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Activation of the explosive-emission-cathode in conditions of artificial initiation of field emission

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Abstract. Low inertial transition of the field emission into explosive electrons emission at the cathode and related fast-rise-time electron beam formation are of interest in a phase-stable excitation of relativistic high-power microwave oscillators. We present experiments on the cathode activation using emission initiation during specially prepared advance voltage pulse (prepulse) possessing variable amplitude of tens-hundreds kilovolts and the width adjustable from tenths to units of nanosecond. Such a prepulse can be separated in time with a main accelerating pulse as well as adjoined to the fast-rise-time voltage front.

1. Introduction
For fixing the phase of relativistic microwave generator towards the front of the voltage at the cathode [1,2] a high-current electron beam with a subnanosecond rise time and a high current rate (dI_e/dt) up to 10^4 A/ns is required [3-6]. This justifies the relevance of studying the dynamics of explosive electron emission (EEE) cathodes [7] in the interval <1 ns and conditions of its initiation, which affect the front beam stability and the magnitude of dI_e/dt. Modern technique of forming high-voltage pulses [8-11], methods of checking the characteristics of the vacuum diode (VD) [12], beam current broadband sensors [13], and modern digital oscilloscopes allow picosecond resolution to study the dynamics of the field emission (FE) into EEE stage for microscopic cathodes with different shape and amplitude of applied voltage pulses [14-16]. This work is devoted to the research of the effects of double pulses [17] - activation of EEE on the cylindrical edge of the cathode with the leading voltage pulses. These effects were studied for the voltage pulses of not less than one hundred kilovolts, with subnanosecond fronts, comparable pulse durations and for different intervals between them. Cathode material, VD geometry and the parameters of the external magnetic field were typical for microwave experiments.

2. Experimental arrangement
Figure 1 presents the layout of experimental set-up, where we have used the special formers of a short high voltage pulses (3,8,10) [8-10]. The installation was operated in three variants, but the gaps of RADAN-303 drivers were always stabilized by triggering pulses from the generator 2. In option #1 (components 8, 9-11 were not used), the cathode was fed by pulse with tunable amplitude up to -330 kV and a duration of ≥ 1 ns. Switching the nitrogen spark gap under the pressure of up to 70 atm in the inductive-capacitive former 3 provided the front voltage shorter than 200 ps, but there was a

nanosecond prepulse (tens of kilovolts) because of the interelectrode capacitance. The duration of the main pulse could be shortened to hundreds of picoseconds (FWHM) with a cut-off discharger at the output of block 3. The transmission line (44 Ohm) between VD 5 and the driver 3 had such a delay that the first unipolar reflected pulse was supplied to the cathode 6 in ~8 ns.

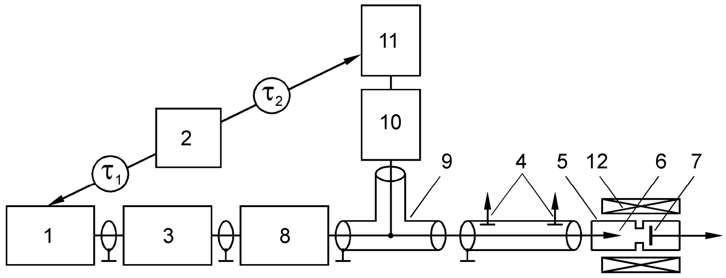

Figure 1. Layout of experimental set-up. *1,11* – nanosecond driver RADAN-303; *2* – triggering pulse generator; *3* – pulse forming L-C network; *4* – capacitive dividers of DTDR section; *5* – vacuum diode; *6* – cathode; *7* – beam collector; *8* – NLTL; *9* – high-voltage T-branch; *10* – pulse slicer; *12* – pulsed solenoid.

Option #2 amended by block 8, representing the gyromagnetic nonlinear transmission line with saturated ferrite (NLTL, [10]). NLTL transformed the pulse from generator 3 in the sequence of decreasing amplitude oscillations with a frequency of ~2 GHz, that is, the interval between the first peaks was ~500 ps. Increasing the delay before initiating pulse and restructuring its shape/length (Option #3) was provided with inclusion of units (9-11). Meanwhile, the delay from the central connection point of the high-voltage T-branch 9 to blocks 8 and 10 determined the valid ahead of the leading pulse from the generator 10 without the influence of reflections on the main pulse delivered to the cathode from the block 8. Fixed change in the delay between pulses was carried out by changing the lengths of the transmission lines from the generator 2, that is, the time τ_1 and τ_2.

Pulse solenoid 12 provided the magnetic field of ~ 2 T in the VD. In the experiments the sequences of the voltage pulses were recorded with identical capacitive dividers 4. For these signals by the method of dynamic time-domain reflectometry (DTDR the current and VD impedance was determined [12]. In part of the experiments, the electron beam current was recorded by the collector sensor 7 [13] with a resolution of ~20 ps.

