Runaway electrons beams in stationary open discharge for technological applications

V S Voiteshonok¹, A I Golovin¹, A V Turkin¹, A I Shloydo¹
¹SSC FSUE Keldysh Research Centre, Russia, 125438, Moscow, Onezhskaya 8

E-mail: kerc@elnet.msk.ru

Abstract. The proposed electron beam generator (EBG) operating in gas medium immediately is a perspective facility for solution of technological problems. Several versions of these EBG designs are proposed. Researches of EBG functioning have been done. The measurements of efficiency with forming of runaway electron beams were conducted for various gases (air, helium, water vapors, argon, xenon) at various pressures and for various cathode materials.

1. Introduction

The electron beams in gas medium have found a lot of technical application. The most known item here is the pumping of gas lasers [1 - 4]. Besides this, the beam-plasma sputtering and the other technological processes [5 - 7] are used successfully and for a long time. The use of electron beams in lightning [8, 9] and in microelectronics [10] also deserves to be mentioned.

Technological working of materials, especially of ceramics and other dielectrics, by electron beams in gases of medium pressure is more preferential because plasma which is generated in a gas medium inhibits the surface electrization of the component being worked.

The compact area of electron beam generator (EBG) based on an open discharge allows to form the electron beam of various aperture; moreover the large aperture can be formed with the set of EBG cells. It is possible to form the beam profile which satisfies the profile of component being worked, and to work the internal surfaces of components.

The review of modern state of researches on electron beam generation in gases for technological applications is given in [11]. It is noted in this work, in particular, that when electron beams are formed in deep vacuum (of 10⁻⁵ Pa order) the problem of beam removal in gas is solved usually by using of bulky differential pumping systems or of foils window. The technological problems during creation of these systems are considered, for example, in researches [12] and [13] respectively.

2. The open discharge

The graving of working pressure in the electron beam gun with high voltage glowing discharge requires of unit sizes decreasing for obeying of similarity criterion, responsible for gas discharge. At the same time, this results in substantial increasing of ionic flow which bombards the cathode. As a result, there is no need in special measures to sustain the sufficiently dense plasma within anode region. With this, the electron-optical system is simplified down to flat cathode and flat gridlike anode (including the limiting case of “grid” with single hole). Since the functioning of unit is provided at the expense of cathode bombarding by the flow of particles from the outside of discharge spacing, it is
reasonable to use term “open discharge”, which was used in [2] work. The pulsed discharges with runaway electrons, including the open discharge, are considered in detail in [14] work.

Figure 1 - Schematic representation of open discharge.

The possibility of operation for units with open discharge in continuous mode was noted some more in [2] work. However, by now time the number of publications on stationary open discharge is substantially smaller, then on pulsed discharge. Two following explanations can be given to this fact.

At first, in many cases of technological application of EBG units, the pulse-periodic action is quite sufficient. This relates, in first turn, to the heat treatment of materials since the characteristic time of thermal processes is much longer then of pulse recurrence periods. Similarly, in lighting technology [8], even with ignoring of luminophor afterlighting, at sufficiently high frequency of pulse recurrence, the glimmering of light source will not be noted. Secondly, the unit operation in pulse mode is more sable then in continuous one. This is because the characteristic time for creation of instabilities together with forming of cathode potential drop is ruled by ion velocity and by size of unit. Therefore, with sufficiently short duration of pulses, the instabilities, parasitic discharges have no time to develop. Exactly for this reason in research [8] continuous mode of luminophor excitation in wide aperture light source was used at low voltages; at elevated voltages pulse-periodic mode was used.

Stationary open discharge has found a number of practical applications. For example, in [15] work this discharge was used for etching of silicon dioxide samples. In work [16] sputtering of oxide films was accomplished when the targets of segnetoelectric and metallic materials were used.

3. Distinction between open discharge units and high voltage glowing discharge guns

If to believe that basic mechanism of emission is the photoeffect then the open discharge should be recognized as principally new type of discharge having nothing of common with the high voltage glowing discharge guns. However, it to take point of view which belongs to opponents of photoemission nature of discharge, then the open discharge was to be regarded as the variety of high voltage glowing discharge, which is the runaway electron beam generators with open discharge may be regarded as a variety of high voltage glowing discharge guns. However, in this case also a number of serious differences exists both in designs of units and in physical processes taking place inside.

