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Plasma Cathode Electron Sources

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Preface

Charged-particle emission is an important fundamental characteristic of plasma. Interest in this phenomenon stems from the feasibility of charged-particle sources spanning a wide range of parameters and functional capabilities. The use of a so-called plasma cathode or plasma electron emitter for electron-beam formation is compelling only when the advantages of this approach for a specific application essentially negate the more commonly employed thermionic cathode approach.

Plasma electron sources can produce greater emission current density, are capable of pulsed beam generation, can operate over a wide range of background gas pressure, and are only weakly dependent on the residual vacuum conditions. The advantages of plasma cathodes are most conspicuous in circumstances where a hot cathode cannot provide the required electron-beam parameters due to limited emissivity, particularly in pulsed mode or when operated at high pressures and in the presence of corrosive media. An important feature of the plasma cathode is that essentially all electrons in the discharge gap can be extracted from the plasma, leading to the high efficiency that is typical of electron-beam sources of this kind.

A shortcoming of plasma electron sources is the relatively high plasma electron temperature, which increases the beam emittance and limits the maximum beam brightness. However, compared to hot cathodes, a plasma-cathode electron source produces a much higher electron-beam current density, allowing, in many cases, considerable reduction or even elimination of the adverse effect of elevated temperature on beam emittance.

The advantageous features of plasma-cathode electron sources make them attractive for various applications such as electron-beam welding and powder cladding, modification of material surface properties, generation of electromagnetic radiation, plasma chemical and radiation technologies, etc.

Research in plasma emission and the development of efficient plasma electron sources constitute an application of the applied physics of low-temperature plasmas – plasma emission electronics. Advances in plasma emission electronics as a new scientific field are intimately linked with the name of its founder – Professor Yuli Efimovich Kreindel, Laureate of the State Prize of the Russian Federation in Physics and Technology. Kreindel pioneered the study of electron emission from the plasma of low-pressure discharges in the former Soviet

Union. Thorough investigations of the emission characteristics of low-temperature plasmas have led to an understanding of the physical mechanisms responsible for plasma electron emission and to the development of efficient methods of stabilizing and controlling the plasma beam characteristics. Following this pioneering work, a wide range of plasma electron sources with unique parameters and various functional capabilities have been made and investigated. Highly efficient plasma cathodes can also be used in plasma ion sources. It should be noted that the parameters of ion or electron beams extracted from plasmas carry information about the physical processes occurring in the plasma, permitting these approaches to be used for studies of fundamental processes occurring in low-pressure discharge plasmas.

In 1977, a remarkable book, *Plasma Electron Sources* by Yu. E. Kreindel, was published [1], presenting a review in this area of plasma emission electronics for the first time. Later, in 1989, *Plasma Processes in Technological Electron Guns* was published [2], with contributions from several authors. The problems and promises of the development of plasma emission electronics have been addressed in various collections of articles [3–5], reviews papers [6–10], and the *Proceedings of the First All-Union Conference on Plasma Emission Electronics* [11]. The formation of large-cross-section electron beams, including those produced in plasma-cathode systems, is discussed in [12]. Research and development of plasma-cathode electron sources has been largely, but not exclusively, a Russian/Soviet Union endeavor. The emphasis on the Russian literature that the reader will notice throughout this book is not due to limited vision but reflects the historical development of the field. Of foreign researchers in this area, we recognize in particular the work of our American colleagues S. Humphries Jr., D. Goebel, and A. Hershcovitch, as well as Professor Ya. Krasik in Israel.

This monograph provides an up-to-date overview of an important subfield of applied plasma physics. It is a review of the current status of plasma emission electronics and its development since the publication of the last monograph on the subject in 1989 [2]. The text concentrates equally on providing physical understanding of the basic processes involved in plasma electron emission and on considering the design and applications of plasma-cathode electron-beam sources. The book will be of interest to designers of electron sources as well as to scientists and engineers who use electron beams in research and industry. The text will also be of benefit to both undergraduate and postgraduate students involved with vacuum and plasma electronics, the generation of charged-particle beams, and their applications.

The book consists of five chapters. The first chapter describes the types of plasma discharges that are most frequently used in plasma-cathode electron sources. These are the hollow-cathode glow discharge, discharges in crossed electric and magnetic fields, such as Penning- and magnetron-type discharges, the constricted low-pressure arc discharge, and the vacuum arc with cathode spots, all of which require no hot electrodes for their operation. The peculiarities of each of these discharge types are discussed, and their characteristics and parameters given.