3. Cathode emissivity variation under action of sequential voltage pulses

For the dynamics of the cathode emission properties the polishing effect [18] is typical. With the increase in the number of HV pulses (*N*) the morphology changes of the emitter affect at the time and amplitude characteristics of the VD current [14,15,19]. The effect is most pronounced for the cathodes made from flexible materials, such as steel [19,20], and at times less than a nanosecond, when the mechanism of regeneration of the emitters is not valid. At the stage of transition of FE into EEE for individual microemitters the condition $j^2t_d \approx const$ known in the EEE theory is in force. Due to the loss of mass and fusion (smoothing) of microemitter the field amplification is reduced, the density of emission current (j) decreased nonlinearly, and as a result, the EEE delay (t_d) may gradually exceed the duration of the voltage and current are generally not recorded [21].

The situation changes if a second voltage pulse with nanosecond delay is applied to the cathode, and this refers to the effects of a "double pulse" [17]. During the first voltage pulse FE occurs at the cathode and maybe EEE, but the field on the emitter in the interval between pulses is missing. Therefore, an important factor is the residual temperature of the emitter, dynamics of dissipation, as well as the presence and expansion of plasma formation [17], occurring on a leading pulse. That is, the level of cathode activation in the first pulse and the time interval to the second are important.

From the expanding plasma, the second pulse pulls the electron current. As a result, plasma formation near the center of the leader charges positively and increases the field in the area of adjacent emitters facilitating their electrical blast. Thus, both factors (the expansion of the plasma and field amplification) are provided a larger emission of current at the second pulse even when its amplitude is smaller than the first one. This mode is illustrated in figure 2, which used the installation option #1 with cut-off discharger block 3 and the steel tubular cathode (flange 100 μm). The ratio of the amplitudes of two pulses at the cathode was almost the same in all cases and is close to (U_1/U_2), since the maximum electron beam current (55 A) is not great. Since $U_2<U_1$, then before training (N=1) $I_{21}\approx0.7I_{11}$. One hundred pulses were enough to obtain (I_{12}/I_{11}) < 2 (polishing!), $I_{22}\approx1.2I_{21}$, and, most importantly, (I_{22}/I_{12}) > 2. With further training (up to N=300) the polishing effect reduced the current of the first pulse more than 20 times as compared to I_{11}. The polishing effect is beginning to emerge at the second pulse also. The current here is decreased, but it exceeded by 5 times the first one.

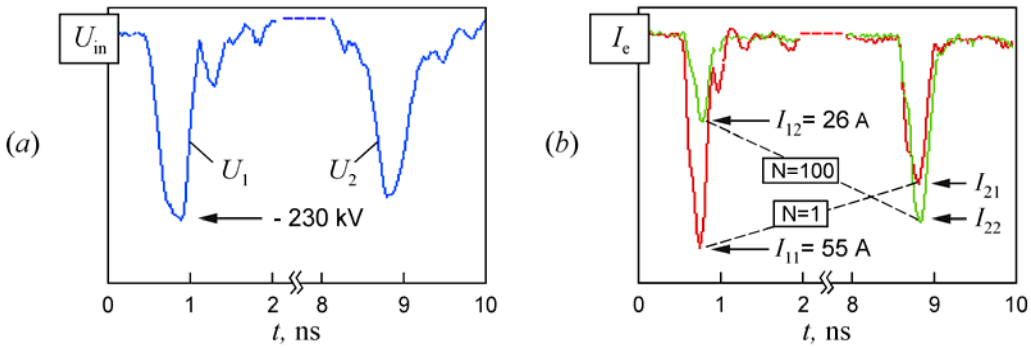

Figure 2. (a) High-voltage pulses U_1 and U_2 applied to stainless steel tubular cathode. (b) Beam current measured by collector for a virgin cathode (I_{11} and I_{21}) and after N=100 shots (I_{12} and I_{22}).

The effect of "polishing" the surface is also observed for the cathodes made of graphite, although it manifests itself with a much larger number of shots [14,19]. When exposed to sequential pulses of voltage, as in figure 2,a, the tendency of changes in current amplitudes is preserved, although the differences ($I_{11} \to I_{12}$) and ($I_{12} \to I_{22}$) were significantly less. For a single voltage pulse of comparable duration (~300 ps FWHM), the ratio of (I_{12}/I_{11}) ~ 0.5 is reached after N~10^4 shots [22]. With the same N the delay growth of the front current at ~200 ps was observed when the duration of the voltage (FWHM) was ~1.5 ns [16]. However, the decline in the amplitude of the current in the latter case does not exceed 10%. We believe that in contrast to steel, the change in the morphology of the edge of a virgin graphite cathode has been associated primarily with entrainment of material in electro explosions [15], where the most small-scale microemitters disappear and a new inhomogeneity with a small structure reveal.

