Open discharge-based electron beam generator with rare gas blown through the discharge gap

A I Shloydo1,2, A V Turkin1, V S Voiteshonok1 and E K Egorova1

1 Keldysh Research Centre, Moscow, 125438 Russia
2 E-mail: kerc@elnet.msk.ru

Abstract. Electron beam generators operating directly in gaseous medium are a promising means of solving several technological problems. In order to solve these problems, it is required to broaden the working pressure range of these generators. Investigations of the current-voltage characteristics of the generator, which was modified to supply the substitutional gas into the discharge gap, showed that by means of blowing helium at a pressure of 2.6 kPa into air medium at a pressure of 2.5 kPa, it is possible to reach a voltage of 5.5 kV at a current of 23 mA. The substitutional gas flows have been determined that ensure the stable generator operation at air pressures in the range from 1 to 2.5 kPa.

1. Introduction
Electron beam generators (EBGs) that are able to operate directly in gaseous medium are a promising means of solving many technological problems [1]. In [2], the authors have proposed several design options for such generators; the results from studies of the EBG operation are presented in [3] and some other publications.

In order to use EBGs for gas conversion [4], treatment of metal and dielectric surfaces, including the plasma-beam coating [5], laser pumping [6], etc., it is necessary to broaden the range of the generator operating pressures.

An obvious way to increase the working pressure of the EBG is to decrease the distance between the electrodes, the reduced discharge gap $pd$ being constant, in order to maintain the generator performance as shown in [7]. Thus, to increase the pressure, it is necessary to decrease $d$ making it less than ~100 μm, which is technically challenging, as proved in [6].

The authors have proposed to increase the working pressure of the EBG by means of supplying the substitutional gas into the discharge channel. In this case, the energy of the produced electron beam is maximal. We note that the medium, in which the EBG is installed and the electron beam is decelerated, considerably differs in its kinetic and chemical properties from those of the substitutional gas.

This paper presents the results from the experimental studies of the characteristics of the modified electron beam generator. The EBG design was modified to ensure blowing of the substitutional gas through the discharge gap. The new EBG design is based on the version 3 of the patent [2] with the minimum size of the discharge gap supplemented by the channel for the substitutional gas supply.

2. Experimental setup
The studies of the gas discharge characteristics were performed at the modified experimental facility described previously in [3, 8]. The discharge is formed in the gap filled with one gas and then it is lead out into another gas. The schematic of the facility is shown in Figure 1a.
The key element of the experimental setup is the CV vacuum chamber, which consists of four 800-mm-diameter and 600-mm-long cylindrical sections. The chamber is pumped out by the N pump through the VD2 valve, and then filled up with the working gas from the C1 gas tank through the VD1 valve or with atmospheric air (in this case, the C1 tank is disconnected).

![Diagram](image)

**Figure 1.** (a) The experimental setup and (b) design of the electron beam generator with the channel for blowing the substitutional gas.

From the C3 tank, the substitutional gas flows to the C2 receiver through the VD4 pressure reducer. Then it is supplied to the EBG discharge gap (indicated as P in the schematic) through the VD3 valve and the adjustable VLV leak valve. To measure the air pressure $P_{\text{air}}$ in the CV vacuum chamber and the substitutional gas (helium) pressure $P_{\text{He}}$ in the supply system, the PD1 and PD2 vacuum gauges are used. The PD3 and PD4 vacuum gauges measure the pressures in the C2 receiver and in the C3 gas tank. The VLV valve controlled the flow and pressure of the substitutional gas. At the end flange of the chamber, there is a special straight-through flange. Figure 1b, shows the design of the electron beam generator P, which is installed on the flange arm and connected to both the substitutional gas supply system and high voltage source $U^k$.

The generator was powered from the source using the high-voltage cable and the ballast resistor $R_b = 5 \, k\Omega$. In the CV chamber, both the cable and electron beam generator were additionally shielded with the help of the foil. The high voltage source provides the voltage $U$ of up to 10 kV with the maximum current $I$ of up to 200 mA. The high-voltage source is equipped by the instrumentation for measuring and controlling the generator current and supply voltage. The vacuum chamber and the cable shield were grounded at the same point, the ground connection resistance being less than 20 $\mu\Omega$.

The $VD$ and IKD6TDa-20 deformation vacuum gauges were used, depending on the air pressure range under study. The readings of the pressure gauges do not depend on the type of gas [9]. The VLV adjustable leak valve allowed tuning the gas flow from $10^{-5}$ to $4$ m$^3$ Pa/s.