First of all it should be stressed that in devices with open discharge sufficient flow of fast particles which bombard the cathode is provided directly in cathode layer, therefore, in contrast to high voltage glowing discharge guns (HVGDG) to provide discharge independence there is no need to take special measures for creation of anode adjacent plasma, which appears to be the source of ions in HVGDG. It is also to bear in mind that this fact differs the open discharge also from the traditional glow discharge in which the bombarding of cathode is provided by diffusion of ions in cathode layer from the positive column.

The other important difference is in fact that electrons in HVGDG devices are accelerated in a anode-cathode gap whereas in the open discharge acceleration of electrons takes place in cathode potential drop, which in most cases is larger than a cathode-anode distance – the “sagging” of electric field beyond the anode [17, 18].

Moreover, the electrons in accelerating gap of HVGDG do not interact practically with the gas medium, whereas in open discharge the interaction of electrons with gas is sufficiently high to provide cathode bombarding with ions at the expense of gas ionization in the cathode layer. With this, the runaway regime is realized in the open discharge, whereas in the HVGDG devices the acceleration regime is close to those in high vacuum guns.
Finally, the cathode-anode gap with the open discharge is so small (from tenths up to several millimeters) that of whatever electronic optics becomes practically impossible, whereas for HVGDG the beam focusing systems are often created, including the classical Pearce-type geometry [7]. As for the open discharge, it is realized as a rule, with the simplest flat geometry, although the devices are known with cylindrical and even spherical geometry [19]. Moreover, in open discharge devices, the characteristic sizes of cathode, as a rule, the cathode-anode gap (wide – aperture discharge) and this is nontypical for HVGDG devices.

It is needless to say that the differences noted are the result of working pressure increase and in this sense the open discharge in presented like the evolution of HVGDG devices. However, these differences allow putting the devices with open discharge into separate class.

4. Experimental investigation of current – voltage characteristics in stationary open discharge

In the course of experiments, we analyzed the current–voltage characteristics of electron beam generators in air and helium under various pressures. In this section, we consider, the design version used, and the results of experiments on the choice of structural materials.

The schematic diagram of the generator is shown in figure 2a. It consists of cathode 1, bush 2, gasket 3, spacer 4, and the anode in the form of washer 5. Electron collector 6 is installed for estimating the beam current.

![Diagram of electron beam generator](image)

Figure 2 - Electron beam generator. (a – layout 1, b - layout 2, c - layout №3).

We have tested several materials of insulating bush 2: fluoroplastic, BGP-10, K-00 epoxy resin, K-68 vikints, and KSP-90 ceramics. Experiments were carried out for thickness of spacer layout from 0.5 to 4.3 mm and the diameter of the aperture in the insulator d has been from 0.4 to 1.5 mm. In addition to above mentioned an attempt has been taken to use the foiled fluoroplastic of FAF-4D. However, the working voltages here proved to be rather low (up to 3 kV) and decision was taken to refuse from usage of fluoroplastic. Possibly, low working voltages can be explained by glass cloth reinforcement of this sort of plastic it which during the drilling of holes in it leaves the wires, provoking a breakthrough. With using of textolite the glass cloth was fully impregnated by epoxy resin and the holes have the smooth boundaries. For all cases the hole diameters were of 3 mm value.

For testing of various materials for cathode, layout №2 was used, given on 2b drawing. Some results on testing of this design are presented in [20] work. The main parts in it are: the cathode 1, insulating bush 2 and the anode 3. For the cathode material, we considered molybdenum, copper, stainless steel, aluminum, graphite, zinc and lanthanum hexaboride. Distance cathode anode, H, was between 1.5 and 2.5 mm.

The third version of plasma generator was designed for operation at higher working pressures. Layout 3 is shown on 2c drawing. Cathode 1 is inserted into insulating sleeve, which is separated from the 3 anode by the 4 washer. In this design the same materials were used as for the second version; additionally for the 2 sleeve pressed hexagonal boron nitride was tested. The 4 washer was made of copper foil of 200-250 mkm thickness. With such a cathode-anode gap the discharge is realized on a left branch of Paschen's curve. This provides the absence of breakdown, except the region of anode
hole. The distance between washer and the cathode is sufficiently large to avoid breakdown along the surface of dielectric. Decreasing of the gap between the cathode and anode as compared with the other versions of design allowed to increase approximately three times the working pressure and, what is more important, to boost the operational stability of high voltages.