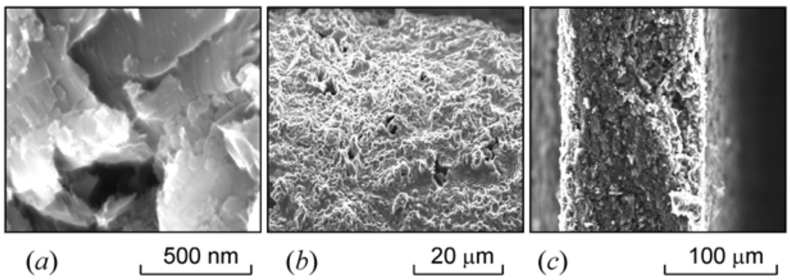

Figure 3. Microphotography of the graphite cathode edge.

4. Graphite cathode emissivity with affect of advance voltage pulse

In the VD with tubular graphite cathode, there are several characteristic spatial scales: the size of microemitters (l_1<100 nm) representing the edge, the edges of the plates, the faces of the crystallites, as shown in figure 3,a; the distance between the protruding agglomerate emitters ($l_2 \leq$ 10 μm, figure 3,b); emissive edge of the cathode ($l_3\approx$100 μm, figure 3,c); the gap between the cathode and the anode (l_4~1 cm). The source of electrons is the plasma after the electric explosion of microemitters expanding with a typical speed ~ 2x10^6 cm/s. Estimating the time of plasma expansion on these scales l_i, it is possible to get times τ_i, in which the cathode emissivity will be different. The set of these times includes the intervals t_1~5 ps, t_2~500 ps, t_3~5 ns, and t_4~500 ns.

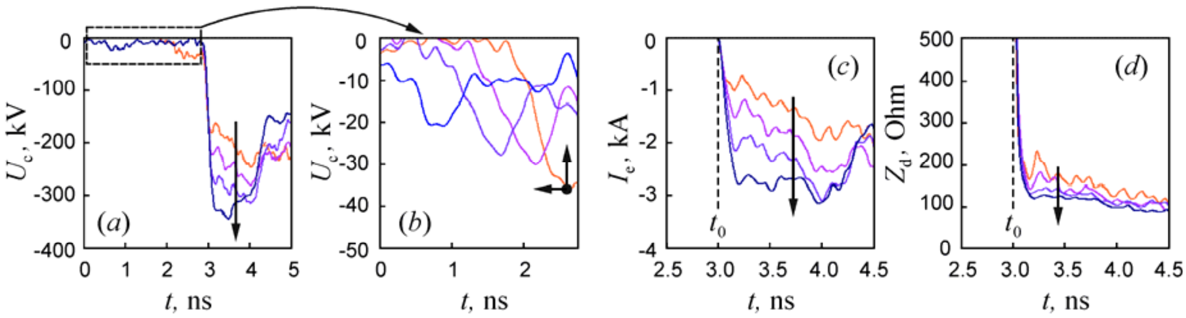

Figure 4. Voltage pulses (a) and prepulses (b) at the cathode. (c) Emitted current. (d) VD impedance. All DTDR-restored waveforms have absolute time reference.

Figure 4 presents an experiment with a graphite tubular cathode on the installation for version #1 (without the chopper spark gap). With the increase of the peaking discharger gap, the voltage breakdown and the amplitude of the generated pulse are increasing (figure 4,a). This reduces the amplitude of the prepulse and increases its duration (figure 4,b). From the abovementioned rule $j^2t_d \approx const$ it follows that in a certain time interval the relatively low prepulse (figure 4,b) does not provide transition of FE into EEE stage. The emitted current during the time of their influence reaches not more than a dozen(s) amperes and does not exceed the oscillographic registration noise. However, the current waveforms in figure 4,c show that the activation of the cathode occurs during the prepulse. With increasing of the prepulse duration (figure 4,b) dI_e/dt at the front of the current pulse at the level of 500 A varied from 15 kA/ns to 22 kA/ns. In addition, for all the voltage amplitudes of the main pulse with the presence of the prepulse leads to a low-inertia emission of kiloamper current at the time of the order of ~100 ps (the beginning of this interval is linked to t_0 = 3 ns). Apparently, it is connected with the current selection from micron plasma formations close to the individual emitters or the most protruding agglomerates of such emitters in the interval shorter than t_2. The low inertia of pre-activated emitters leads to the fact that in ~200 ps the envelope of the current (figure 4,c) repeats the burst and the local downturn in the voltage front (figure 4,a). These characteristics are correct for variations of $Z_d(t)$ (figure 4,d) as well. Previously, we observed the effect of activation of the graphite cathode with different prepulses for close amplitudes and durations of sub-nanosecond high-voltage pulses [23]. The effect was to increase the amplitude of the current and the charge of generated beam by a longer activation of the cathode on the prepulse. However, it is clear that, ceteris paribus, the voltage difference during activation of the cathode is a more fundamental factor than the time of exposure. This is due to the nonlinear dependence of emission current from the electric field at the emitter. As a result, with the smallest voltage amplitude (figure 4,a) after ~ 1 ns the VD impedance has not been established. If the largest voltage the impedance at t > 4 ns (figure 4,d) is almost stabilized. Apparently, the influence of plasma expansion is already expressed, which in a few nanoseconds ($t \rightarrow \tau_3$) including the duration of the prepulse can cover not only the area between the agglomerates' emitters (figure 3,b) but the emissive edge of the cathode as a whole (figure 3,c).

