

Overview of the Gas Discharge Gun: Physical Foundations, Applications and Prospects

V. I. Trokhymchuk,  [0009-0006-3388-4115](https://orcid.org/0009-0006-3388-4115)

S. B. Tugay, PhD, Assoc. Prof.,  [0009-0006-3388-4115](https://orcid.org/0009-0006-3388-4115)

Department of Electronic Devices and Systems
Faculty of Electronics

National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"  [00syn5v21](https://www.researchgate.net/publication/368005921)
Kyiv, Ukraine

Abstract – Pulsed gas-discharge guns are promising tools in modern electron beam processing technologies. These devices operate on the basis of a high-voltage glow discharge (HVGD) and are capable of generating high-power electron beams. The article provides an overview of existing gun designs, examines the physical processes of plasma formation and beam focusing, and describes the influence of design features on operational stability and thermal load. Special attention is paid to the influence of the working gas type on beam characteristics, the technological capabilities of the device, and prospects for improving discharge current control. The principles of constructing automated beam parameter control schemes that ensure stability in the pulsed mode are considered. Examples of practical applications of guns based on HVGD are provided.

Keywords: gas discharge gun; high-voltage glow discharge (HVGD); electron beam; triode system; electrode system (cathode–anode); plasma processing; pulsed operation mode; vacuum technology; electron beam control system; electron-beam processing.

I. INTRODUCTION

Gas-discharge electron guns belong to a class of vacuum devices that provide the formation of powerful electron beams for technological and scientific applications. Their operation is based on the physical processes of a high-voltage glow discharge, which creates plasma with a sufficient concentration of charged particles for stable electron generation under low-pressure conditions [1].

A notable advantage of such guns is the possibility of using a cold cathode, which significantly simplifies the design and increases the durability of the device. The pulsed mode of operation allows achieving peak powers of hundreds of kilowatts with low average power consumption, making such systems energy-efficient and technologically attractive [2].

Over the past decades, gas discharge guns have undergone significant evolution: from laboratory experimental models to industrial systems with wide beam control capabilities, stable operation, and adaptability to specific technological processes. Their applications include electron beam melting and cleaning of materials, deposition of thin and multilayer coatings, high-precision welding, surface modification, and additive technologies [2].

However, despite the evolution of these devices from laboratory models to industrial systems, there is a lack of comprehensive analysis regarding their stability in high-frequency pulsed modes required for modern applications, such as additive manufacturing. The objective of this paper is to analyze the physical foundations of HVGD guns, classify their design variations, and present experimental results on the implementation of a low-inertia pulsed control system. Specifically, this study focuses on addressing the stability challenges in triode systems and demonstrating the efficiency of cold cathodes in various gas environments.

II. MATERIALS AND METHODS

A. Physical foundations of high-voltage glow discharge and electron beam formation

High-voltage glow discharge (HVGD) occurs under conditions of low gas pressure ($10^{-3} \dots 10^{-1}$), when electrons accelerated by an electric field reach energies sufficient to ionize gas molecules present in the discharge gap. In this case, the plasma density is maintained at a level that prevents the transition to an arc discharge, ensuring a stable high-voltage glow discharge mode with controllable parameters [4].



In a gas discharge gun capable of operating in pulse mode, the electron beam is formed in a triode system consisting of a cathode, a control electrode, and an anode. Plasma ions accelerated in the cathode potential drop bombard the cathode surface and induce secondary electron emission. The formed electron flow is directed towards the anode, passes through the plasma zone, which acts as an electron-optical lens, and forms a focused beam [5].

Studies of the electron-optical properties of triode guns have shown that the position of the anode plasma boundary significantly affects the beam geometry. Control of these parameters allows obtaining a beam diameter from tenths of a millimeter to several millimeters, a convergence angle in the range from 1° to 10° , and a power density of up to 10^6 W/cm² [6].

B. Gas discharge gun designs

Typical designs include diode and triode cold cathode guns, providing high durability and ease of operation. The main elements of the design are the cathode, anode, discharge chamber, working gas supply system, and magnetic elements for beam focusing and deflection.

Cathode materials are usually chosen taking into account high emission capacity and structural feasibility. Aluminum alloys are commonly used because aluminum is strong, forms thin oxide films with a high coefficient of secondary ion-electron emission, is widely available, and is easy to machine. To improve individual gun parameters or ensure the purity of processed materials, cathodes made of other metals (such as titanium) or compounds (lanthanum hexaboride) can be used.

