On Limitation of the Current of Low-Energy, High-Current Electron Beam Formed in Plasma-Filled Diode[1]

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Abstract – In the present work, the limitations of the current of low-energy, high-current electron beam formed in plasma-filled diode are studied. It is shown that on one hand, beam current is limited by the carrying capacity of double layer between the cathode and anode plasmas and, on other hand, it is limited by the speed of beam space charge neutralization in the drift channel. Experiments and estimations have shown that if the excess plasma compared in density with beam electrons presents in the drift channel, so the beam current may significantly exceed the critical currents of aperiodic instabilities leading to the appearance of the virtual cathode.

1. Introduction

Low-energy (10–30 keV), high-current (10–20 kA) electron beams HCEBs are usually formed in the plasma-filled diodes (PFD) [1]. It is characterized for non-relativistic HCEBs that the foil separating the acceleration gap and the drift channel is absent and it means the essential correlation between the processes running in them. In PFD, the double layer (DL) between the cathode (cathode plasma) and anode plasma serves as the acceleration gap and the anode plasma column serves as the drift channel. According to Nezlin [2], the chaotic electron current of the anode plasma $I_{ea} = Sen_a(2kT_e/m)^{1/2/4}$ (S is the beam area, n_a and T_e are the plasma density and electron temperature, correspondingly, k is the Boltzmann constant, e and m are the electron charge and mass, respectively) serves as the limit current in DL if the cathode emission is high enough. At this, it is assumed that cathode emissive boundary is immobile. At the same time, Nezlin [2] supposed the value I_{ea} as the limit transportation current through the anode plasma. In other words, if plasma density in some part of the drift channel is less than in the DL region, so the virtual cathode arises in the beam being situated just in the place with lower plasma density. The condition of the virtual cathode appearance is written in в [2] as follows:

$$n_b u > \frac{n_a v_{ea}}{4} \text{ or } I_{inj} > I_{ea}, \qquad (1)$$

where n_b and u are the density and the velocity of beam electrons, respectively $v_{ea} = (2kT_e/m)^{1/2}$; I_{inj} is the current in DL or the injection current.

However, it has been established that while the transportation of low-energy HCEBs formed in PFD with explosive-emission cathode [1] the beam current exceeds the value I_{ea} more than by order of magnitude. One of the main reasons of this is concluded in the fast movement of the cathode plasma ($v_p \approx 2$ cm/ms), which means the sharp increasing of the ions velocity at the enter of DL. Hence, the injection current can be written as follows:

$$I_{inj} = ASen_a\left\{0.4\left(2kT_e/M\right)^{1/2} + v_p\right\} \times \left(M/m\right)^{1/2}. \qquad (2)$$

Here M is the ion mass; v_p is the velocity of cathode plasma. The Eq. (2) at $A = 1$ is well known from the works devoted to DL in direct discharge [3]. The coefficient $A > 1$, which is introduced in [1], takes into consideration the excess of the current over the quasi-steady value (e.g. at $A = 1$) caused by the fast growth of the acceleration voltage (for example, during the voltage rise-time).

It should be noted, that the increase of current in DL caused by cathode plasma movement does not mean that beam propagates through the drift channel without losses in spite of the plasma density is still higher than n_b. Beam current may be limited, for example, by Pierce of beam-drift instabilities [2]. According to [2], beam current can exceed the Pierce limit, I_P, due to presence of excess plasma by a factor of n_a/n_b: $I_b = I_P(n_a/n_b)$. Since the fast movement of the cathode plasma means the increasing of initial velocities of ions in DL, so for keeping the same value of current the value of n_a should be correspondingly decreased. For example in the case of single charged argon ions, this decreasing should be about ten times. However, does it mean the corresponding decrease of Pierce limit? We think – no, and the reason is as follows. Consider the expression for Pierce limit given in [2]:

$$I_p = \frac{ma^2}{4e} k^2 u^3, \left(k^2 = k_s^2 + k_r^2 = \frac{\pi^2}{L^2} + \frac{2}{a^2 \ln(R/a)} \right). \qquad (3)$$

Here L is the length of the drift channel, R is its radius, and a is the beam radius. According to [2] at the presence of the excess plasma, the factor $(1 + k^{-2} r_D^{-2})$ appears in the right part of Eq. (3), and r_D is Debye radius of the excess plasma. If beam radius makes up

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several centimeters, so the second item in brackets becomes much higher than unit starting from $n_e = (n_a - n_b) \approx 108$ cm^{-3}. Substituting this factor into Eq. (3) one can obtain

$$I_P \approx \frac{ma^2}{4e} u^3 r_D^{-2}. \tag{4}$$

Compare I_P with I_{ea}, one can obtain the following expression:

$$\frac{I_P}{I_{ea}} \approx 8\left(\frac{u}{[2kT_e / m]^{1/2}}\right)^3 \frac{n_e}{n_a}. \tag{5}$$