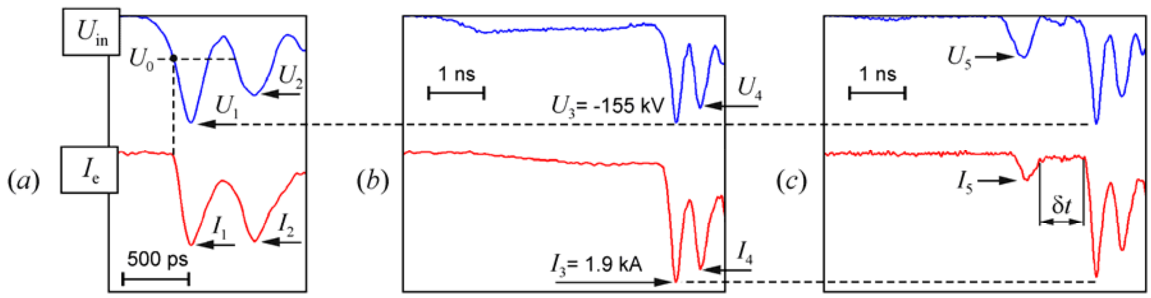

Figure 5. The emission of the beam when applying pulses with a delay of 500 ps (a), for activation of the cathode by a prepulse (b) and with a short pulse (c). The current registration – the collector sensor.

Complementary effect on the VD current of electric field exposure, its magnitude and EEE-plasma dispersion after the advancing voltage pulse is observed in the experiments shown in figure 5. When there is no prepulse (set-up option #2), its role is play the first surge delivered from NLTL (figure 5,a). If (U_2/U_1)≈0.7 at the second pulse the increased current (I_2/I_1)≈1 is emitted. There is an obvious role of plasma expansion in the interval of t_2~500 ps, and the activation of a larger number of EEE centers in the field, strengthened by the expanding plasma. Note the fact of the inertia of the emission of the cathode in the presence of prepared plasma: between the peaks the voltage falls below the voltage level of the initial activation of the cathode (U_0), but the current does not stop. The second important point is that the current pulse I_1, that occurs when a significant voltage on the cathode (-60 kV) has a fairly steep front: $dI_e/dt \approx$ 14.5 kA/ns at the level of I_1=500 A.

When all installation components are in operation (option #3) it is possible to form the elongated prepulse (figure 5,b). EEE-current occurs during the prepulse when the front passes at the “shelf”. This occurs when the voltage U_0 is by half less than in the case in figure 5,a, but the time of voltage rise until the current appears (~1 ns) is by 5 times more. For 2.5 ns the current during the prepulse increases and then there is a tendency for its decrease because of the decline of the prepulse voltage. In this mode of the cathode activation in the first voltage peak the maximum current I_3≈1.9 kA ($dI_e/dt \approx$ 6.5 kA/ns at the level of I_e=500 A) is emitted and the VD impedance is stabilized. Indeed, (U_4/U_3)≈(I_4/I_3) is achieved. Almost the same ratio of the peaks of current and voltage, and the maximum amplitude of the current is maintained when the cathode is fed by a short lead pulse (figure 5) with the amplitude U_5 increased in comparison with a prepulse in the previous case. Large enough EEE - current I_5≈400 A corresponds to U_5 pulse. On the δt interval this current practically disappears, but the plasma expansion and a greater number of activated "hot" centers lead to the effective emission of the beam on subsequent pulses.

5. Conclusions

In the conclusion, advance high-voltage pulses demonstrate pronounced influence on the cathode emission initiation. This effect includes preliminary transition of FE into EEE stage and depends on the advance voltage value (i.e., *E*-field) applied, a spread of the EEE plasmas nearby emitters, and amplification of the microscopic *E*-field strength by charged plasma clouds resulted in activation of even more EEE-centres. As a result, electron beam pulse may achieve the rate of current rise exceeding 20 kA/ns which is attractive in the tasks of phase-stable high-power microwave generation.

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