Losses of Low-Energy, High-Current Electron Beam at its Transportation through Plasma Channel

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Abstract – The dynamics of radial losses of high-current electron beam transported through plasma channel in guide magnetic field has been studied experimentally. It was established that maximum losses are observed in the regions where the strong radial electric field presents – near the explosive-emission cathode and near the virtual cathode in the case of its appearance. The behavior of losses in dependence on acceleration voltage, guide magnetic field strength and working gas pressure was investigated.

1. Introduction

Low-energy (10–30 keV), high-current (10–30 kA) electron beams (LEHCEBs) find more and more applications for material surface treatment [1]. Fulfillment of such tasks as enhancement of the electric strength of vacuum insulation or treatment of the medicine parts requires an improved purity of the treatment process itself. One of the main sources of contaminations is the explosive-emission cathode of electron gun. It is possible to decrease the amount of the cathode erosion products impacting the treated target if the length of transportation channel is enlarged. If it is assumed that erosion products fly away isotropically, so their flux onto the target will decrease proportionally to L^2, where L is the distance between the cathode and target (collector).

In [2] we have demonstrated a principal possibility of LEHCEBs transportation over the distances of 0.5 m through the plasma channel formed with the use of high-current reflected discharge in guide magnetic field. Beam current exceeded 30–50 times the critical Pierce current and 5–10 times the chaotic electron current of anode plasma. The observed beam currents have not explained satisfactory yet, and this fact stimulated the present work together with solving the practical task on suppressing the cathode erosion products flux. The report presents experimental data on radial beam losses, and the qualitative explanation of the results obtained is given.

2. Experimental Apparatus

Block-diagram of experimental setup is shown in Fig. 1. An electron gun with explosive-emission cathode and plasma anode based on high-current reflected discharge was used. Beam collector and explosive-emission cathode grounded through the inductance (100 μH) coil of high-voltage pulsed generator (HVPG) are the cathodes of reflected discharge. A thin-wall cylinder of inner diameter 8 cm and 10 cm in length was used as anode. The transportation channel represented itself a metal tube of inner diameter 15.4 cm and 66 cm in length. Guide magnetic field of strength up to 2 kOe created by sectioned solenoid provided both discharge operation and beam transport. Gas filling (argon) was performed in a steady mode. The discharge was triggered by positive 4–5 kV-pulse applied to the anode. Discharge current amplitude was defined by a ballast resistor and made up about 150 A. In the beginning of beam formation, anode plasma density n_p was about 3×10^{12} cm^{-3}. After the installed

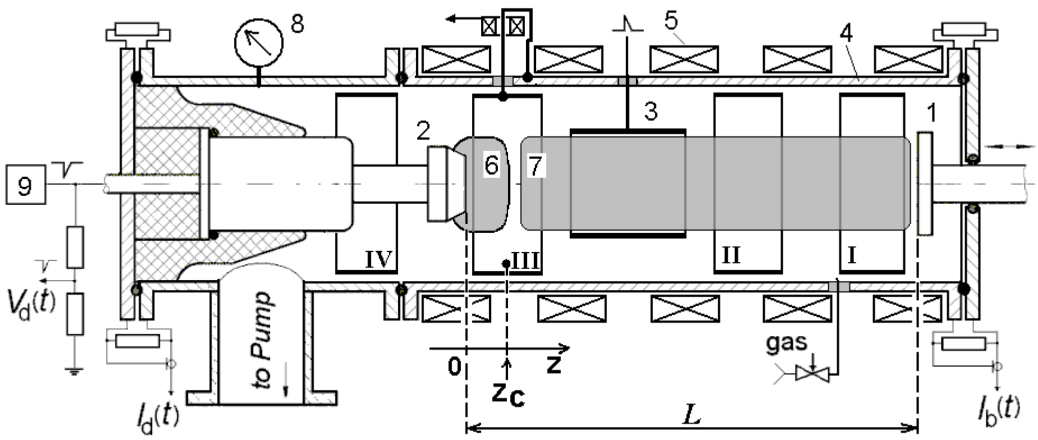

Fig. 1. Experimental arrangement. 1 – collector; 2 – cathode; 3 – anode; 4 – drift tube; 5 – solenoid; 6 – cathode plasma; 7 – anode plasma; 8 – vacuum gage; 9 – high voltage pulsed generator; I–IV – wall current collectors