It is evident from (5), that if the velocity of beam electrons in the drift channel is even if five times higher than the thermal velocity of plasma electrons and $n_e \sim n_a$, the limitation of beam current by Pierce and/or beam-drift instability practically disappears. One more important consequence follows from Exp. (5): for essential increasing of the Pierce limit, there is need in the significant amount of the excess plasma as it is stated in [2]. Our result agrees with the results obtained by Zharinov with co-workers [4] in those respect that their calculations give the similar values of the excess plasma density (about 1012 cm^{-3}) for removal of the Pierce limitation.

Properly speaking, the statement of author [2] about the increase of beam current to the value of $I_b = I_P\,(n_a/n_b)$ is based on the comparison of beam current obtained in experiment (4 A at 120 eV kinetic energy) with the calculated one (25 mA) for the case $n_e = 0$. In fact in the experiment described in [2], $I_b = I_P\,(n_a/n_b)$, but simultaneously the beam current was close to I_{ea}, e.g., to the current which must propagate through plasma. Thus, we have deal with simple coinciding. As we show above, beam current may significantly exceed Pierce limit with the presence of comparatively small amount of the excess plasma. We observed this in our previous experiments [1], in which beam current exceeded the Pierce limit by 30–50 times while the relation n_a/n_b was about 10 only. Taking into account the finite value of guide magnetic field [5] may increase the Pierce limit by a factor of 2–3 only, so this cannot explain experimental data.

Pay attention that according to Exp. (4) the Pierce limit (and beam current too) should not already depend on the length of drift channel if the excess plasma is available inside it. The same conclusion follows from Eq. (3) in the case of $L >> a$. However, the results of experiments [1] as well as experiments described below have shown that beam current decreases with the increasing of L. For example in [1] the increase of L from 27.5 cm to 57.5 cm results in decreasing the beam current amplitude from 23 kA to 11 kA. Thus, there is another reason of HCEB limitation caused by the processes in the drift channel. The present work is devoted to the refinement of the reasons responsible to limitation of the HCEB current in PFD.

2. Experimental apparatus

The block-diagram of experimental setup is given in Fig. 1. The body of electron gun made of stainless steel represents itself the tube of length 340 mm and inner diameter of 158 mm mounted to vacuum chamber of 400 mm in diameter. Thus, the drift tube was stepped in contrast to the case of [1], where the transportation was performed in the strait tube. Cathode diameter was 48 mm.

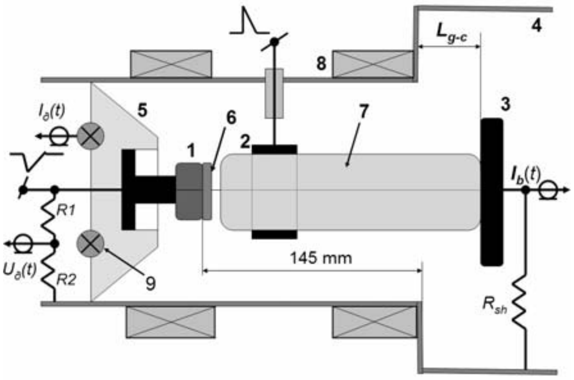

Fig. 1. Experimental setup: 1 – explosive-emission cathode; 2 – Penning discharge anode; 3 – collector; 4 – chamber; 5 – insulator; 6 – cathode plasma; 7 – anode plasma; 8 – solenoid; 9 – Rogowsky coil

Plasma anode was formed with the use of high-current (120–150 A) reflective (Penning) discharge in argon at the pressure $p = 0.015$–0.07 Pa. The residual gas pressure was 5×10^{-3} Pa. The discharge was triggered by applying the positive pulse (5 kV) to the anode. The anode represents a stainless steel thin-wall ring of 69 mm in diameter and 20 mm in length.

The external guide magnetic field of 2.5 kOe provided both reflective discharge operation and beam transport. The acceleration voltage pulse was monitored by resistive divider $R1$, $R2$. Cathode current was measured using Rogowsky coil 9, and beam current onto the collector was measured by low-inductance shunt Rsh. Signals were registered using 4-channel digital oscilloscope Tektronix TDS-2024 with bandwidth 200 MHz.

In experiments, the dependences of beam current and beam energy at the distance $L_{g\text{-}c}$ (Fig. 1) were studied. Working gas pressure and guide magnetic field strength was also varied. Beam energy was measured using calorimeter of 110 mm in diameter.

