On efficiency during the generation of runaway electrons beams in stationary open discharge

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Abstract. Measurements of energetic efficiency were accomplished in generation of runaway electrons beams for helium, air and water vapor with various cathode materials. The efficiency near 80% was demonstrated for runaway electrons beam generated in helium and water vapour.

Generators of electron beams (GEB), working directly in gas environment, are the advanced means for solving many technological problems [1]. Several variants of the design of such GEB were proposed in [2], also in work [3] and several others, studies of the operation of the GEB were carried out.

Evaluation of efficiency of the formation of an electron beam is proposed in [4]. Energetic efficiency or efficiency is defined as the ratio of the power of the generated electron beam \( W_n \) to the total input power \( W \):

\[
\eta = \frac{W_n}{W}
\]

As a rule, the calorimetric method, based on heating of specially installed target by a beam, is used to measure the efficiency of electron-beam guns [5]. As applied to the open discharge, this method can give significant errors since the target heated by the beam must be installed at a distance much smaller than the beam residual range – otherwise there will be significant energy losses in the gas. However, such installation of the target can affect the operation of the generator, what was experimentally confirmed in [6] (the beam residual range was estimated by the method of [7]).

It should be noted that measurements of the efficiency of electron beams generation in an open discharge in works [8] and [9] by measuring of currents flowing to the anode and to the special collector of electrons are based on an incorrect determination of the coefficient of efficiency, not taking into account the contribution of the secondary electrons. These measurements were criticized in many works, in particular, in [10-13].

In this connection, it was decided to estimate the energetic efficiency by measuring the heating of the electron beam generator itself, assuming that all supplied electric energy, with the exception of the energy carried away by the electron beam, goes to the heating of the generator and the vacuum chamber, due to the heat rejection. In this case, the heat capacity of the generator \( C_{gen} \) can be easily determined from the book reference [14] on the heat capacity of constructional material and from results of weighing the details of the generator.

The temperature dependence of the generator body on time can be represented as,

\[
\frac{dT_{\text{body}}}{dt} = \frac{W - W_n - W_o}{C_{\text{gen}}},
\]

where \( W_o \) is the rate of heat rejection from the generator.
The power $W$ delivered to the discharge during the operation can be measured by measuring the voltage and current of the discharge supply taking into account the losses on the ballast resistance $R$. Assuming the uniform heating body, the dependence of the heat rejection rate on temperature can be determined from (2) according to the derivative of temperature of the body during the cooling at once after the power-off.

Thus, the measurement of efficiency includes measuring the power supply of the discharge and the temperature of the generator body for some time during the heating process and measuring the temperature when the generator is cooled after the discharge is turned off. In the second measurement, the heat rejection power $W_0$ is determined as a function of temperature, which makes it possible to determine the beam power $W_n$ from the results of the first measurement. Further, the value of efficiency can be found by the formula (2) for any moment of time of the heating stage.

In the case of the generator transfer to the stationary thermal mode, the power for its heating is equal to the heat rejection power and the efficiency of the generator can be determined by measuring the supplied electric power and the rate of change of the body temperature immediately at once after the power supply is turned off $-n T_{off}$. Then from (1) and (2)

$$\eta = 1 - \frac{C_{gen}}{W} |T_{off}|.$$

This method of determining of efficiency is not always possible, since the output to the stationary mode can take a long time (hours), and the temperature of the generator body in this case can reach hundreds of degrees. In addition, this method has a greater error than the processing of data collection on the rates of heating and cooling.

The method of processing of experimental data, based on the assumption that the amount of heat given off by the unit of the generator surface per unit of time, according to the Newton-Rikhmann law, is proportional to the difference between the generator and vacuum chamber temperatures. This method, which also takes into account the inconsistency of the input power during the heating stage, is described in [15]. All values of efficiency given below are obtained by using this method of processing.

In the first series of experiments, the efficiency measurements were carried out in helium for various hole diameters in the discharge-limiting insulator, power-supply voltages and cathode materials. In the second series - with a design without an insulator in helium, air and water vapor. In this series, a steel cathode and an anode with a 1 mm diameter hole were used. The gap between the cathode and the anode was 0.23 mm.

All measurements are performed on installation, the description of which is given in [3]. The diagram of the electron-beam plasma generator during the efficiency measurement using an insulator design is shown in Figure 1. The generator consists of: cathode 1, insulator 2, union nut 3, body 4, anode 5.

![Diagram of the electron beam generator.](image-url)
The main measurements of the generator temperature were carried out with a thermocouple of chromel-copel type located on the body 4 at the point indicated in Fig. 1. Shielded twisted pair of F/FTP type was used as signal wires. The error in measuring the temperature did not exceed ± 0.5 K.