delay time (usually 10–20 μs) of the discharge transition into high-current mode, an acceleration voltage pulse with rise-time 10–20 ns and amplitude V_d = 8–25 kV was applied to the cathode. Preliminary plasma creation provided the effective excitation of explosive emission and beam formation in double layer between cathode and anode plasma. The formed beam was injected into the drift channel filled with anode plasma and transported onto the collector.

Acceleration voltage V_d was monitored by resistive divider, cathode (diode) current I_d and beam current I_b were monitored by low-inductive shunts. The wall current collectors (WCC) I–IV represented thin-wall cylinders of 8 cm in width were used for registration of radial currents (beam losses). These currents were monitored with Rogowsky coils. Signals were applied to the inputs of 2- and 4-channel digital oscilloscopes **Tektronix** with bandwidth 100 MHz. Waveforms V_d,

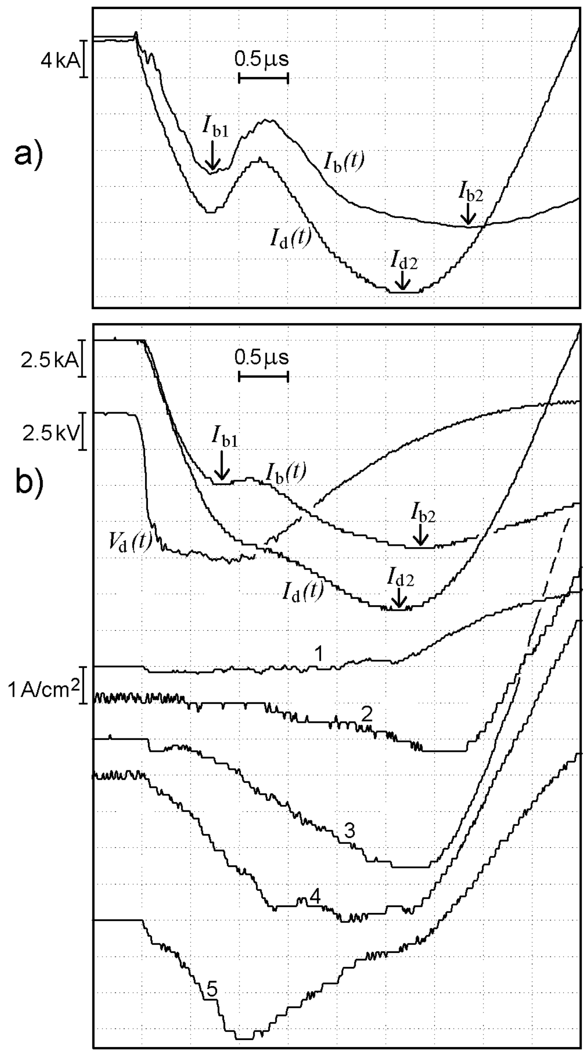

Fig. 2. Typical waveforms: (a) cathode current $I_d(t)$ and beam current $I_b(t)$ at H = 2 kOe, p = 0.2 mTorr, V_0 = 18 kV, L = 28 cm; (b) – currents $I_d(t)$ и $I_b(t)$, acceleration voltage $V_d(t)$, WCC current densities WCC-II, Z = +33 cm (1), and WCC-III and WCC-IV, Z = –16.5 (2), –12.5 (3), –4 (4), and +3 cm (5). H = 1.4 kOe, p = 0.2 mTorr, V_0 = 14 kV, L = 42 cm

I_d and I_b had good reproducibility, and in contrary, WCC waveforms were demonstrated large amplitude and temporal distortion. That is why we used WCC waveforms averaged from 16 shots.

