A 120-kV electron welding gun with plasma cathode: vacuum and non-vacuum application

N G Rempe

1 Elion Ltd., ul. Sadovaya, 17, 634510, Tomsk, Russia
Tomsk State University of Control Systems and Radioelectronics, 40 Lenina Prospect, 634050, Tomsk, Russia
E-mail: remnik77@gmail.com

Abstract. The article studies the generation of small-diameter focused electron beams using electron-optical system of a welding gun with plasma cathode. The results show that the beams always form in the electron-optical system with plasma cathode when the gas in the region of beam emission, acceleration and transportation is present. The presence of the gas causes positive volumetric charge formation during the passage of electrons. This charge electrically neutralizes the beam, and in some cases can lead to overcompensation of its electron charge. The compensation of the volumetric charge in the region of beam formation and acceleration is the principal discrepancy of an electron-optical system with plasma cathode from a thermal cathode system. It is demonstrated that the brightness of the electron beam from a plasma cathode gun meets that of the beams from a thermal cathode gun. The paper describes the electron gun featuring voltage up to 120 kV and presents images of polished samples of weld penetration in stainless steel and titanium in vacuum. The gun served as the basis of a device for ejecting electron beam into the atmosphere. It is shown that the pressure rise up to the atmospheric one is provided through two gas-dynamic stages. The main characteristics of the atmospheric gun are given.

1. Introduction
Currently, plasma cathode electron guns are widely studied and implemented in practice to generate electron beams with various parameters. Electron beams produced by plasma guns can be used virtually in all modern electron-beam technologies, such as welding, cladding, material modification, etc. [1–4]. The guns are constantly enhanced; new information about their peculiarities and practical application regularly comes out.

The most complex to investigate and improve, from our perspective, are guns generating focused electron beams with high brightness. Such beams can be used in both traditional technologies and new fields that have been rapidly developing over the recent years. They first of all include additive technologies [2] and non-vacuum application that requires ejecting beam into a pressurized gas through a reliable and inexpensive system.

Such guns require much effort to investigate, because in addition to studying plasma as electron emitter, specific attention should be paid to the processes of beam formation [2–7]. Often, such studies are performed to achieve parameters that were already obtained by guns with solid state cathode. The primitive transfer of design principles from thermal cathode guns to plasma cathode guns is impossible.
This study exhibits the results obtained over the last several years of investigation on the specificities of the electron-optical system with plasma cathode aimed at formation of focused small-diameter electron beams.

2. Electron-optical system of guns with plasma cathode

Despite a vast diversity of plasma cathode guns available, focused electron beams can be produced only by using a limited range of discharge types. These include discharges with hollow cathode, high-voltage glowing discharge and some other [1]. Moreover, plasma beam industrial technologies implement plasma cathode guns of only one type based on reflective discharge with hollow cathode [3–7].

The electrons in an electron-optical system based on reflective discharge with hollow cathode are captured into the accelerating gap from the plasma surface. Plasma is generated in a discharge chamber schematized in Figure 1. The discharge chamber includes hollow cathode 1, anode 2 and emitter cathode 4 with a hole along its axis. Permanent magnet 3 creates a magnetic field to initiate and preserve stable discharge in the chamber. In the stationary regime, the discharge chamber contains plasma with nonuniform concentration distribution which maximum corresponds to the axial region of the discharge. In an electron-optical system with plasma cathode, four typical regions can be distinguished: region of primary beam formation, acceleration region (accelerating gap), transportation region (drift space), focusing region (focusing system).

![Figure 1. Scheme of discharge chamber of plasma cathode gun: 1) hollow cathode; 2) cylindrical anode; 3) permanent magnet; 4) emitter electrode.](image1)

The region of initial formation of the electron beam includes emitting surface of plasma 1 (Figure 2) and electric field near this surface. The emitting surface of plasma can form both in the cylindric channel inside emitter electrode 2 of the discharge chamber and outside of it.

The accelerating region (Figure 2) is the region between electrodes 2 and 4 where high-voltage electric field is concentrated which strength determines the electron energy in beam 6.

The transportation region (drift space) is an equipotential space between accelerating electrode 4 and electron collector (welded part) 7.

![Figure 2. Electron-optical system with plasma cathode: 1) emitting surface of plasma; 2) emitter electrode; 3) crossover; 4) accelerating electrode; 5) focusing system; 6) electron beam; 7) electron collector; d is the accelerating gap; a is the distance from the crossover to the focusing system; b is the distance from the focusing lens to the electron collector.](image2)
Focusing region, as a rule, is a part of transportation region where the magnetic field of focusing system 5 is localized.

