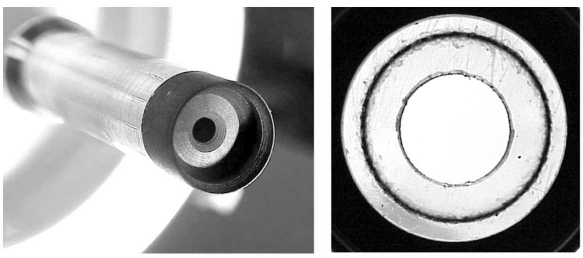
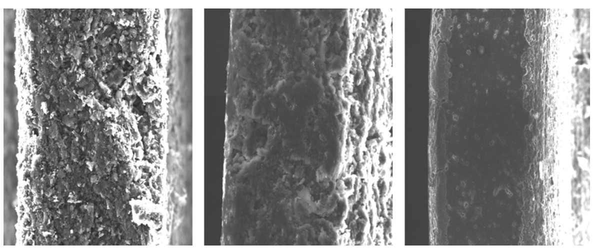


Fig. 1. Design of the magnetically isolated vacuum electron diode of a high-current accelerator and the beam current probe installed in the drift chamber



a) b)

Fig. 2. Tubular graphite cathode 8.6 mm in diameter (a) and a beam reprint on a polymer film (b)



a) b) c)

Fig. 3. Microphotographs of the cathode edge of 150 μm thick: a – virgin cathode; b – after $12\cdot10^3$ pulses; c – after $34\cdot10^3$ pulses

Fig. 4 presents control waveforms of current pulses of an electron beam. The waveforms were recorded as the cathode was trained at PRF = 1000 Hz and then PRF = 3500 Hz. The corresponding variation dynamics of the beam charge is given in Fig. 5.

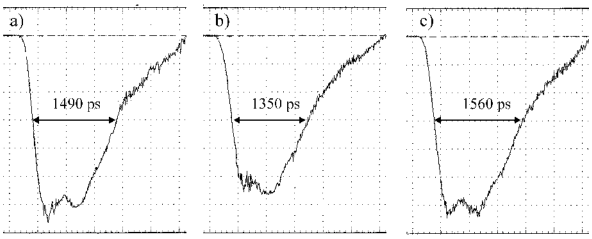


Fig. 4. Electron beam current pulses with an amplitude of ~2 kA, which were recorded during bursts of 1000 pulses each: a – virgin cathode (PRF = 1000 Hz); b – training with 12000 pulses at the same PRF; c – further training (up to 17000 pulses) at PRF = 3500 Hz

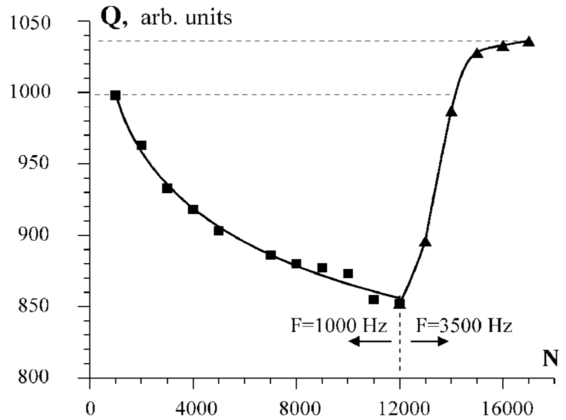


Fig. 5. Variation of the electron beam charge at PRF = = 1000 Hz over the cathode training interval $N = (0{\div}12){\cdot}10^3$ and at PRF = 3500 Hz over $N = (12{\div}17){\cdot}10^3$. Bursts of 1000 pulses each

At $N = (0{\div}12){\cdot}10^3$ this curve summarizes measured values of the beam charge at a PRF of 1000 Hz in bursts of 1000 pulses each. The waveform in Fig. 4a corresponds to the beginning of the descending section (N = 1000). The waveform in Fig. 4b was recorded after $12{\cdot}10^3$ pulses. The drop of the characteristic amplitude of the beam current, shortening of the pulse length and some increase in the rise time were obvious in this training regime. Running at PRF = 3500 Hz (also by bursts of 1000 pulses each) led to changes shown for the interval $N = (12{\div}17){\cdot}10^3$. The oscillogram in Fig. 4c corresponds to the last value ($N = 17{\cdot}10^3$). The curve in Fig. 5 followed qualitatively the dependence of the beam current pulse width on the number of operations. With that, the pulse width was measured at 0.5 of the amplitude level corresponding to the injection current of the virgin cathode.