In the second chapter, emphasis is on the general problems of plasma electron emission, including the principles of stabilization of plasma emission parameters and methods of controlling the electron-beam current. The same chapter reports on the results of studies of electron-beam extraction from plasma at fore-vacuum pressures and considers the characteristics of electron beams formed from nonstationary plasmas.

In the third and fourth chapters, the design of a number of different kinds of plasma electron sources and their characteristics are presented. In particular, the third chapter focuses on sources of axially symmetric (cylindrical and narrow-focused) electron beams, and the fourth chapter is concerned with sources of large-cross-section electron beams, including ribbon beams.

Finally, the fifth chapter considers some of the most typical areas of application of plasma-cathode electron sources.

This book cannot provide a complete coverage of all related work and all relevant source designs known to date, and therefore in a number of cases the reader will find a limited number of references to the appropriate papers. The choice of one or another publication for representation was in many ways dictated by my own preference, and I apologize in advance to colleagues whose work has not been covered in full measure in this book.

After publication of this book in Russian [13], various additions as well as corrections of misprints were made in this English version. For the convenience of the reader, most of the references to articles in the Russian journals have been replaced by their translated sources published in the West, such as *Russian Physics Journal*, *Instruments and Experimental Techniques*, *Technical Physics* and many others.

I am indebted to my Russian-to-English translators, Tatiana Cherkashina and Anna Korovina, as well as to Ekaterina Chudinova, who provided great help in preparing the book for publication. Special thanks go to Ian Brown, my co-author of many years (work related to the investigation of vacuum-arc ion sources) and very good friend, for “forcing” me to write this book, and also for his careful reading of the manuscript and useful advice and comments. This input has provided me with a truly invaluable aid in approaching the subject matter.

It is my great honor to dedicate this work to Professor Yu.E. Kreindel, my first supervisor and scientific father.

Tomsk, May 2006

Efim M. Oks

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1

Low-Pressure Discharges for Plasma Electron Sources

Two conflicting requirements occur in the design of *plasma-cathode* electron sources, both of which need to be met simultaneously. In order to ensure the required *emission current* density, adequate *plasma density* must be attained, for which efficient ionization in the plasma near the *emission boundary* must be provided. On the other hand, accelerating the *electron beam* to the required energy calls for the application of high voltage in the region of electron-beam formation and acceleration; this in turn necessitates decreasing the ionization processes that can cause *breakdown* within the *acceleration gap*. High electric field in the acceleration gap is needed to provide the electron energy, but this same high field can cause breakdown in the gap. This problem can be solved by establishing a pressure difference between the *plasma generation region* and the *electron extraction region*. This is possible, however, only for the case of a relatively small plasma emission surface area, e.g., for small-area focused electron beams. For large-cross-section electron beams or electron beams generated at fore-vacuum pressures, it is difficult or almost impossible to produce such a pressure difference. In this case the choice of an appropriate discharge system that is capable of providing conditions for efficient generation of electrons in the plasma and their stable extraction is likely to be the only way for successful operation of a plasma-cathode electron source.

The discharge employed in plasma-cathode electron sources must provide generation of dense plasma in the region of electron extraction, at the lowest possible pressure. From this standpoint the most suitable kinds of plasma sources are the hollow-cathode glow discharge, discharges in crossed electric and magnetic fields, such as Penning or cylindrical magnetron discharges, the constricted arc discharge, and the vacuum arc. Note that for most plasma cathodes, two different discharge systems are combined into a single device. For instance, one of the discharges (the main discharge) is used to produce the emissive plasma and the other (the auxiliary discharge) is employed to initiate and sustain the main discharge. Let us briefly consider the peculiarities of each of the discharge systems that are most commonly employed in plasma-cathode electron sources.

1.1

Hollow-Cathode Discharge

The *hollow-cathode discharge* [1] is widely used in various plasma devices, including plasma electron sources. A characteristic feature of this kind of discharge is the oscillation of fast electrons emitted from the inner walls of the cathode cavity and accelerated into the cathode sheath. Unlike reflex discharges in *crossed electric and magnetic fields* where electrons are confined by the magnetic field (see Section 1.2), in the hollow-cathode glow discharge the fast electrons reside within the plasma for a long period of time, being repeatedly reflected in the cathode fall region [2, 3]. There are a number of different hollow-cathode configurations that can provide *electron oscillation*. In plasma electron sources, the *cathode cavity* is normally a hollow cylinder with a central hole in one of its faces (see Fig. 1.1). The characteristic dimensions of the cavity vary from several millimeters to tens of centimeters, depending on the required plasma emission parameters. The optimal ratio of the cavity length l_{cav} to the cavity diameter d_{cav} lies in the range $l_{\text{cav}}/d_{\text{cav}} \approx 7\text{--}10$. The diameter of the hole in the open face of the cavity d_o is typically several times smaller than d_{cav} . *Electrostatic confinement* of electrons in the cathode cavity is responsible for the so-called *hollow-cathode effect*, which shows itself as an abrupt decrease in *discharge operating voltage* and an increase in *discharge current* (see Fig. 1.2), and as an extension of the *operating pressure range* toward lower pressures. Note that the hollow-cathode effect occurs only when the electron mean free path exceeds the characteristic dimensions of the cathode cavity. The type of hollow-cathode discharge is determined by the mechanism of *electron emission* from the cathode surface. In this connection, one can distinguish arc discharges with cold and hot hollow cathodes [4], including a *self-heating* cathode [5, 58, 59], and also high-voltage [6] and low-voltage hollow-cathode glow discharges [12, 57].