### 3. Electron beam generator with substitutional gas supply system

The EBG based on the stationary open discharge (OD) with runaway electrons is the cylindrical discharge channel with small length and diameter (of the order of tenths of a centimeter) and constant potential difference applied to the interelectrode gap (of the order of several kilovolts). In such EBGs, the anode is either a grid or an aperture with high geometric transparency. The bulk of electrons accelerated in the discharge gap can easily leave it and, while slowing down in the working medium,
they create plasma with the inhomogeneous spatial structure. We note that the runaway electrons are observed both under natural conditions (e.g., in lightning discharges [10, 11]) and under controlled conditions. In particular, the runaway electrons are usually observed in the fusion facilities, namely, in the toroidal magnetic traps [12]. According to the estimates performed in [13], the runaway electrons are the second most important reason for the possible disordering the ITER operation. The term "open discharge" is widely used in the scientific publications from 1985 [14] to the present [6].

The key advantage of the EBGs based on the stationary OD is their ability to create the high-energy electron beam (EB) directly in the working medium without using any complex systems for the beam focusing and transport. The energy efficiency of the stationary OD reaches 85%, depending on the geometry of the grid cell and type of the working gas [8]. It was demonstrated in [15] that the highest operating efficiency and working pressure are typically achieved when the discharge is ignited in the noble and light gases without air impurities. In studies [3, 8], the maximum helium pressure was up to 3.0 kPa at the beam energies of up to 6 keV, while in air the maximum working pressure hardly reached 0.4 kPa.

To increase the operating pressure range, the EBG design was supplemented with the channel providing gas supply to discharge gap 5 (it is shown schematically in Figure 1b); at the EBG inlet, the channel diameter was 1 mm. The generator is connected to the substitutional gas supply system by the silicone tube with an inner diameter of 2 mm. In addition, the generator includes the following elements: cathode 1 installed inside ceramic insulator 2, anode 3 with spacer 4, which regulates the size $H$ of the discharge gap between the electrodes. The anode is grounded, and the negative voltage $U^*$ is supplied to the cathode. The electron beam escapes from the discharge gap through the aperture in the anode with the diameter $D$ equal to 2 or 3 mm. Anode 3 and spacer 4 are made of stainless steel with a thickness of 1 and 0.2 mm, respectively; cathode 1 is made of molybdenum, and ceramic insulator 2 is made of boron nitride.

4. Experimental conditions

The studies of the EBG operation were performed both with and without blowing the substitutional gas through the discharge gap.

The main way for describing and analyzing the EBG operation is to measure its current-voltage characteristics. In this work, it was measured in the supply voltage range from 0 to 7 kV in 0.5 kV steps and the current in each step was recorded. In this study, the maximum voltage was limited by the maximum current, which was 25–30 mA. After 300 seconds of the EBG operation, at a voltage of 5 kV, the experiment was terminated. Whenever reaching a certain voltage, a sharp change in the EBG operating regime was observed followed by a several times increase in the consumed current and a change in the size and shape of the glowing plasma region.

The air pressure in the vacuum chamber ranged from 20 Pa to 2.5 kPa.

We used the grade A helium as a substitutional gas; the maximum pressure measured with the PD2 vacuum gauge was not less than 2.6 kPa. The helium pressure in the supply system was controlled by the $VLV$ leak valve. The calculated results for the substitutional gas flow are shown in the table.

At pressures lower than 2.6 kPa, the reduced thickness of the discharge gap did not exceed 0.52 Pa·m both in air and in helium, which is thinner than the normal thickness of the cathode layer. Consequently, the glow discharge conditions correspond to the left branch of the Paschen curve in the entire pressure range under consideration [16, 17].

The current-voltage characteristics measured at a pressure of approximately 160 Pa is similar to those shown in [3, 8, 15]. It is given in the table for comparison. Typical image of the glowing plasma region is shown in Figure 2a at a voltage of 5 kV. Its dimensions are approximately 200 mm. This result confirms our initial assumptions that the implemented design of the gas supply system does not drastically change the characteristics of the generator.

5. Measurements of EBG parameters

The images of the plasma cloud formed by the EBG at $P_{air} = 1$ kPa are shown in Figures 2b (without substituent gas) and 2c (with helium supplied at $P_{helium} = 2.6$ kPa). In the first case, it was not possible to
increase the voltage higher than 1.5 kV, as the current becomes higher than the set limit. The size of the plasma glowing region was approximately 20 mm. At voltages higher than 1.5 kV, a short circuit occurred in the discharge gap between the electrodes, accompanied by the bright flash, triggering of the power source current protection system and release of a large amount of heat.

At the air pressure $P_{\text{air}} \sim 1$ kPa and with blowing helium into the discharge gap, we obtained a voltage of 5.0 kV at a current of 17.8 mA. Based on the image shown in Figure 2c, the size of the plasma cloud is approximately 150 mm. Using the mixture of air and helium at pressures $P_{\text{air}} \sim 2.5$ kPa and $P_{\text{He}} \sim 2.6$ kPa, respectively, it is possible to obtain the $U$ voltage of $\sim 5.5$ kV; and the $I$ current of $\sim 23$ mA. The results of measurements of the EBG current-voltage characteristics are presented in the table.