The experimental data show that, oppositely to operation of the electron injector at 1000 Hz, a sharp decrease of interpulse interval (from 1 ms down to 300 μs) resulted in full recovery and, even more, in enlargement of emission. The microphotographs (Fig. 6) of the cathode surface were taken in the current measurement regimes corresponding to Figs. 4 and 5.

4. Interpretation of Experimental Results

The following analysis [5] was performed to interpret variation of the emission characteristic shown at Fig. 5. The emission current density, which was sufficient for heating and further destruction of an individual emission site, was determined considering properties of the cathode material. The spatial scale of the micro-emitter was estimated from the Child-Langmuir law and the emission current density. The temperature relaxation dynamics of the emitter was analyzed over the pulse-to-pulse interval.

In accordance with the concept of explosive electron emission it was assumed that a high voltage induced electron emission from separate microscopic areas having the largest gain of the electric field [6]. Photographs of the cathode surface (Fig. 6) and available literature data (see [6, 7] and the literature cited therein) suggested that the emitter represented a projection whose shape approached a hemisphere or a truncated cone with a large opening angle. Energy extraction in the material of this emitter was described by a balance equation relating variation of the internal

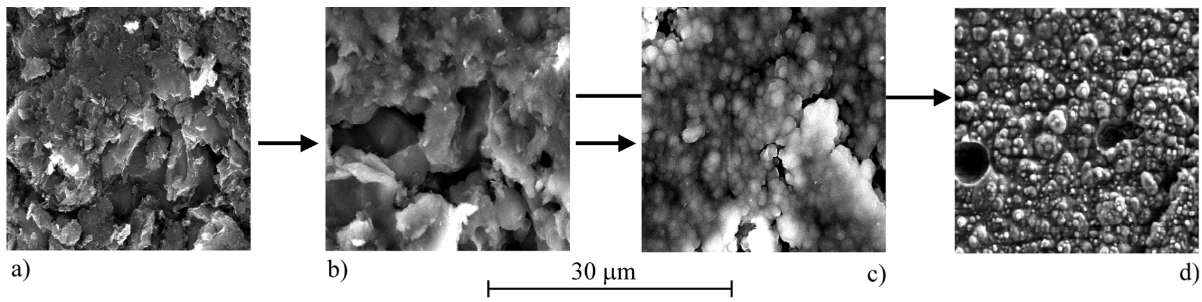


Fig. 6. Photographs of the emitting edge of the cathode: a – before training; b – after training at PRF = 1000 Hz and the number of pulses equal to $1.2{\cdot}10^4$; c – after training at PRF=1000 Hz and the number of pulses equal to $3{\cdot}10^4$; d – after sequential training at PRF = 1000 Hz and 3500 Hz with the number of pulses corresponded to the regime shown in Fig. 5

energy of the cathode material to its heating determined by the Joule current dissipation. This process was not affected by thermal conductivity. Taking into account thermophysical and electrophysical constants of bulk graphite [8] and the binding energy per atom (10 eV, [7]), we estimated the current density, at which a temperature of ~10^5 K (sufficient for the failure of an emitter) is attainable during the pulse time (~10^3 ps). The current density proved to be $j \sim 10^9$ A/cm^2 (Fig. 7).

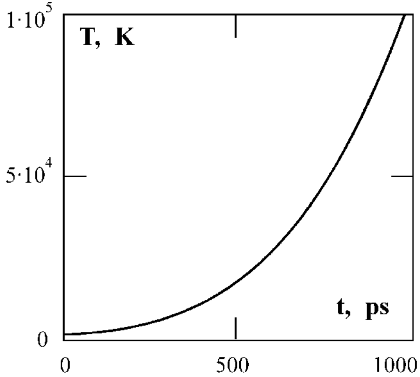


Fig. 7. Time dependence of the emitter temperature calculated for the emission current density of $j = 10^9$A/cm^2

Considering the j value, the applied voltage and the Child-Langmuir law, the emitter electric field and the size of an emitting inhomogeneity were estimated at $E \approx (4 \div 5) \cdot 10^8$ V/cm and $r \approx 5 \cdot 10^{-4}$ cm, respectively. If the current in a single emitter was $i \approx j \cdot r^2 \approx$ $\approx (2 \div 3) \cdot 10^2$ A, then the number of these centers was equal to $N \approx I_1/i \approx (5 \div 10)$. It should be noted that if inductance of the external magnetic field is 2 T, screening of the cathode surface [9] could influence discreteness of emission centers.