A low-voltage discharge with a “cold” hollow cathode is rather easily produced; it is characterized by time stability [7] and spatial uniformity [8] of the plasma parameters. This kind of discharge is quite commonly employed for producing

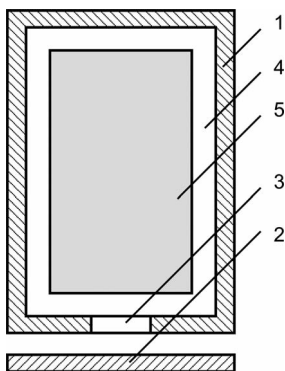


Fig. 1.1 Electrode assembly of the hollow-cathode discharge: 1 – cathode; 2 – anode; 3 – hole; 4 – cathode sheath; 5 – plasma.

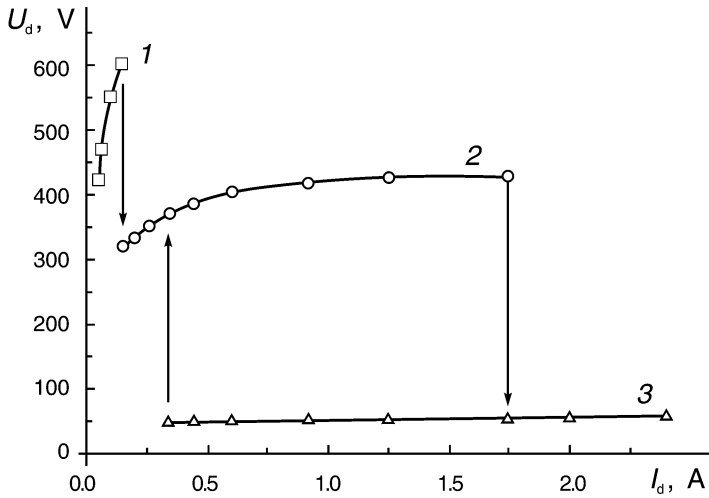


Fig. 1.2 Current–voltage characteristic of the hollow-cathode discharge in different regions of its existence [57]:
 1 – glow discharge in the absence of the hollow-cathode effect; 2 – hollow-cathode glow discharge; 3 – cold-cathode arc with cathode spots.

plasmas in plasma-cathode electron sources. Under steady-state conditions, the discharge current I_d in such systems is, as a rule, no greater than 1 A at a discharge operating voltage $U_d=400\text{--}600$ V, yet it can be increased by about an order of magnitude provided that the formation of cathode spots is precluded [9].

In pulsed mode, it is possible to realize a diffuse form of a hollow-cathode discharge in the microsecond range with a current of hundreds of amperes [10]. In this kind of discharge, the plasma electron temperature T_e is generally several electronvolts. The plasma density n_e is determined by the discharge current density to the cathode (from several milliamperes to several amperes per square centimeter) and typically lies in the range $n_e \sim 10^{10}\text{--}10^{13}$ cm $^{-3}$.

In studies of the low-voltage hollow-cathode discharge [11], the suggestion was made that *UV radiation* from the *bulk plasma* may result in additional electron emission from the cathode surface. However, the authors [12] came to recognize that *photoelectron emission* can be of only secondary importance. They also suggested that the main factor responsible for the development of the hollow-cathode effect is multiplication of electrons in the cathode potential fall region. The contribution from this factor becomes less significant with increasing discharge current and decreasing operating pressure, when the thickness of the cathode fall region decreases compared to the dimensions of the cathode cavity, and the electron mean free path λ_e becomes much greater than the characteristic width of the discharge gap.