### Table. EBG parameters measurements

| Air pressure, kPa | 0.16 | 1.0 | 1.0 | 1.1 | 1.2 | 1.3 | 1.4 | 1.5 | 2.5 |
|-------------------|------|-----|-----|-----|-----|-----|-----|-----|-----|
| Substitutional gas pressure, kPa | - | - | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 | 2.6 |
| Substitutional gas flow, m$^3$/Pa/s | - | - | 0.11 | 0.11 | 0.11 | 0.2 | 0.07 | 0.09 | 0.08 |
| Anode aperture diameter, mm | 3 | 3 | 3 | 3 | 3 | 3 | 2 | 2 | 2 |
| Operating time at maximum power, s | 60 | - | 400 | 300 | 120 | 180 | 300 | 300 | 200 |
| Maximum power, W | 41 | 38 | 95 | 98 | 119 | 131 | 140 | 80 | 115 |
| Voltage, kV | Current, mA |
| 0.5 | 0 | 3.6 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1.0 | 0.1 | 15.4 | 0.2 | 0.2 | 0.2 | 0.7 | 0 | 0.2 |
| 1.5 | 0.4 | 24.4 | 0.9 | 0.9 | 1.1 | 1.5 | 2.4 | 0.6 | 1.0 |
| 2.0 | 1.0 | - | 2.2 | 2.1 | 2.7 | 3.5 | 4.8 | 1.3 | 8.3 |
| 2.5 | 1.8 | - | 4.5 | 4.1 | 5.1 | 6.2 | 8.2 | 2.6 | 4.6 |
| 3.0 | 2.8 | - | 6.5 | 6.8 | 7.8 | 9.0 | 12.0 | 4.3 | 7.2 |
| 3.5 | 3.8 | - | 9.6 | 9.2 | 11.1 | 12.7 | 15.4 | 6.8 | 10.4 |
6. Discussion

When comparing the results obtained to the results presented in [3, 8, 15], we revealed the following facts:

1. At voltages of ~5 kV, the discharge current increases with increasing air pressure. The dependence of the current on the air pressure is not the quadratic dependence predicted by the theoretical estimates and confirmed by the previous experiments. [8, 15].

2. For the anode apertures with diameters of 2 and 3 mm, at the air pressures $P_{\text{air}}$ of 1.4 and 1.5 kPa and the helium pressure $P_{\text{He}}$ of ~2.6 kPa, we did not observe the proportional dependence of the discharge current on the aperture area discovered in [3]. A possible explanation for the observed deviation is the change in the initial EBG operating conditions with increasing discharge voltage (and current). For example, the considerable heating of the substitutional gas in the discharge gap not only lowers the gas density, as noted in [18], but also increases the hydrodynamic resistance of the discharge gap to such an extent that the critical heat flux can arise in it (see [19]).

In such a configuration, determining the efficiency of electron beams generation using the calorimetric method proposed in [15] faces some difficulties due to the heat carryover by the substitutional gas flow.

Without supplying the substitutional gas, at $P_{\text{air}} \sim 1$ kPa and $D = 3$ mm, the mean discharge current density, at which the current $I$ starts growing, is of the order of 3 A/cm$^2$, which corresponds to the conditions when the glow discharge turns into the arc discharge [16]. Thus, it has been experimentally shown that, without supplying the substitutional gas, at pressures $P_{\text{air}} \sim 1$ kPa and higher, the steady-state open discharge regime is inaccessible at the given geometrical dimensions.

Conclusions

For electron beam generators based on the open discharge, we have proposed the method for increasing the working pressures of the gaseous medium. The experimental EBGs with the substitutional gas supply channel have been designed and manufactured.

The experimental studies of the EBG with the substitutional gas supply channel showed that the generator that uses helium ($P_{\text{He}} \sim 2.6$ kPa) as the substitutional gas in the cathode-anode gap can operate in air ($P_{\text{air}} \sim 2.5$ kPa) at a voltage of 5.5 kV and a current of 23 mA. In these experiments, the maximum attainable characteristics have not been studied, and they may be higher. At pressures $P_{\text{He}} \sim 2.6$ kPa and $P_{\text{air}}$ ranging from 1 to 2.5 kPa, the generator forms the electron beam till the pressure of substitutional gas in the cathode-anode gap becomes equal to the air pressure. The gas flow ensuring the generator stable operation ranges from 0.07 to 0.2 m$^3$/Pa/s.

The proposed generator design should be tested at different combinations of the substitutional and ambient gases. For example, to use such EBG for the conversion of different gases with the help of the electron beams [4], it is important to study the combinations of hydrogen with the following gases: methane, nitrogen, carbon dioxide, complex hydrocarbons, etc. In addition, the extension of the EBG operating pressure range to the lower pressures seems to be promising in terms of developing the electric propulsion systems.

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