Additional control measurements by KTY-200 thermistor were made to estimate the non-uniformity of the surface temperature. The thermistor was installed on the union nut 3, separated from the zone of maximum heat-removal by threaded joint. The error in measuring the temperature is not more than ± 0.1 K.

The temperature and pressure of helium during the tests were constant. The content of the admixture of air in helium was in the range of 0.1-3%.

The conditions for the first series of experiments and the obtained results are given in Table 1. The following notations are used: \(d\) – the diameter of hole in the insulator, \(R\) – ballast resistance, \(U\) – power supply voltage, \(P_{He}\) – helium pressure in the vacuum chamber. The first column of the table indicates the number of experiment; the same numbering is used later in the text.

| no | \(d\), mm | Cathode material | \(U\), kV | \(P_{He}\), Pa | Efficiency, % |
|----|-----------|-----------------|--------|-------------|---------------|
| 1  | 0,5       | LaB\(_6\)      | 6,5    | 1504        | 51            |
| 2  | 2,3       | steel           | 4,4    | 494         | 54            |
| 3  | 1,0       | LaB\(_6\)      | 4,4    | 1513        | 71            |
| 4  | 1,0       | Mo              | 4,4    | 1507        | 48            |
| 5  | 0,3       | Cu              | 8,0    | 2060        | 83            |
| 6  | 1,0       | Cu              | 4,4    | 2025        | 54            |
| 7  | 1,0       | Cu              | 4,4    | 1501        | 53            |
| 8  | 0,5       | Cu              | 4,4    | 1507        | 63            |
| 9  | 0,5       | Cu              | 7,0    | 1504        | 78            |

In experiments 5-9, an aluminum disk with a diameter of 200 mm and a thickness of 1.5 mm was placed coaxially on the front end of the generator body (not shown in Fig. 1), which led to an increase in both the heat capacity and the heat dissipation.

As an example, Figure 2 shows the temperature variation of the generator body and the discharge power during the full measurement cycle, including heating, reaching the steady state of thermal conditions, and cooling down after the power-off.

![Figure 2](image-url)

**Figure 2.** Dependence of temperature (curve 1) and electric power of the generator (curve 2) on time in the measurement 8.
The fragment of the heating process in experiments 1-7 is shown in Fig. 3. It can be seen that in the experiment 5 the operation of the generator was unstable and the power consumption varied from 50 to 150 W. Probably such work of the generator is explained by the small hole diameter in the insulator - only 0.3 mm. In other experiments, the power may spontaneously changed during the operation, probably due to a change in the state of the cathode due to erosion.

![Figure 3. Dependence of temperature (solid lines) and electric power of the generator (dashed lines) on time in the process of heating in measurements 1-7.](image1)

Experiments 8 and 9 achieved a steady-state thermal regime; temperature and power in the steady state regime are shown in Fig. 4.

The temperature difference between the thermocouple (BK) and the thermistor (RK) did not exceed 3-5% and decreases as the generator cools down. The relative error in determining of efficiency is estimated at 10%.

![Figure 4. Dependence of temperature (solid lines) and electric power of the generator (dashed lines) on time in steady state regime in measurements 8 and 9.](image2)

Based on the results of both the first and second series of experiments, it is seen that with increasing voltage, the coefficient of efficiency also increases. The only exception is measurement 1. Probably, due to some assembly defect in the generator, the parasitic discharge was ignited in this experiment, which led to the decrease in the coefficient of efficiency.

The results of second series of experiments are given in Table 2.
Table 2. Conditions for the second series of measurements and the obtained results.

| no | Working gas | $P$, Pa | $U$, kV | Efficiency, % |
|----|-------------|---------|---------|--------------|
| 10 | helium      | 1545    | 4,4     | 66           |
| 11 | helium      | 951     | 4,4     | 59           |
| 12 | helium      | 964     | 6,5     | 76           |
| 13 | air         | 322     | 4       | 57           |
| 14 | air         | 307     | 4       | 59           |
| 15 | water       | 300     | 3       | 53           |
| 16 | water       | 310     | 6       | 79           |
| 17 | water       | 508     | 3       | 46           |

Values of the efficiency measured at different pressures, but at the same voltage, differ somewhat from each other. However, no dependence is observed, and the difference in the value of efficiency is slightly higher than the error in the evaluation of this parameter.

Unfortunately, measurements in air and water vapor are performed at several other voltage values than measurements in helium. According to Table 2, it can be assumed that the efficiency in experiment in these gases is somewhat higher, especially in water vapor. However, although differences are observed in all measurements, they are close to the error of the method.

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