The geometry of the electrodes determines the focusing parameters and the maximum specific power of the gun. The gas supply system controls the pressure in the discharge gap and, accordingly, the plasma density, which allows regulating the electron beam power as required by specific technological requirements.

Modern gas-discharge guns cover a wide range of technological applications. Based on their power and accelerating voltage, they can be classified into three main categories:

- Melting and Evaporation Guns: High-power systems (e.g., BTP-100, BTP-300, BTP-450 models) operating at powers up to 450 kW and voltages of 30-40 kV. These guns are designed for high-rate evaporation of refractory metals (Ti, Zr, Ta) and melting in vacuum arc remelting (VAR) furnaces [14].
- Welding Guns: Precision systems operating at higher accelerating voltages (60 kV and above) to ensure deep penetration. They typically

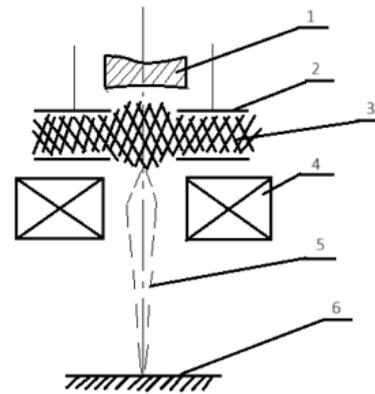


Fig. 1 Gun model based on HVGD (1 - cold cathode; 2 - anode; 3 - plasma; 4 - magnetic lens; 5 - electron beam; 6 - sample.)



Fig. 2 Gas-discharge electron beam guns (left to right) BTP-100 (100kW), BTP-300 (300kW), BTP-450 (450kW) [14]



Fig. 3 A gas-discharge electron gun (cold cathode, housing with focusing modules) [8]

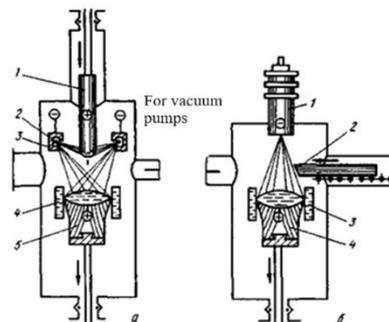


Fig. 4 Diagram of an electron beam metallurgical plant [9]: a – with a ring cathode (1-material, 2 – ring cathode, 3 – screen, 4 – water-cooled crystallizer, 5 – drawn ingot); b – with axial gun (1 – axial gun, 2 – remelted metal, 3 – water-cooled mold, 4 – drawn ingot)

require a vacuum level of approximately 10^{-2} Pa to minimize beam scattering.

- Coating and Surface Modification Guns: Medium-power systems (10-60 kW) optimized for operation in reactive gas environments (1-10 Pa). These are widely used for depositing nitride or oxide coatings.

The operational stability of these guns is typically maintained within $\pm 1\%$ current deviation using feedback loops that regulate gas pressure and discharge voltage.

C. Implementation of pulsed operation mode

In electron beam technology processes, stationary heating by an electron beam is traditionally used. However, the pulsed mode of operation offers significant advantages, including increased thermal efficiency, reduction of heat-affected zones, and the implementation of precision processing modes. Despite these benefits, the widespread adoption

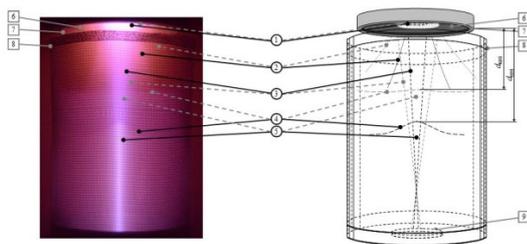


Fig. 5 Photo and schematic representation of the discharge gap of the HVGD electron gun model with a triode electrode system in pulsed operation mode [3]: 1 – cathode emission zone in pause (—) and pulse (- - -); 2 – ion flux to the cathode in pause (—) and pulse (- - -); 3 – electron beam in pause (—) and pulse (- - -); 4 – plasma boundary on the cathode side in pause (—) and pulse (- - -); 5 – beam plasma in pause (—) and pulse (- - -); 6 – cathode; 7 – anode; 8 – cylindrical electrode of the auxiliary control discharge; 9 – hole for the electron beam output

of pulsed electron beam methods has been limited by the complexity of equipment capable of stable operation [3].