3. Results and Discussion

Typical averaged waveforms of V_d, I_d, I_b and WCC currents are presented in Fig. 2. I_d and I_b waveforms have two characteristic maximums. The values of the first and second maximums I_{b1} и I_{b2} allows us to analyze the properties of double layer and transportation channel. To characterize the beam losses WCC waveforms and the difference between I_d and I_b were examined. Let's discuss the dependence of these values on basic electron gun parameters: acceleration voltage (Fig. 3), working gas pressure (Fig. 4), magnetic field strength (Fig. 5), and the length of drift channel (Table 1).

Fig. 3 presents the dependence of I_{b1}, I_{b2} and I_{d2} on the charge voltage V_0 (the measured acceleration voltage at the moment of the first current maximum was

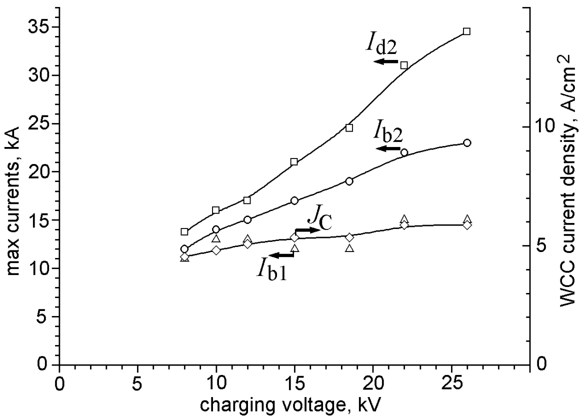

Fig. 3. Dependence of the beam current values at first maximum I_{b1}, at second maximum I_{b2}, cathode current amplitude I_{d2}, and current density onto WCC-III placed at Z = –4 cm, J_C, on the charge voltage of HVPG V_0.
p = 0.25 mTorr, H = 2 kOe, L=42 cm

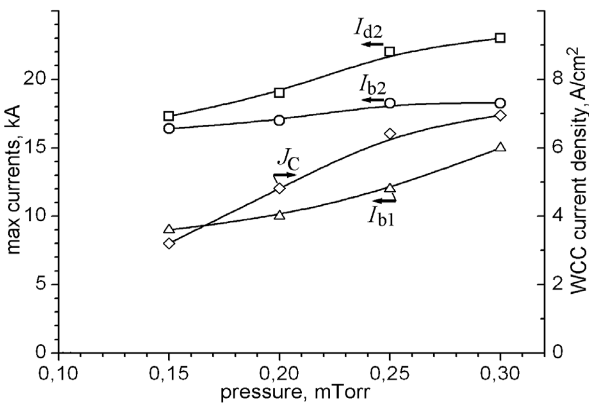

Fig. 4. Dependence of the beam current values at first maximum I_{b1}, at second maximum I_{b2}, cathode current amplitude I_{d2}, and current density onto WCC-III placed at Z = –4 cm, on working gas pressure. V_0 = 14 kV, H = 2 kOe, L = 42 cm

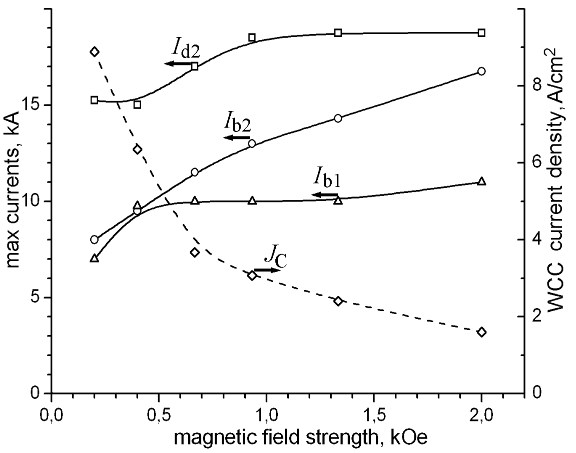

Fig. 5. Dependence of the beam current values at first maximum I_{b1}, at second maximum I_{b2}, cathode current amplitude I_{d2}, and current density onto WCC-III placed at Z = –4 cm, on the guide magnetic field strength.
p = 0.2 mTorr, V_0 = 15 kV, L = 42 cm