3. Results and discussion

Typical waveforms obtained for different $L_{g\text{-}c}$ are presented in Fig. 2. It is evident that beam current amplitude falls with the increase of $L_{g\text{-}c}$, and beam current failure is observed after reaching some critical value. At the moment of failure, the high-frequent oscillations of high amplitude are observed on the beam current waveform. These oscillations decay at the end of pulse when the acceleration voltage becomes less than

3–5 kV. The higher $L_{g\text{-}c}$ the earlier the beam current failure comes. Besides, the second maximum in beam current waveform does not observe at large distances $L_{g\text{-}c}$, e.g., the integral of beam current (beam charge) falls faster then its amplitude. Thus, beam current waveforms in the system with stepped drift tube sharply distinguishes from the ones obtained in the strait tube where the amplitude of oscillations is much lower and the second maximum in beam current does not disappear.

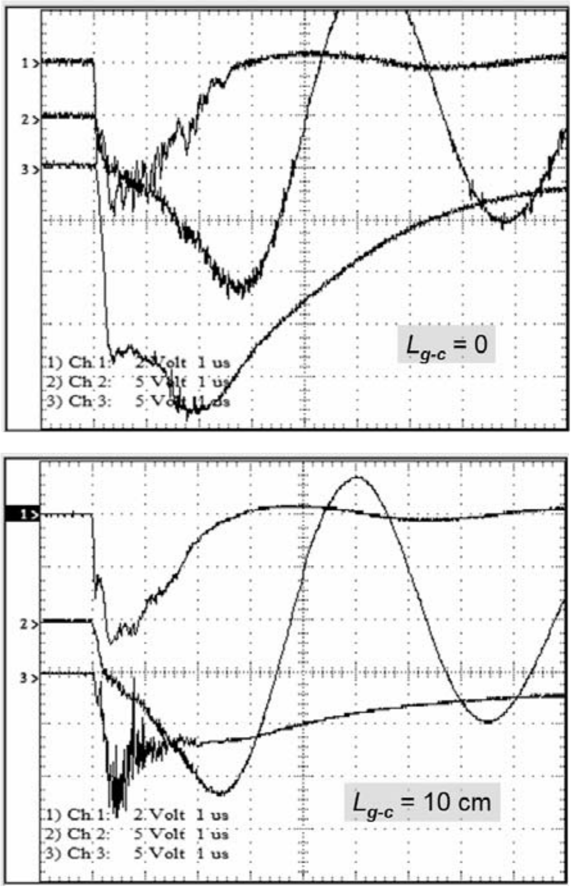

Fig. 2. Waveforms of acceleration voltage (Ch 1, 10.6 kV/div), cathode current (Ch 2, 14.4 kA/div), and beam current onto collector (Ch 3, 3 kA/div) obtained at different distances $L_{g\text{-}c}$. $H = 1.3$ kOe, argon pressure is 0.04 Pa, $n_a = 3 \times 10^{12}$ cm^{-3}

The plots of beam current amplitude and beam energy in dependence on $L_{g\text{-}c}$ are given in Figs. 3 and 4. It is evident, that beam current and energy decrease rather faster. The comparison with the results obtained in [1] shows that in the stepped tube the current and energy decreasing runs approximately 1.5 times faster than in the case of strait tube.

The obtained results show existence of beam current limitation related to the processes in the drift channel. The reason of this is rather simple and well known. At the high rate of beam rising, its charge neutralization runs with some delay specified by the finite time of plasma electrons going away from the drift channel [6, 7]. This time makes up about several nanoseconds in our case.

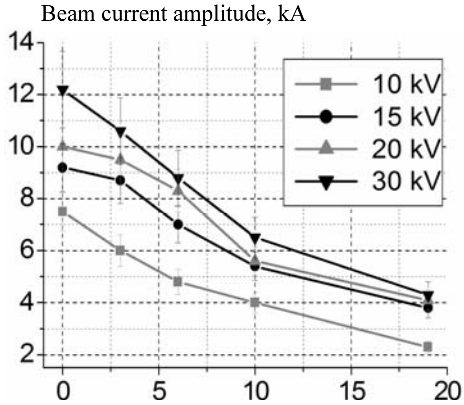

Fig. 3. The dependences of beam current amplitude on the distance $L_{g\text{-}c}$ for different charge voltages of high-voltage pulsed generator (HVPG) supplying the electron gun. $H = 1.3$ kOe, $p = 0.04$ Pa, $n_a = 3 \times 10^{12}$ cm^{-3}