Based on the analysis of physical processes in HVGD, it is shown that the pulsed mode can be effectively implemented in triode gas-discharge guns using a low-inertia electrical control method. In such systems, an auxiliary low-voltage non-self-sustained discharge is ignited within the main HVGD volume when a potential (ranging from tens to hundreds of volts) is applied to the control electrode [3].

Changing the control electrode potential modulates the anode plasma density, which directly regulates the ion flux to the cathode and, consequently, the electron beam current. The time constant for this control is determined by the inertia of plasma processes in the anode region, which is typically in the range of milliseconds. This allows for relatively simple pulse modulation by applying pulses of a specific duration and amplitude to the auxiliary electrode, with control voltages several orders of magnitude lower than the main discharge voltage [3].

Thus, using electrically controlled HVGD triode guns allows for pulsed operation without significant complication of the high-voltage power supply.

To validate the theoretical approaches described above, an experimental study of the pulsed operation mode was conducted. This mode allows significantly increasing the peak power of the electron beam without overheating the electrodes, which is especially important when processing heat-sensitive materials.

In the specific experimental setup developed for this study, capacitive energy storage devices were used to generate pulses. Unlike inductive systems that provide smoother pulses, capacitive systems create short pulses with a sharp current front. The mode is controlled by high-speed switching elements (IGBT transistors or thyristors), which guarantees process stability [3].

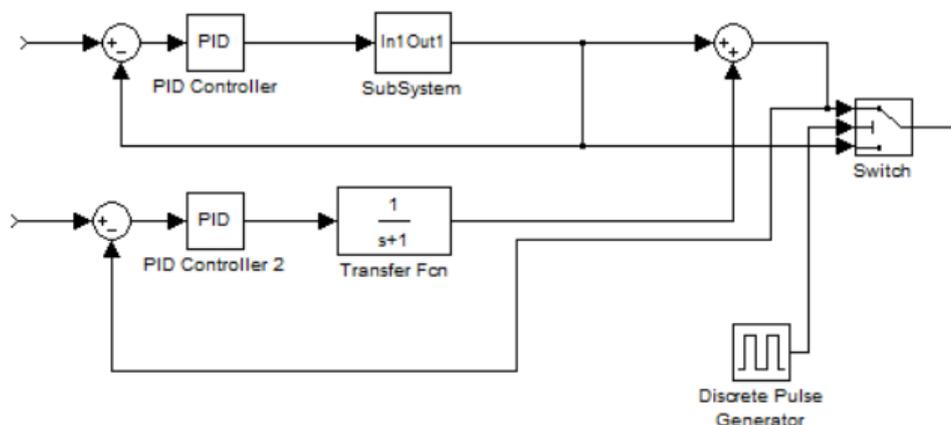


Fig. 6 Scheme of a pulsed two-channel control system [4]



The key advantages of the implemented pulsed mode include:

1. Reduction of average heat load – critical for extending the life of cathodes and the vacuum chamber equipment.
2. Increased peak power – achieving levels several times higher than in continuous mode, with the same average power consumption.
3. Controllability of beam parameters – the ability to flexibly change the duration, frequency, and amplitude of pulses depending on technological requirements.
4. Increased secondary emission efficiency – achieved by reducing the exposure time of the cathode surface to the continuous flux of working gas ions and fast neutral particles.

In the experimental guns tested within this work, the pulse mode was implemented using large-capacity capacitive accumulators (up to 1000 μF) and high-voltage switches. This configuration enabled the formation of pulses with the following parameters:

- Voltage: 20-40 kV;
- Pulse Duration: 50-200 μs ;
- Frequency: Up to 200 Hz.

The experimental results confirmed that this configuration allows achieving peak powers of over 200 kW with an average thermal power of only 10-15 kW [10].

The dual-circuit system stabilizes current via gas pressure and adjusts amplitude via electrode potential, enabling precise pulses up to 750 mA (10 kW, 1 kHz) [4].