The maximum number of tests was executed with the 3-nd version of layout. These tests were directed toward the refining of generator design for using it in experimental plasma test unit, rather than on researches of discharge. Therefore, the most of results given below are related to 1-st and 2-nd versions of design. The plasma generators considered here are protected by patent of Russian Federation [21].

4.1. Experimental results

The most experimental results on influence of design materials on characteristics of electron beam plasma generator are published in [22] work. The results of measurements of the current density je on voltage U across the cathode for anode aperture diameter D = 3 mm and an air pressure of 140 ± 20 Pa are given in figure 3. (1 — BGP ceramic spacer, H = 3.0 mm, and d = 0.8 mm; 2 — foil coated textolite spacer, H = 3.0 mm, and d = 0.4 mm; 3 — foil coated ceramic spacer, H = 4.3 mm, and d = 1.4 mm; 4 — ceramic spacer with K 68 filling, H = 2.5 mm, and d = 1.5 mm; and 5 — KSP 90 ceramic spacer, H = 2.0 mm, and d = 0.5 mm). The curves 1 — 4 was measured with the 1-nd version of layout, the curve 5 was measured with 2-nd version of layout.

![Figure 3 - Dependences of the EBG current density on voltage for various isolating materials.](image1)

![Figure 4 - Dependence of the EBG current on voltage for various cathodes materials.](image2)

It should be noted that although the difference in the shape of I–V curves is noticeable, the cathode material does not affect significantly the attainment of the maximal parameters It is seen from the curves given here that the material of isolator has no substantial influence on current-voltage characteristics at the discharge and on generation of electron beam. With this, the maximum working voltage is reached for the 2-nd version in which the breakdown on internal surface of isolator is impossible radically.

The current \( I_e \) – voltage \( U \) characteristics for aluminum (Al), lanthanum hexaboride (LaB6), graphite, copper (Cu), stainless steel (Fe), Molybdenum (Mo) and zinc (Zn) on the 2-nd layout produced from KSP-90 ceramics having sizes \( H = 2.0 \) mm, \( d = 0.5 \) mm, \( D = 3 \) mm at the air pressure of 130 Pa are given on figure 4. These results are taken from the [22] work.

The Table 1 shows that for the most of materials the limiting current density is in the \((8,7 – 10,4)\) mA/mm². For the lanthanum hexaboride current density is approximately 3 times awaitingly higher. The low current density of zinc and graphite can be explained by destruction of such cathodes under their ionic bombarding and heating. The same reason can also explain the lower limiting working
voltage – the products of cathode erosion can result in contamination of internal surface of insulator which can create the conditions for breakdown.

In general, it follows from the table 1 that limiting current density is approximately the same for metallic cathodes, what coincides with the data from [23] work.

| Table 1 - Maximal values reached for various materials of the EBG cathode. |
|---------------------------------|-------------------|-------------------------------|
| Cathode material               | Maximal voltage, kV | Maximal current density, mA/mm² | Extrapolation to 9.5 keV, mA/mm²² |
| Aluminum                        | 6,5                | 7,3                           | 8,7                           |
| Lanthanum hexaboride            | 9,7                | 29,4                          |                               |
| Graphite                        | 7,4                | 4,7                           | 6,2                           |
| Copper                          | 9,5                | 10,3                          |                               |
| Stainless steel                | 9,5                | 8,8                           |                               |
| Molybdenum                      | 9,8                | 10,4                          |                               |
| Zinc                            | 8,4                | 3,2                           | 5,5                           |

Cathodes, which passed through the tests, had always clearly defined traces of erosion. This fact works in support of conclusion that ionic bombarding is the main source of electron emission [24]. The lowest erosion was obtained on lanthanum hexaboride cathodes. As for the metallic cathodes, the lowest corrosion was observed on molybdenum cathode. The bulk volume of experimental tests appearing in this work relates to molybdenum cathodes, however the stainless steel cathodes were also used rather often - they have the lower resource, but are much more easily to be worked and inexpensive.