Plasma, as an electron emitter, has a number of peculiarities that make difference between an electron-optical system with plasma cathode and a system with solid state cathode. The shape and position of the surface are not fixed and depend on plasma concentration, strength and shape of the electric field, pressure and type of gas and other factors [1]. When the electric field strength changes, the emitting surface displaces. The displacement continues until the equality of the electrostatic field pressure and gas-kinetic pressure of plasma.

The displacement of the emitting surface can determine the type of emission parameters and electron-optical characteristics of the electron gun. This is why the development of plasma guns requires measures for stabilizing the emission surface of plasma. Typically, the parameters of electron gun are chosen for the emitting surface to be localized in the channel [6,7]. The emission channel sets the lateral dimensions of the emitting surface and limits the penetration of the electric field into the discharge chamber from the side of the accelerating gap.

According to the experimental results, the velocity distribution of the main fraction of electrons emitted from plasma can be considered to be similar to the Maxwell distribution. The electron temperature—depending on the discharge parameters and type—can amount to 5–15 eV [1,2], which is considerably higher than the temperature of thermoelectrons. It was believed that obtaining fine-focused beams in such beams is complicated due to high temperature of electrons in plasma. However, there is a range of factors specific for plasma cathode which action can have additional effect on focusing. One of such factors is permanence of gas in the acceleration region and electron drift space.

3. Gas in electron-optical system with plasma cathode

The plasma cathode guns are specific due to the necessity of certain gas pressure in the vicinity of plasma emitter, which in majority of cases is higher than that in the working chamber. A pressure of plasma gas in the discharge chamber is about 5·10⁻² torr. Such pressure is provided by controlled gas puffing with a rate of 10–20 cm³ atm/hr. The puffed gas, as a rule, is evacuated through the accelerating gap.

Electron emission from plasma occurs through the hole in the cathode in the discharge chamber into the region of the accelerating field between the cathode and grounded high-voltage anode (extractor), as shown in Figure 3. The figure shows the pressure distribution in the accelerating gap for constant pressure in the vacuum chamber of 10⁻³ torr during gas puffing into the discharge chamber with a rate of 10 cm³ atm/hr. Pressure distribution in the region of electron beam generation was modeled in ANSYS software.

The pressure distribution (Figure 4) in the accelerating gap of the plasma cathode gun was calculated for different combinations of the rate of gas puffing into the discharge chamber and pressure in the vacuum chamber. The distributions demonstrate that pressure gradient is always present in the accelerating gap. Near the emission channel and inside of it, the pressure can exceed that in the vacuum chamber by 1–2 orders of magnitude. This means that the formation of electron beam in
plasma cathode gun occurs in appreciably different conditions from those of thermal cathode guns. In the accelerating gap, along with accelerated electrons, plasma electrons and ions constantly present that can substantially affect the motion of fast electrons in the beam.

**Figure 4.** Distribution of electrons (1), ions (2) and volumetric charge (3) on the axis of the accelerating gap.

Figure 4 presents axial (along coordinate z) distribution of electrons, ions born due to ionization and spatial charge in the accelerating gap. In calculations, the gap was filled with nitrogen with pressure distribution corresponding to dependence 1 in Figure 5. The maximum of electron distribution (dependence 1) corresponds to the position of the electron beam crossover that—according to the calculations—is localized in the acceleration space. The electron current density in the crossover is maximum. Following the calculations, the ion concentration is also maximum here (dependence 2) and is comparable with that of electrons. The equality of concentrations of electrons and ions in the region of crossover neutralizes the beam charge (dependence 3). In the remaining part of the calculation domain to the left and to the right of the crossover, the total charge is positive. Hence, the volumetric charge of the electron beam here is overcompensated. The simplest explanation exists for the overcompensation effect in the region to the right of the crossover. This region has the conditions for ion accumulation. These conditions express in low mobility of ions because they reside in the equipotential space.

The distributions demonstrate that gas ionizes along the whole accelerating gap. The majority of ions escape along the field into the region of plasma boundary. The ion current into plasma does not exceed 1% of the electron beam current for all pressure distributions in the accelerating gap and is maximum for conditions that correspond to the pressure distribution as per dependence 2 (Figure 4).