III. RESULTS AND DISCUSSION

A. Features of working with different gases

The gas environment in which a gas-discharge electron gun operates is one of the key factors determining the stability of operation, the energy characteristics of the electron beam and the final result of material processing. The choice of the working gas affects the discharge parameters, ionization potential, the degree of thermal load on the electrodes, as well as the chemical interaction with the surface being processed. Each gas has unique physicochemical properties that determine the specifics of the processes occurring in the discharge gap.

A critical advantage of HVGD guns with cold cathodes - often overlooked in standard reviews - is their unique ability to operate stably in chemically active gas environments. Standard thermionic guns (hot cathodes) degrade rapidly in oxygen or nitrogen atmospheres due to filament oxidation and poisoning. In contrast, cold

aluminum cathodes in HVGD guns are resistant to these gases and even benefit from them.

- Nitrogen Atmosphere: Used for depositing hard nitride coatings (e.g., TiN, AlN). The plasma generated by the gun facilitates the chemical reaction between the evaporated metal and the gas directly at the substrate surface.
- Oxygen Atmosphere: Employed for oxide deposition (Al_2O_3 , SiO_2). The oxide film formed on the aluminum cathode surface during operation actually sustains the secondary ion-electron emission mechanism, making the gun self-sustaining and robust in oxidizing environments [7].
- Hydrogen: Due to its lowest molecular weight and high thermal conductivity, hydrogen is used mainly in processes where it is necessary to minimize oxide formation. It actively reduces oxides, ensuring a clean surface during welding. However, working with hydrogen requires strict safety measures due to its explosive nature [7].
- Helium: This is the most widely used gas due to its inertness, high thermal conductivity, and stability. It ensures long electrode life and does not interact with materials. Helium provides stable discharge combustion at low pressures and excellent beam focusing.

The discharge plasma in HVGD guns acts not only as an electron source but also as a catalyst for plasma-chemical reactions. This enables Ion-Assisted Deposition (IAD), where the substrate is simultaneously bombarded by the electron beam and ions from the gun's plasma. This ion bombardment improves the stoichiometry, density, and adhesion of the deposited films, which is impossible to achieve with conventional vacuum evaporation. These features make HVGD guns superior tools for reactive evaporation and hybrid plasma-beam technologies used in the optical and protective coating industries [6].

Among the working gases for gas discharge guns, helium has received the most widespread application, which is due to its inertness, high thermal conductivity and stability of the electrical characteristics of the discharge. Due to the lack of chemical activity, helium does not interact with the materials of the electrodes, ensuring their long service life. Its use contributes to the formation of a uniform and stable electron beam, and also reduces the risk of contamination of the working chamber with reaction products. Helium also provides more stable combustion of the glow discharge at low pressures, which is critical for precise control of the parameters of the electron beam.



Compared to hydrogen, helium has no explosive properties, which significantly simplifies the operating conditions of the gun and increases overall safety. In addition, its high ionization potential contributes to the formation of plasma with better focusing characteristics, which directly affects the quality of sample surface treatment and reduces the risk of local overheating.

In general, the choice of working gas is always determined by the specific technological task. For welding processes, the key is to achieve maximum beam stability and minimal influence of the gas environment on the chemical composition of the weld metal, therefore, preference is given to inert gases.

B. Development prospects

Further development of gas-discharge electron gun technologies is driven by scientific and technical tasks aimed at increasing efficiency, reliability, and versatility. Modern trends in industrial material processing, microelectronics, and instrument-making require equipment capable of operating with high accuracy in difficult conditions with minimal energy consumption.

One of the priority areas is miniaturization, which allows the use of gas-discharge guns in micro- and nanoprocessing for forming ultra-thin structures and modifying biomedical implants [11]. Special attention is paid to introducing new cathode and anode materials, such as high-temperature alloys and carbon composites, to increase operating life.

The integration of digital control systems provides adaptive regulation of pulse parameters in real-time. Additionally, combining gas discharge guns with other energy sources (laser, microwave) is promising for achieving high precision and efficiency [11].

In the medium term, it is expected to introduce automated modules based on gas discharge guns, integrated into robotic production complexes. This will allow for continuous processing of materials on an industrial scale with high accuracy and minimal operator involvement. The combination of compactness, energy efficiency and versatility makes gas discharge guns a promising tool for high-tech production, in particular in the aerospace, medical and electronics industries [11].