Figure 5 shows the cathode’s working surface under an optical microscope. The cathode was used together with a ceramic isolator having a hole d = 0.5 mm in diameter. It is seen that a heavily eroded area on the cathode has a diameter of about 0.2 mm. Since the cathode is expected to emit exactly from this area, one can suppose that the diaphragming of the cathode by the isolator decreases the diameter of its working part by 0.3 mm.

When diameter D of the anode hole changes, the I–U characteristic of the discharge remains invariable. However, when ratio D/d decreases to less than 1.5, the discharge becomes very unstable and the maximum attainable voltage sharply drops. The EBG is almost insensitive to ratio D/d up to a value of 7–10. As this ratio grows further, its operation becomes unstable and the maximal voltage also drops. In addition, when diameter D is large, the voltage triggering the EBG rises. Accordingly,
the field strength in the discharge gap decreases since the distance between the working part of the cathode and anode increases.

Figure 6 gives the results of current density measurements for discharge in air with current density being normalized on square of pressure (reduced current density). The 2-nd design version was used with KSP-90 ceramics and with molybdenum cathode, having sizes: \( H = 2 \text{ mm} \), \( d = 0.5 \text{ mm} \), \( D = 3 \text{ mm} \). Curves are obtained for various air pressures: 1 — \( P = 100 \text{ Pa} \); 2 — \( P = 133 \text{ Pa} \); 3 — \( P = 150 \text{ Pa} \); 4 — \( P = 200 \text{ Pa} \); 5 — \( P = 250 \text{ Pa} \), 6 — \( P = 400 \text{ Pa} \).

![Figure 6 - Reduced current density of the EBG vs. the cathode voltage for various air pressures.](image)

Curves 1, 3, 5, and 6 in Fig. 6 were taken with one EBG and in one series of experiments. In this series, the pressure in the vacuum chamber was successively raised starting from 100 Pa (curve 1). Unfortunately, the heavy erosion of the cathode and the fusion and erosion of the ceramic isolator near the working hole after the long-term operation of the EBG do not allow us to argue that measurements were taken under identical conditions even if the EBG was not replaced between measurements.

With the curves 1, 2, 4, and 5, the reduced current density grows with the pressure growth, that is current-pressure dependence is stronger than quadratic. However, the 3 and 6 curves do not correspond to this behavior. If this effect really takes place, it is explained, most likely, by decreasing of diffusion of neutral molecules and ions to dielectric walls of discharge channel and hence by decreasing of cathode diaphragming effect. At the same time, difference between the curves in figure 6 is not too great; the similar diffencies between the curves of various discharge gap geometries were related to errors in preparing and conduction of experiments. For instance, for 1 and 2 curves of figure 6 the discretization behavior is clearly seen at current measurements.

Similar measurements were conducted for water vapor and for the 3 layout of plasma generator, in which isolator between cathode and anode were removed. The results are given on figure 7 in the same units as on figure 6. The sizes are as follows: \( H = 0.23 \text{ mm} \), \( D = 2 \text{ mm} \). The curve 1 corresponds to \( P = 150 \text{ Pa} \); 2 — \( P = 200 \text{ Pa} \); 3 — \( P = 300 \text{ Pa} \); 4 — \( P = 400 \text{ Pa} \).
Figure 8 - Reduced current density of the EBG vs. the cathode voltage for various air and helium pressure.

Figure 8 shows the current density $j_e$ versus cathode voltage for 2-nd layout fabricated of KSP-90 ceramics with the sizes $H = 2$ mm, $d = 0.5$ mm, $D = 3$ mm. The curve 1 measured for helium of 0.5 kPa, pressure with volumetric air content of 2.05%; curve 2 corresponds of operation in helium of 1 kPa, pressure with volumetric air content of 1%; curve 3 — to 1.5 kPa of helium, pressure with volumetric air content of 0.7%; curve 4 — to 2 kPa of helium, pressure with volumetric air content of 0.1%; curve 5 — to 3 kPa of helium, pressure with volumetric air content of 0.04%. The curves 6 and 7 were obtained for air with 150 Pa and 200 Pa respectively.

It is seen than during the operation with the air higher, than with helium that corresponds to difference in the normal current density. Helium with the lowest air content (curve 5) was a minimum reduced current density, as for the rest of helium curves they are placed close to each other no matter what are the pressure air content.