The probability of ionization is known to drop with increasing electron energy. This means that the main contribution to gas ionization and formation of ion current is made by electrons with low energy that corresponds to the maximum of the ionization function. Such conditions are created for electrons emitted from plasma near the emission surface. Gas flow from the discharge chamber leads to the formation of the increased pressure region localized in the accelerating gap near the emission channel. Therefore, the presence of gas in the accelerating gap of the plasma cathode gun causes the formation of positive volumetric ion charge after electron beam passage. This charge can not only electrically neutralize the beam, but in certain cases overcompensate its electron charge. The compensation of the volumetric charge in the region of beam formation and acceleration is the principal discrepancy of an electron-optical system with plasma cathode from a thermal cathode system. The compensation affects
the electron trajectories of the beam, while the overcompensation can facilitate additional ion focusing of the beam. Beam overcompensation in the thermal cathode gun is also possible, but only in the drift space after electron beam passage in residual gases and vapors of metals from heated or melted metal. Thus, we can state that higher pressure in the accelerating gap and plasma cathode gun in the majority of cases promotes its higher quality.

This statement was checked by measurements made elsewhere [2]. The brightness of the electron beam was assessed by measuring the diameter and gun beam convergence angle at accelerating voltage of 60 kV and distance of more than 0.5 meters from the focusing lens.

To assess the brightness of the electron beam with Gauss law of current distribution along the section, the following expression was used:

\[ B = \frac{i_b}{\pi^2 \cdot r_f^2 \cdot \theta^2} \]

where \( i_b \) is beam current; \( r_f \) is the effective radius of beam in the focal spot, \( \theta \) is convergence angle.

To measure the effective radius of beam and convergence angle, a measurement system was used developed by TWI Ltd. (Cambridge, UK). The measurements demonstrated that the brightness of the electron beam in plasma cathode guns is about \( 1 \cdot 10^{10} \, \text{A} \cdot \text{m}^{-2} \cdot \text{sr}^{-1} \), which corresponds to the brightness of electron beams generated by thermal cathode guns with LaB\(_6\) cathode [2].

4. Vacuum electron gun with high beam brightness.

The results of the study were used to design the plasma cathode gun schematically presented in Figure 6. The discharge forms in the discharge cell formed by inner surfaces of a hollow cathode 2, cylindrical anode 3 and emitter cathode 1 (Figure 6, highlighted region). Between the hollow and emitter cathodes an axially symmetric field is created by a permanent magnet, the field possessing induction on the axis of about 0.1 T. The discharge sustains continuously with the current from 0.1 to 1.5 A, which allows generating electron beam with the current from several to some hundreds of mA. Electron emission from plasma occurs through the hole in the emitter cathode in the discharge chamber into the region of the accelerating field between the cathode and grounded extractor. The electron beam formed in the accelerating gap is focused by the field of electromagnetic lens 4 and transported by beam guide 6 to the welded part.

The gun body has pipe 5 with ISO100-KF flange enabling connection of a turbomolecular pump. The turbomolecular pump can evacuate the accelerating gap and beam guide 6 of the gun.

The gun forms an electron beam with an energy of up to 120 keV and power of up to 24 kW.
Welding capability of the gun was assessed by weld penetration of specimens from various metals. Figure 7 depicts polished weld penetrated specimens from AISI 321 stainless steel (a) and VT14 titanium (b). The weld penetrations were made with a power of the electron beam of 12 kW for stainless steel and 6 kW for titanium. The working distance (from the focusing lens to the specimens) was 300 and 670 mm. The beam was focused on the part surface. For the same rates of the welding manipulator moving rate, the shape and depth of penetrations made for different distances differed negligibly. The presented specimens are characterized by narrow and deep penetration profile with parallel walls, which is characteristic of the electron beam with an electron beam with small convergence angle.

Figure 7. Polished weld penetrated specimens from AISI 321 stainless steel (a) and VT14 titanium (b).

5. Non-vacuum electron-beam system based on plasma cathode gun

The implementation of plasma as a source of electrons allows largely reducing the requirements to residual atmosphere in the region of initial formation and acceleration of an electron beam. An electron beam can be generated by a plasma cathode gun under a pressure 2–3 orders of magnitude higher than that of thermal cathode guns. According to the above, higher pressure in the accelerating gap and plasma cathode gun in the majority of cases promotes its higher quality. The noted specificity allows assuming that plasma cathode guns can turn out to be effective both for vacuum applications and as a component of non-vacuum (atmospheric) electron-beam systems. Such work was accomplished in [7, 8]. The beam was transported into the atmosphere through gasdynamic windows enabling step-wise increase of gas pressure up to atmospheric one. A scheme consisting of two windows was chosen and studied. Figure 8 shows the model of electron beam ejecting into the atmosphere obtained primarily by calculation methods. The ejection device is designed in a way that the accelerating gap of the gun (region between the emitter cathode surface and extractor) and beam guide separated by the extractor make up the second stage. The stages are counted starting from the atmosphere.