Further development gas-discharge electron guns is closely related to the expansion of their application in additive technologies, particularly in 3D-printing metal, where highly precise local thermal effects are required with minimal heat spread to adjacent areas. Research shows that gas discharge guns can be effectively integrated into wire-based additive manufacturing systems. The works have proven that special configurations of such guns are capable of creating profile electron beams at relatively low voltages (10-30 kV), providing controlled melting of wire and substrate [12].

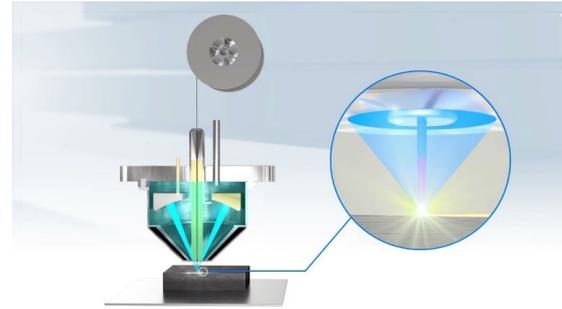


Fig. 7 3D metal printing [14]

The main technical challenges of this technology include synchronizing the wire feed with the beam energy profile, precise thermal control to avoid overheating, electrode wear in a metal vapor environment, and the need for adaptive control of the modes during the process of building up the printed part material. However, the experimental results confirm that with proper regulation of the parameters, it is possible to achieve a homogeneous microstructure and satisfactory mechanical properties of the finished samples [13].

CONCLUSION

As a result of analyzing the modern state of existing and promising HVGD electron beam gun designs, physical principles of operation, and their application areas, the following conclusions can be drawn:

1. Significant Progress: Significant scientific and technical results have been achieved in the field of high-voltage glow discharge guns, allowing their use across the entire spectrum of electron beam technologies.
2. Design Advantages: HVGD guns possess distinctive advantages over traditional hot-cathode systems due to the relative simplicity of their design, low cost of consumables, resistance to reactive working gases, and the ability to work in medium and low vacuum conditions.
3. Key Applications: Promising application areas include the remelting of metals and alloys, reactive coating deposition, precision welding, and additive technologies.
4. Control Systems: The application of modern digital automatic control systems, which manage discharge current by controlling gas pressure and electrode potential, effectively maintains beam energy parameters, ensuring stable and flexible operation in pulsed modes.
5. Experimental Validation: Theoretical and practical studies presented in this work confirm that the proposed control model for triode guns

with a cold cathode successfully implements a pulsed operation mode (up to 200 kW peak

power) that meets the rigorous requirements of modern electron-beam technologies [4, 15].

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Огляд газорозрядної гармати: фізичні основи, застосування та перспективи

В. І. Трохимчук,  [0009-0006-3388-4115](https://orcid.org/0009-0006-3388-4115)

С. Б. Тугай, канд. техн. наук, доц.,  [0009-0006-3388-4115](https://orcid.org/0009-0006-3388-4115)

Кафедра електронних пристроїв та систем

Факультет Електроніки

Національний технічний університет України

"Київський політехнічний інститут імені Ігоря Сікорського"  [00syn5v21](https://doi.org/10.20535/2523-4455.me.341617)

Київ, Україна

Анотація—Імпульсні газорозрядні гармати є перспективними інструментами в сучасних технологіях електронно-променевої обробки. Ці пристрої працюють на основі високовольтного тліючого розряду (ВТР) і здатні генерувати потужні електронні пучки. У статті наведено огляд існуючих конструкцій гармат, розглянуто фізичні процеси формування плазми та фокусування пучка, а також описано вплив конструктивних особливостей на стабільність роботи та теплове навантаження. Особливу увагу приділено впливу типу робочого газу на характеристики пучка, технологічним можливостям пристрою та перспективам удосконалення керування струмом розряду. Розглянуто принципи побудови автоматизованих схем керування параметрами пучка, що забезпечують стабільність в імпульсному режимі. Наведено приклади практичного застосування гармат на основі ВТР.

Ключові слова: газорозрядна гармата; високовольтний тліючий розряд (HVGD); електронний промінь; тріодна система; електродна система (катод-анод); плазмова обробка; імпульсний режим роботи; вакуумна технологія; система керування електронним променем; електронно-променева обробка.

