Simulation of electron beam generation with a constant, rising and falling beam power during its pulse

M S Vorobyov and S S Kovalsky
Institute of High Current Electronics SB RAS, 2/3 Akademichesky Ave., Tomsk, 634055, Russia

E-mail: vorobyovms@yandex.ru

Abstract. In this work, we simulated the operation of an electron source with a grid plasma cathode based on a low-pressure arc discharge, where a high-voltage capacitor bank of a given capacity is used to accelerate the beam electrons. Based on the unique ability of such electron sources to generate electron beams with parameters independent of each other, capable of being regulated within relatively wide limits, the calculations were carried out with the aim of producing an electron beam whose power can be controlled during a beam pulse of a millisecond duration when the beam power is constant or has a linear rise or fall. The calculations confirm the uniqueness of plasma electron sources and open up new possibilities for their use in scientific and technological purposes.

1. Introduction
For generating pulsed (hundreds of microseconds) intense (hundreds of amperes) electron beams, two methods are most often used to apply a high voltage to an accelerating gap: 1. using a high-voltage artificial forming line, the energy from which is completely transferred to the load during the beam current pulse; 2. using a high-voltage capacitor battery with its partial discharge [1, 2]. The second method is most popular due to the possibility of generating an electron beam with a wider range of pulse durations, which, as was shown in many experiments on the surface modification of various inorganic materials [3–5], is of great importance. So, in the electron source SOLO (included in the list of unique installations of Russia “UNICUUM”) with a grid plasma cathode based on a low pressure arc discharge [6, 7], the amplitude of the beam current and its duration can vary in the ranges 10–200 A and 10–300 µs, respectively. The shape of the beam current in such a source usually has a quasi-rectangular shape, which leads to a linear decrease in the accelerating voltage during a beam current pulse, the initial value of which most often does not exceed 20–25 kV. Thus, depending on the intensity of irradiation of any material, the accelerating voltage may decrease by 50% or even more during a beam pulse, thus, when using a high-voltage capacitor battery and a constant amplitude of the beam current, the power of the electron beam decreases linearly during its pulse duration.

However, most often the focus on reducing the beam power during its duration is not emphasized, since when the electron energy in the beam changes in the range of 10–30 keV, their depth of penetration weakly depends on the electron energy and is significantly less than the depth of the thermal effect of the beam on any inorganic materials (few µm Vs hundreds µm). At the same time, to carry out materials science calculations, it is usually not used the beam power, but its energy density, which is embedded in the sample over a certain time. Also, the electron energy is most often taken to
be constant, and accordingly, it is believed that the beam power is also constant during a pulse, and the change in accelerating voltage is simply neglected. However, such an assumption may not always be made. In addition, several papers [8, 9] have already shown that the main thermal processes initiated in the surface of materials occur over a period of about several tens of microseconds. This suggests that with the total beam duration reaching hundreds of microseconds, it is necessary to control the rate of energy input into the sample surface, and, consequently, the beam power during its pulse.

Using the feature of such electron sources with plasma cathodes, such as the possibility of providing a wide range of parameters of the generated electron beam with a weak dependence on each other, the operation of such an electron source in the generation mode of an electron beam having a controlled power during its pulse is carried out.

2. Emission model

A detailed description of the operation of the electron source SOLO can be found in [6, 7]. From these works it is known that the easiest way to control the beam current is to change the arc discharge current, which, therefore, allows to adjust the concentration of the emission plasma [1, 2]. Despite the fact that in the accelerating gap there are electrons, produced as a result of ion-electron emission from the emission electrode surface, their number still depends on the concentration of the emission plasma, since the ions of the anod plasma responsible for the emission of secondary electrons appear in the accelerating gap as a result of ionization of the working and residual gases by the primary electrons of the beam, extracted from the emission plasma of the plasma cathode. In this case, the current in the accelerating gap is the sum of three currents [10]:

\[ I_0 = I_e + I_i + \gamma I_i \]  

(1)

where \( I_e \) is the current of the primary electrons extracted from the emission plasma; \( I_i \) is the current of ions bombarding the emission electrode surface; \( \gamma \) is the ion-electron emission coefficient.