The beam guide tapers at the exit; the small taper base faces the first stage and transits into elongated cylindrical channel 3 with a length of 10 mm and diameter of 2.5 mm.

Figure 8. Three-dimensional model of the device ejecting electron beam into the atmosphere: 1) beam guide, 2) first-stage evacuation pipe, 3) second-stage diaphragm, 4) first-stage diaphragm, 5) cross-jet.
In the transportation channel, the electron beam is focused by the magnetic field in the plane of first-stage output diaphragm 4. The second stage is evacuated by a turbomolecular pump with a production rate of 800 l/s (nitrogen). The first stage has a 2-mm output diaphragm which ejects the electron beam immediately into the region with atmospheric pressure. The stage is evacuated with the rate of 500 l/s through pipe 2 by a Roots vacuum pump. In the first stage, there is a channel to create a cross-jet located in perpendicular to the output diaphragm axis.

The gun with the output device was mounted on a robot (Figure 9) that was performing welding, cutting and cladding in the atmosphere. The characteristics of equipment are presented in Table.

| Parameter                              | Value        |
|----------------------------------------|--------------|
| Accelerating voltage [kV]              | 120          |
| Electron beam current [mA]             | 1-200        |
| Number of evacuation stages            | 2            |
| Pressure drop [torr]                   | from 5·10⁻⁴ to 760 |
| Coefficient of current passage, not less [%] | 86        |
| Working distance in atmosphere [mm]    | 5-15         |

Preliminary experiments on metal welding at atmospheric gas pressure were carried out. The welding joint was made between two 6-mm plates (from copper and aluminum) with 80 foils between them with average thickness of 15 μm each (terminals of accumulator batteries). The welding of such joint by electron beam with an energy of 120 keV and power of 4 kW (for copper terminal) and 2 kW (for aluminum terminal) was performed over 30 seconds. The length of the welding seam was 280 mm. The studies have demonstrated high mechanical strength of the joint. However, the presence of pores and defects in the joint disallowed recommending the technology for welding metal parts for vacuum-tight applications.

6. Conclusions
The presented characteristics in combination with the level of development of plasma cathode electron guns allow using them in the majority of traditional electron-beam vacuum technologies, in newly elaborated thermal processes (for instance, non-vacuum ones), in scientific experiments and other applications.

References
[1] Zavyalov M.A., Kreindel Yu.E., Novikov A.A. and Shanturin L.P., 1989 *Plasma processes in technological electronic guns*. Moscow: Energoatomizdat, 256 p.
[2] Hassel T, Rempe N, Kornilov S, Beniaysh A, 2012 Welding and Cutting, V. 11, No. 2, P. 122-127.
[3] Kornilov S, Rempe N, Beniaysh A, Murray N, Hassel T and Ribton C, 2013 Technical Physics Letters, V. 39, № 10, P. 843-846.
[4] Osipov I and Rempe N, 2000 Review of Scientific Instruments, V.71, №4, V.1638–41.
[5] Galansky V.L., Gruzdev V.A., Osipov I.V., Rempe N.G, 1992 Russian Physics Journal, V. 35, № 5, P. 28-33.
[6] Kornilov S, Rempe N, 15th International Symposium on High Current Electronics: Proceedings. Tomsk: Publishing house of the IAO SB RAS. 19-24 September 2010, P. 76-79.
[7] Kornilov S and Rempe N, 2012 Technical Physics, V. 57, No. 2, P. 236-241.
[8] Aksenov A, Kornilov C, Motorin M and Rempe N, 2017 Instruments and Experimental Techniques, V. 60, No 2, P. 233-236.
[9] Borovik V, Shatravin V, Kornilov S, Rempe N, Junusov I, Shidlovskiy S and Shashev D, 2016 MATEC Web of Conferences 7. Cep. "7th Scientific Conference with International Participation "Information-Measuring Equipment and Technologies", IME and T 2016", Article number 01034.