Figure 9 shows the current density $j_e$ versus cathode voltage for 2-nd layout with the sizes $H = 2$ mm, $d = 0.5$ mm, $D = 3$ mm, helium with pressure 2 kPa, cathode fabricated of molybdenum. The curve 1 measured with volumetric air content of 0.2%, the curve 2 - measured with volumetric air content of 2.25%, the curve 3 measured with volumetric air content of 5%, the curve 4 measured with volumetric air content of 0.2%.

Curves 1–3 have a characteristic peak in the voltage interval 3–6 kV. The position of this peak depends on the air content.

Since the ionization potential of helium is high, the cross section of nonresonance charge exchange between helium ions and molecules of other gases may be fairly large. Because of this, the helium discharge is sensitive even to a low impurity content [25]. In addition, metastable helium levels with a relatively high energy considerably increase the probability of impurity molecule ionization due to the Penning effect.

Thus, in the presence of air in helium, a flux of excess (compared with the partial fraction of impurity) nitrogen and oxygen ions will move toward the cathode and the emission factor rises. However, with a rise in the discharge current, the majority of impurity molecules from the discharge gap will be involved in the motion toward the cathode and the fraction of impurity ions bombarding the cathode will decline. Such an effect is expected to result in the appearance of the maximum in the I–U characteristic.

4.2. On efficiency during the generation of runaway electrons

All measurements are performed on installation, the description of which is given in [26]. The diagram of the electron-beam plasma generator during the efficiency measurement using an insulator design is shown in figure 10. The generator consists of: cathode 1, insulator 2, union nut 3, body 4, anode 5.
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%.

**Table 2 – Conditions for conducting the one of series of measurements and the obtained results.**

| № | d, mm | Cathode material | U, kV | \( P_{\text{He}} \), Pa | Efficiency, % |
|---|---|---|---|---|---|
| 1 | 0,5 | LaB₆ | 6,5 | 1504 | 51 |
| 2 | 2,3 | steel | 4,4 | 494 | 54 |
| 3 | 1,0 | LaB₆ | 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 |

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 measurements, 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.

From the comparison of two series of experiments the conclusion can be made that the energetic efficiency of the 3-rd layout in not lower than of the 2-nd one. This conclusion is especially valuable, if to keep in mind that the 3-rd layout has the principal defect, noted earlier – sharpening of electric field along the cathode perimeter, therefore a cathode – anode discharge can develop in this region at the voltages lower than is needed for breakthrough of the cathode – anode gap. The traces of these discharges in this region were regularly observed. Obviously, such discharges should diminish the efficiency, however this is not observed in experiments conducted, that is the parasitic discharges do not play substantial role and this is important for practical use.

The results are in qualitative and quantitative agreement with the available efficiency estimations of the electron beam generation in the open discharge. Here, the values differ essentially from the experimental results based on the supposition that the electron beam formation efficiency is the same as the ratio of the beam current to the total discharge current. This is evidence of the fact that, when measuring the gas-discharge device efficiency, use of more complicated (in implementation) thermal measurement is preferable.

5. Conclusion
The EBG operating in gas medium immediately is a perspective facility for solution of technological problems. Several versions of these EBG designs are proposed. Researches of EBG functioning have been done. The range of values reached and typical characteristics of EBG obtained are as follows:

- Voltage, kV: 1 – 18 (8);
- Current per cell, ma: 1 – 100 (50);
- Power per cell, W: 1 – 1000 (400);
- Anode hole diameter, mm: 0,4 – 3;
- Cell diameter, mm: 18;
- Depth of working area, mm: 2 – 5 (2);
- Cathode material: LaB6, Mo, Cu, sLaB6, Mo, Cu, stainless steel;
- Sort of gas: air, helium, water vapor, argon, xenon;
- Pressure, Pa: 90 – 3000 (1500, helium);
- Time of continuous operation, hr: more than 8;
- Energetic efficiency, %: 50 – 80 (75).

The energetic efficiency is the most important characteristics of technological EBG. For its evaluation, measurements of EBG body temperature were accomplished during prolonged EBG operation and during its subsequent cooling. The measurements of efficiency with forming of runaway electron beams were conducted for various gases (air, helium, water vapor, argon, xenon) at various pressures and for various cathode materials.