Since all the terms of this equation depend on the current of primary electrons extracted from the emission plasma, the fraction of the current of accelerated electrons can be considered constant regardless of a shape and an amplitude of the total current in the accelerating gap. In addition, the power supply system of the discharge and the acceleration system of electrons in such sources are separated. The combination of these conditions for the operation of electron sources with plasma cathodes that have a grid stabilization of the plasma emission boundary makes it possible to significantly simplify the model of energy consumption from a high-voltage capacitor battery shown in figure 1. The model assumes energy consumption from a capacitor battery \( C \) by allocating power at a nonlinear resistance \( r \). The amplitude of the current \( I_0 \) is determined by the discharge current \( I_d \) [1, 2], which controls the gate of the key element SW.

So, let’s suppose there is energy \( W_c(0) \) in a capacitor bank:

\[ W_c(0) = \frac{C \cdot U(0)^2}{2} \]  

(2)

where \( U(0) \) is the voltage on the high-voltage capacitor battery at the beginning of the beam current pulse. Also \( W_c(0) \) is equal to:

\[ W_c(0) = W_c(t) + E_b(t) = \frac{C \cdot U(t)^2}{2} + E_b(t) \]  

(3)

where \( W_c(t) \) is the energy and voltage remaining in the capacitor battery after passing the beam; \( E_b(t) \) is the energy that was removed from the capacitor battery (spent on the generation of the electron beam) and which is equal to:

\[ E_b(t) = \int P_b(t) dt \]  

(4)

where \( P_b(t) \) – beam power.
It can be seen from formula (4) that, knowing the law of change in the power of the electron beam, one can simply calculate its total energy content. In order to solve this equation as applied to an electron source with a grid plasma cathode, it is necessary to specify the duration of the electron beam, as well as the initial value of the accelerating voltage. Then, knowing the law of the change of the beam power during its duration and the fact that \( I_b(t) = P_b(t)/U(t) \), one can explicitly determine the law of change of current and voltage on a high-voltage capacitor battery, and vice versa:

\[
U(t) = \left( U(0)^2 - \frac{2}{C} \int P_b(t) \, dt \right)^{1/2}
\]

(5)

3. Results of modelling

For simplicity, we consider only three laws of a beam power change during its pulse, namely, a linearly falling form, with a constant power and a linearly increasing one. To set the initial values of the beam parameters, the authors were guided by the actual operating conditions of the electron source SOLO, however, for better visibility of the current and voltage forms on the high-voltage capacitor battery, the pulse duration was chosen to be 1 ms. The authors understand that it was possible to ask a smaller battery capacity or reduce the initial accelerating voltage, however, since the parameters of such electron sources may differ, and the current selection mechanism in different sources will be the same, this question is not a matter of principle.

For the calculations the beam parameters were taken, summarized in table 1, where \( P_{av} \) is the average power of the beam during its pulse duration \( t \). Let us consider three modes of electron beam generation.

| \( U(0) \) (kV) | \( P_{av} \) (W) | \( t \) (ms) | \( C \) (\( \mu F \)) | \( E_b \) (J) |
|---------------|--------------|-------------|----------------|--------|
| 20            | 10^6         | 1           | 6              | 10^3   |

3.1. Constant beam power (\( P_b = P_{av} = \text{const} \))

It can be seen from figure 2 that the beam current is non-linear in nature, which is associated with a non-linear decrease in the accelerating voltage according to the law:

\[
U(t) = \left( U(0)^2 - \frac{2 \cdot P_{av} \cdot t}{C} \right)^{1/2}
\]

(6)
3.2. Linearly increasing beam power during its pulse

To solve this task, it is necessary to enter the power change factor during its pulse (for simplicity, we will consider this factor constant over time, which will give a linear change in the beam power during its pulse), and also set the initial value of the beam power further increase in beam power):

\[ A_p = 1 \times 10^9 \text{ W} \cdot \text{s}^{-1}; \quad B_p = 5 \times 10^5 \text{ W}. \]

(7)

It can be seen that in this case the initial value of the beam power must satisfy the condition \( P_{\infty} > B_p \). Then:

\[ P_b(t) = A_p \cdot t + B_p \]