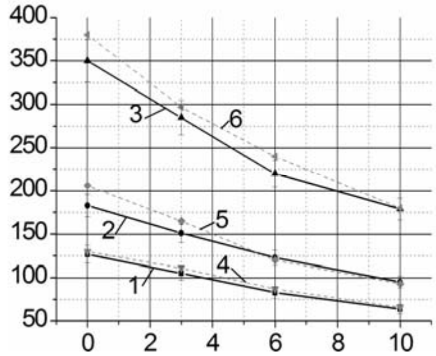

Fig. 4. The dependences of beam energy on the distance $L_{g\text{-}c}$ for different charge voltages of: (1; 4) – 15 kV; (2; 5) – 20 kV; (3; 6) – 30 kV. Plots 1–3 correspond to calorimetrical data, plots 4–6 obtained by integrating the acceleration voltage and beam current waveforms. $H = 1.3$ kOe, p = 0.04 Pa, $n_a = 3 \times 10^{12}$ cm^{-3}

Estimate roughly the current rise rate, at which the delay of charge neutralization may limit the beam current. Let beam current rises linearly in time and τ is characteristic time of plasma electron going away from the drift channel toward the collector. During this time, beam inputs an excess charge $q = I_b \times \tau$, which creates radial, E_r, and longitudinal, E_z, electric fields. According to Ostrogradsky–Gauss theorem one can write

$$E_r 2\pi a L + E_z 2\pi a^2 = \frac{I_b \tau}{\varepsilon_0} = \frac{dI_b}{dt}\frac{\tau}{\varepsilon_0}. \qquad (6)$$

Since $E_r a \approx E_z L \approx U_0$, so it can be assumed $E_r/E_z \approx L/a$. Here U_0 is the acceleration voltage which we believe to be equal to potential drop in the beam (the condition of the virtual cathode appearance). After simple computations, we get

$$U_0\left(1+\frac{a^2}{L^2}\right)\approx\frac{dI_b}{dt}\frac{\tau^2}{2\pi\varepsilon_0 L}. \qquad (7).$$

Neglecting the second item in brackets and assuming $\tau = L/(2eU_0/m)^{1/2}$, e.g. equal to the time flight of beam electron without deceleration (minimum time value), one can get an expression for maximum current rise rate at exceeding of which the virtual cathode may appear:

$$\left(\frac{dI_b}{dt}\right)_{\max}\approx\frac{4\pi e\varepsilon_0 U_0^2}{mL}. \qquad (8).$$

Substituting into (8) the typical values $U_0 = 20$ kV and $L = 0.3$ m, we get $(dI_b/dt)\max \approx 2.5 \times 10^{10}$ A/s which is rather close to those observed in our experiments. At the absence of current neutralization, the value $(dI_b/dt)\max$ may be several times lower since time of charge neutralization due to electrostatic ejection is, at least, two times larger [6].

According to the mentioned above, the observed decrease of beam current with the increasing of L becomes understandable. If the length of drift channel increases, so the time of plasma electron going away increases also; the degree of charge neutralization decreases, hence, the decreasing of beam current is observed. The presence of the step in drift tube in the case of incomplete beam space charge neutralization must cause an additional limitation of current which was observed in the present work.

As concerned the statement of Nezlin, that if plasma density decreases from DL to collector, so the virtual cathode must appear, we believe that this statement is not well-founded enough. Nezlin proceeds from the results of experiments [8] in which such a gradient was created by the corresponding gradient of the working gas pressure from which plasma column was formed due to ionization by beam electrons. But let us pay attention what was the concrete pressure gradient in these experiments. In the near-cathode region, the working gas pressure makes up $p_1 = 10^{-4}$ Torr, and at the distances of tens centimeters from the cathode, the pressure was $p_2 = 10^{-5}$ Torr. Of course, in such a situation plasma density in the low pressure region was lower than the density of electrons of the injected beam since in [8] the ratio $(eU/kT_e)^{1/2}$ makes up about factor of 5–8, e.g. it was even lower than p_1/p_2. At such conditions, from our point of view, beam space charge neutralization was partial only, and this was the reason for virtual cathode appearance.

4. Conclusions

1. In plasma-filled diode, the value of beam current is limited, on one hand, by the injection conditions in double layer between the cathode and anode plasmas according to Eq. (2), and on other hand, it is limited by the speed of beam space charge neutralization in the drift channel.

2. Experiments and estimations show that beam current may significantly exceed the critical currents of aperiodic instabilities responsible to the virtual cathode arising. To achieve this, it is needed the excess plasma with density comparable with the density of beam electrons. We believe that such excess plasma density is enough for suppressing the initial fluctuation of the beam charge density and potential.

References

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