Taking into account the calculated electric field averaged over the cathode edge (~3 MV/cm) and using the Child-Langmuir law, the macroscopic current density was estimated at $j_{av} \approx 6 \cdot 10^4$ A/cm^2, which is close to the experimental value of $5 \cdot 10^4$ A/cm^2.

In accordance with estimated temperature dynamics of the emitter, at the pulse length of ~10^3 ps the relaxation processes are "started" after the current injection ends. Cooling is realized by evaporation and heat conduction only during the pulse-to-pulse interval, while emission cooling is insignificant. Calculations showed that evaporation prevailed during ~10 ns and reduced the emitter temperature to $T \approx 2 \cdot 10^4$ K. Then heat conduction played the decisive role.

The curve in Fig. 8 showed that the emitter cooled completely to 300 K in about a millisecond, i.e. during the interval between pulses at a PRF of 1000 Hz. The experiments demonstrated that in this case the cathode surface changed sequentially (Fig. 6, a $\rightarrow$ b $\rightarrow$ c) in accordance with the known effect of polishing of explosive emission cathodes [10]. This effect arises under the action of short voltage pulses. Smoothening of the relief increased the delay of the beam current emission (Figs. 4a and b) and decreased smoothly the charged transferred per pulse (Fig. 5). However, the decrease in emission of the virgin cathode could be due, in addition to the "polishing" effect, to graphite degassing and removal of various impurities from the graphite surface.

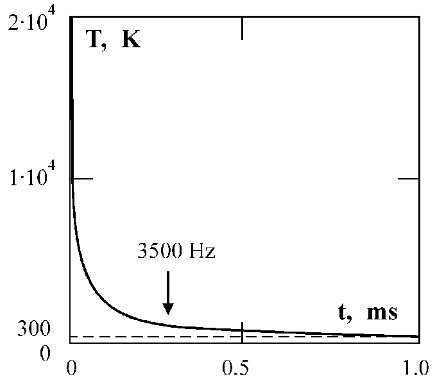


Fig. 8. Calculated temperature of an explosive emission center after the current pulse ends and evaporation cooling is complete

At PRF = 3500 Hz an emission center had not time to cool in 300 μs and, therefore, one can assume that a new center appeared during the next pulse would be localized near the previous center. This process is facilitated by thermionic emission from a high- temperature region. Thus, the cathode could be heated progressively near the emission zone. Judging by the photograph in Fig. 4d, this regime led to melting of the edge surface if the number of burst pulses was sufficient. This inference was confirmed also by homogenization of the cathode surface, the decrease in its visible porosity and appearance of solidified craters typical of emerging blisters of adsorbed gas. New emission centers could be localized on crater edges when consequent pulses were applied. Thus, the increase in the temperature of the emission zone and a specific regeneration of the microrelief could explain quite well the growth of the beam charge at high repetition frequencies, which was observed in the experiment (Figs. 4d and 5).

5. Conclusion

From the above discussion it follows that the "polishing" effect had a kind of a frequency threshold. If emission characteristics of the cathode change during training at limited pulse repetition frequencies, it is necessary to take into account the effect of their variation on parameters of electron beams having the length of tenth fractions or units of nanoseconds. Specifically, at PRF = 1000 Hz changes in parameters of a current pulse proved to be critical for subnanosecond relativistic BWO studied in [2]. When the length and the amplitude of the beam current pulse decreased in this device (compare Figs. 4a and 4b), then the power, duration and stability of microwave radiation genera tion were impaired (Fig. 9). This observation corresponded to results of numerical experiments, which were performed using the KARAT code [11].

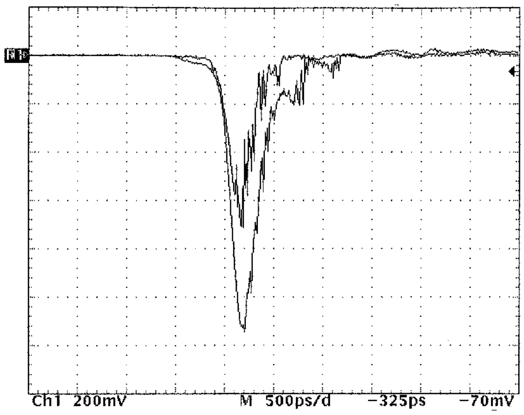


Fig. 9. Variation of the power and the width of a microwave pulse generated by 38-GHz subnanosecond BWO vs. the amplitudes and the length of the electron beam current shown in Figs. 4a and b

It has been still topical to look for conditions when degradation of explosive emission cathodes is retarded or does not take place in the general case of low pulse repetition frequencies. Composite materials will be applied alongside graphite in further studies of the cathodes.

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