(8)

\[ U(t) = 3 \frac{U(0)^2}{C} \left( \frac{A_p \cdot t^2}{2} + B_p \cdot t \right)^{1/2} \]

(9)

From the dependencies shown in figure 3, it can be seen that the beam current has a larger range of values; however, the nature of the beam current and the voltage across the capacitor battery has changed little.
3.3. Linearly decreasing beam power during its pulse

To construct dependences for linearly decreasing beam power, one can use the same coefficient as for the growing power (as in (7)), taking into account that the initial value of the beam power must satisfy the condition \( P_{av} < B_p \). Take \( B_p = 15 \times 10^5 \) W. Then the beam power will vary according to the law:

\[
P_b(t) = -A_p \cdot t + B_p
\]

\[
U(t) = \left( U(0)^2 + \frac{A_p \cdot t^2}{C} - \frac{2 \cdot B_p \cdot t}{C} \right)^{1/2}
\]

One of the options for implementing a system with a linearly decreasing power is a system with a constant discharge current of a capacitor. This mode is most interesting because it is very often found in practice [3–5]. Indeed, when a capacitor is discharged by a constant current, the voltage on it will fall off according to a linear law:

\[
U_c(t) = U_c(0) - \frac{1}{C} \int I_c \, dt = U_c(0) - \frac{I_c(0) \cdot t}{C}
\]

In this case, the power, as the product of current and voltage, will also decrease linearly. Let us estimate the power decay rate \( A_p \) in this system. To do this, multiply (12) by the discharge current of the capacitor battery and equate to (10), taking into account the fact that \( B_p = U(0) \cdot I(0) \):

\[
A_p = \frac{I_c^2(0)}{C} = U_c'(t) \cdot I(0)
\]

The result of the simulation is shown in figure 4. As can be seen from the graph, the received energy in this case is somewhat higher than that given in table 1. Obviously, in this case, the required energy on the substrate can be achieved, but for this, in addition except to the beam current, the voltage of the high-voltage capacitor must also be varied.

Consider the case that coincides in the average beam energy with the variant considered in “a”, retaining the initial conditions, as well as the value of the initial power in the beam adopted above. Then, at given times, the power change factor \( A_p = 10^9 \) W·s\(^{-1}\). Note that \( A_p > A_{p0} \), i.e. the rate of power reduction will be slightly higher than in the case of a constant current beam.

As can be seen from figure 5, the current becomes monotonously decreasing. The nature of the change in the function of the voltage graph changes as well – from linear to concave.

Considering the results of the simulation as a whole, it can be concluded that with the linear nature of the power change, it is quite simple to obtain the necessary energy density on the substrate by changing the discharge current of a plasma emitter.

![Figure 4](image)

**Figure 4.** The change in the voltage \( U \) on a capacitor battery and the beam power \( P_b \) during its pulse at a constant beam current \( I_b = \text{const} \).
4. Conclusion
The resulting model allows us to determine the nature of the current dependence in the discharge cell of an electron source with a grid plasma cathode to obtain the required level and nature of the change in the power of the generated electron beam. This can be extremely important from the point of view of using such a technological parameter as the rate of energy introduction into the material. It is important to note that in this work the simplest laws for varying the beam power during its pulse were considered, however, this model allows to obtain other, more complex dependencies. This model did not take into account such factors as the presence of limiting resistance in the discharge circuit of a high-voltage capacitor bank, usually a component of Ohms, which leads to a voltage drop across this resistance as the beam current (usually up to 1 kV). In addition, the model does not take into account the presence of the ion component of the beam current, which does not bring energy to the sample, but which reduces the voltage on the high-voltage capacitor battery and can reach more than ten percent of the total current in the accelerating gap (depending on the material of the emission electrode used, pollution, type of working gas and energy of accelerated ions). However, these assumptions can only lead to the appearance of additional coefficients in the resulting equations, which will not change the nature of the dependencies obtained.

In the future, this model is planned to be used to optimize the processing modes of the surfaces of materials and alloys at the SOLO facility, as well as when designing new accelerator systems based on grid plasma cathodes.

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