Table. 1. Average values of the I_{b1}, I_{b2} and I_{d2} for different transportation length L. V_0 = 17 kV, H = 2 kOe, p = 0.2 mTorr

L, cm	I_{b1}, kA	I_{b2}, kA	I_{d2}, kA
28	14	21	27
42	12	18	24
54	10	14	21

lower than V_0 by a factor of 4–5 kV). It is clear, that I_{d2} is linear changed with the charge voltage and it means that total conductivity of the system is approximately constant. Therefore, acceleration voltage pulse duration does not change essentially with voltage amplitude. The value I_{b1} does not depend on V_d and increases linear with gas pressure (Fig. 4). On the contrary, the second maximum of beam current I_{b2} increases with acceleration voltage. Such a behavior is evidence of the difference of conductivity mechanism of the double layer and drift channel in the time moments corresponding to the first and second maximums of currents. The first maximum is directly connected with the initial anode plasma density and transportation channel length but the further current growth is defined by additional ionization of the working gas caused by beam itself.

It is clear from analysis of the data shown in Figs. 3–5 and Table 1, that the losses of electron beam current increase essentially at increasing of acceleration voltage, gas pressure, transportation length, and decreasing of the guide magnetic field strength. The losses value achieves tens of percent of beam current. Thus, radial losses become a significant factor defining the electron gun efficiency.

Measurement of the WCC-I and WCC-II average currents showed that current density of radial electron fluxes increases with the decrease of electron energy and magnetic field strength, however, their value makes up not more than 1 A/cm^2, hence, they do not play a great role in beam losses. The essentially high current density has been registered by WCC-III and WCC-IV gages. The current density onto the cathode WCC (WCC-III) is weakly increased with acceleration voltage (Fig. 3), has a tendency to increase linear with pressure (Fig. 4), and significantly increases with lessening of the magnetic field strength (Fig. 5). The behavior and the value (up to 10 A/cm^2) of radial losses in the cathode region define mainly the total beam current losses. Temporal and spatial dynamics of these losses may be easy observed from the Fig. 2, b. The bottom part of Fig. 2, b shows (averaged from 16 shots) current density waveforms onto the WCC placed on the following distances from the cathode plate (see Fig. 1): Z = +3, –4, –12, and –16 cm. It is evident, that at the moment of first beam current maximum, electron losses reach maximum on WCC-III placed in opposite to the cathode. Further, the losses channel moves to the behind-cathode region (the velocity of the channel movement exceeds 10^6 cm/s). Finally, during the low-voltage stage the losses are localized mainly in the behind-cathode region. It should be noted, that such a tendency becomes weaker at decreasing of the guide magnetic field strength and at $H \approx 0.5$ kOe and lower, electron current was mainly observed on WCC-III.

According to the data obtained, the development of the electron losses channel may be imagined as follows. During the first 0.5–0.8 μs after applying of the acceleration voltage to the cathode, beam current increases rapidly. Explosive-emission cathode generates metallic plasma expanding with velocity more than 10^6 cm/s in axial direction. Cathode plasma non-uniformities may cause the initial losses due to the drift of electrons in crossed $\boldsymbol{E}_\theta \times \boldsymbol{H}_Z$ fields ($\boldsymbol{E}_\theta$ is an azimuth component of electric field caused, for example, by cathode plasma density non-uniformity). The essential growth of losses appears when the beam and cathode currents achieve some critical values. The first critical value I_{b1} (and the corresponding value of I_d) is determined by the expanding of the double layer owing to its relaxation to the stationary one [3] as well as achievement of the limiting beam current in drift channel [4] (the dependence I_{b1} on the drift channel length testifies to the last). It should be noted that in our case, the voltage rise-time (10–20 ns) is several times lower than characteristic time of ion flight across the double layer and it means the increased current admission in initial stage of the pulse as well as unavoidable fall down of current at relaxation of double layer into stationary state.