References
[1] Ivanov I G, Latush E L and Sem M F 1990 Ion lasers on Metal Vapors Moscow Energatomizdat.
[2] Bokhan P A and Sorokin A R, Zh. Tekh. Fiz. 55(1), 88 (1985)
[3] Azarov A V, Mit’ko S V and Ochkin V N Generator of electron beam. Patent of RF No 2172573.
[4] Rocca J J, Meyer J D, Farell M R and Collins G J 1984 Glow-discharge-created electron beams: Cathode materials, electron gun design, and technological applications J. Appl. Phys. 56 (3) 790-7.
[5] Tyunkov A V, Yushkov Yu G, Zolotukhin D B and Savkin K P 2014 Generation of magnesium ions using fore-vacuum plasma electron source Proc. of Tomsk State University of Control Systems and Radioelectronics 4(34) 60-2
[6] Burdovitsin V A, Oks E M, Skrobov E V, Yushkov Yu G 2011 Ceramic surface modification by pulse electron beam, generated by fore-vacuum plasma source Inorganic Materials: Applied Research 6 77-82.

[7] Zav’yalov M A, Kreindel Y E, Novikov A A and Shanturin L P 1989 Plasma Processes in Technological Electron Guns Moscow Energoatomizdat)

[8] Muratov E A, Rakhimov A T and Suetin N V 2004 Technical Physics 49 (5), 638.

[9] Bokhan P and Zakrevsky D 2002 High-efficiency electron beam generation in an open discharge without anode grid Technical Physics Letters 28 73-8.

[10] Kovalev A S, Mankelevich Yu A, Muratov E A, Rakhimov A T and Suetin N V 1992 J. Vac. Sci. Technol. 10, 1086.

[11] Golovin A I and Shloydo A I 2016 Modern electron beam generators for technological applications (a review) Advances in Applied Physics 4 (5) 439-48

[12] Koroteev A S and Rizakhanov R N, 2010 Plasma Phys. Rep. 36, 1173.

[13] Bodakin L V, Gusakov A I, Komarov O V, Kosogorov S L, Motovilov S A and Uspenskii N A 2016 Application of aluminum and titanium foils in low-energy wide-aperture electron accelerators Technical Physics 61 (9) 1404-10.

[14] Tarasenko V F 2014 Runaway Electrons Preionized Diffuse Discharges New York Nova Science Publishers.

[15] Kazanskii N L and Kolpakov V A 2003 Komp’yut. Opt., 25, 112.

[16] Zinchenko S P, Kevtun A P and Tolmachev G N 2014 Tech. Phys. Lett. 40, 21.

[17] Sorokin A R 2006 Electron beam formation in an anomalous glow discharge Technical Physics 51 580-8

[18] Kolpakov V A, Kolpakov A I and Podlipnov V V, 2013 Tech. Phys. 58, 505.

[19] Bel’skaya E V, Bokhan P A and Zakrevskii D E 2008 Tech. Phys. 53, 1091.

[20] Golovin A I, Turkin A V, Shloydo A I 2014 Electron beam generator based on runaway of electrons out of high-voltage glow discharge XLI Zvenigorod Int. Conf. on Plasma Physics and Controlled Fusion ed L M Kovrizhnykh and V E Fortov (Zvenigorod) 49

[21] Bobrov V A, Voiteshonok V S, Golovin A I, Golubev M M, Turkin A V and Shloido A I 2014 Electron beam generation RF Patent 2535622.

[22] Golovin A I, Golubev M M, Egorova E K, Turkin A V and Shloydo A I 2014 Dependence of electron beam generation in an open discharge on the discharge gap configuration and gas pressure Technical Physics 59 (5), 670-4.

[23] Hayden H C and Utterback N G 1964 Ionization of helium, neon, and nitrogen by helium atoms Phys. Rev. 135 (6A) 1575-9.

[24] Sorokin A R 2000 Tech. Phys. Lett. 26, 1114.

[25] Bogdanov E A, Kapustin K D, Kudryavtsev A A, Kirillov A A, Simonchik L V, Zgirousski S M 2010 XXXVII Zvenigorod Int. Conf. on Plasma Physics and Controlled Fusion ed L M Kovrizhnykh and V E Fortov (Zvenigorod)

[26] Voiteshonok V S, Golovin A I, Egorova E K, Lomakin B N, Turkin A V and Shloydo A I 2017 Experimental investigation of high-voltage glow discharge efficiency as a source of beams of run-away electrons High Temp. 55 1–8