Current falling and superfluous emissive ability of the cathode plasma cause the further development of current losses. Cathode plasma expanding both in axial and radial (of course, with much lower speed) directions amplifies this process. Then, losses channel expands to the behind-cathode region and becomes comparable in admission value to beam transportation channel. It should be noted at the moment, that losses current density can not be explained in the frames of diffusion model because of low density of plasma (gas).

At $L = 54$ cm, relatively low gas pressure (< 0.2 mTorr) and low acceleration voltage ($V_0 \approx$ ≈ 10 kV), we have also observed big electron losses onto the WCC-I placed near collector. These signals were unstable from shot to shot however, its maximum amplitude was comparable to those of WCC-III and WCC-IV. These big losses are caused, on our opinion, by appearance of the virtual cathode in the beam and the position of virtual cathode coincided with WCC-I position in this case.

Now, we shall try to answer the following question: what is the critical value of beam current from the point of view of appearance of the virtual cathode? At first, let us use the expression for Pierce current value given in [4]:

$$I_{\mathrm{P}} = 130\times10^{-6}\, V_{\mathrm{d}}^{3/2}(1 + 2\ln(R/a))^{-1}, \qquad (1)$$

where R and a are the tube inner radius and beam radius, correspondingly. At $V_{\mathrm{d}} = 10$ kV, the value I_{P} makes up 57 A, and taking into account the limiting value of guide magnetic field strength [5] I_{P} may increase 2–3 times else. According to [4] at the presence of excess plasma the critical current I_{P} increase by a factor of $n_{\mathrm{p}}/n_{\mathrm{b}}$ (n_{p} and n_{b} are the plasma density and density of beam electrons, correspondingly). With that, the calculated value of I_{P} makes up about 1 kA, i.e. in order of magnitude less than observed in experiments. Possible explanation of this fact we connect with the forming of “ion coat” outside the beam. Such of “ion coat” may arise owing to negative potential appearing on the anode because of deposition of the part of beam electrons on it. Thus according to [6], current limitation connected with Pierce instability may be neglected.

The other critical value according to [4] is the chaotic electron current of the anode plasma $I_{ea} = en_{\mathrm{p}}(2kT_{\mathrm{e}}/m)/4$. It is easy to estimate, that this value makes up 5–10 times less than those observed in experiments. Concerning the current in double layer, i.e. injection current, its value exceeds I_{ea} approximately in order of magnitude due to the fast movement of the cathode plasma and also due to the non-stationarity of the double layer at fast rising of the acceleration voltage. Both factors mean increasing of the ion current in double layer [1]. Therefore, we consider the following value as critical one:

$$J_{\mathrm{b}} = A(0.4en_p(2kT_{\mathrm{e}}/M)^{1/2} + en_p v_{\mathrm{d}})(M/m)^{1/2} S, \qquad (2)$$

where A is the coefficient depending on relation between ion flying time through double layer and voltage rise-time, e is electron charge, m is its mass, k is Boltzmann constant, T_{e} is temperature of the anode plasma electrons, M is ion mass, v_{d} is the velocity of mutual motion of plasmas (including the velocity of layer expansion), and S is the beam cross section area [3].

Since beam current is often essentially lower than injection current and, besides, it falls with the increase of L, so it may be supposed that virtual cathode arises. One of the reasons of the virtual cathode appearance, we consider the axial non-uniformity of the anode plasma. Such non-uniformity may appear, for example, inside the anode electrode space since the ionization here is performed not only by the axially oscillating electrons but those drifting in the anode layer during the reflected discharge.

4. Conclusions

During the LEHCEBs transportation in a long plasma channel, the significant radial electron current losses were observed. The virtual cathode appearance in the beam is considered as the main reason of the current losses.

Spatially, losses are localized in the regions where strong radial electric field presents, i.e. in cathode region and in virtual cathode region.

From the practical point of view, the LEHCEBs energy density achieves 8–10 J/cm^2 for lengths about 0.5 m, that is quite enough for material surface treatment.

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