The thickness of the cathode sheath (region of potential fall at the cathode) l_s can be determined by solving simultaneously the well-known *Child-Langmuir* and *Bohm equations* [13]:

$$l_s \approx (\epsilon_0/n_i)^{1/2}(U_c)^{3/4}/(ekT_e)^{1/4}. \quad (1.1)$$

Here e is the electron charge, U_c is the cathode fall potential, n_i is the plasma ion density, and T_e is the electron temperature.

The uniformity of the ion current density distribution over the hollow-cathode surface depends on both the cathode geometry and the operating pressure. In a long and narrow cathode cavity, the plasma density, and hence also the ion current density to the cathode, increases as the exit aperture facing the anode is approached [14]. The discharge system geometry considerably affects the conditions under which the discharge plasma is generated, and consequently the discharge parameters [15, 16]. For efficient oscillation of fast electrons, one should either decrease the exit aperture of the cathode cavity or increase the cathode dimensions. It was shown in [17] that decreasing the ratio of the exit aperture area S_a (in most cases equal to anode area) to the area of the inner surface S_c of the cathode, S_a/S_c , significantly decreases the lower limit to the operating pressure. Moreover, the operating pressure p in this region is directly proportional to S_a/S_c . As S_a/S_c is reduced, the discharge operating voltage rises steeply in response to the decrease in pressure. At a specified operating voltage, the lower limiting pressure and the operating pressure also show an abrupt increase, and a double electrostatic sheath across which $U_s=10\text{--}40$ V is formed in the region of the exit aperture.

Since the cathode cavity is an *electrostatic trap* for *fast electrons* which, oscillating chaotically, can escape only through the exit aperture, the energy of a primary electron expended in ionization depends on the ratio A/L . (Here A is the relaxation length of the electron: the average distance over which its initial energy decreases to the ionization potential U_i of the working gas, and L is the average distance traversed by an electron inside the cathode cavity before it leaves through the aperture.) For the case where the energy lost by a fast electron is determined only by inelastic collisions with gas molecules, A is approximately equal to the *ionization relaxation length* A_i , which, according to [17], is estimated as

$$A_i = (U_c/U_i)\lambda_i, \quad (1.2)$$

where λ_i is the mean free path of the electron between two successive ionization events. For $S_a/S_c \ll 1$, the spatial distribution of primary electrons is near-uniform and isotropic. Under these conditions, the S_a/S_c dependence of L can be obtained assuming the oscillating primary electrons to move with equal probability toward all parts of the cathode surface. It has been shown [17] by the use of expressions for the probability of an electron leaving the cavity and for the average length of a single electron transit that

$$L = 4V/S_a, \quad (1.3)$$

where V is the volume of the cathode cavity.

For a hollow-cathode glow discharge, the energy of a primary *fast electron* in the operating pressure range is determined by the *cathode fall* potential, which depends on the ratio of the area of the exit aperture to the area of the inner surface of the cathode. The fast electron energy is fully expended in ionization in the cathode cavity only for the case where $A < L$. At pressures approaching the lower limiting pressure ($\sim 5 \times 10^{-2}$ Pa), the *electron mean free path* at an energy of 300–600 eV is ~ 2 m, which is 10–100 times greater than the commonly used cathode cavity diameters. Consequently, the loss of *primary electrons* due to their absorption by the cathode surface does not affect the discharge parameters, whereas electron losses through the exit aperture of the cavity are critical [15–17]. As the exit aperture of the cathode cavity is reduced, an electrostatic *double sheath* may form in the region of the exit aperture where the potential jump is localized. The criterion for the formation of this sheath follows from the equality of the discharge cathode current and anode current [17]. The author of [17] assumed the anode, of rather large surface area, to be negatively charged with respect to the plasma. In this case, the potential difference that results in electron reflection vanishes for $S_a/S_c \approx (m_e/M_i)^{1/2}$. As the ratio S_a/S_c is further decreased, the condition for current passage in the discharge can be fulfilled only if a double sheath with a surface area greater than S_a is formed inside the cathode cavity in the region of the exit aperture. The electrons accelerated in the double sheath are focused and, passing through the (small) exit aperture, ensure equality of the current through the aperture to the anode and the cathode current. Thus the condition for the formation of a double sheath in the region of the exit aperture of the cathode cavity takes the form [17]

$$S_a/S_c < (m_e/M_i)^{1/2}. \quad (1.4)$$

Condition (1.4) agrees well with the experimental data for argon reported in [17], where it is demonstrated that with an optimal ratio S_a/S_c a glow discharge can exist in the high-current (2 mA cm^{-2}) low-voltage (below 1000 V) form at pressures of up to 0.03 Pa.

Thus a decrease in S_a/S_c has a beneficial effect on the parameters of the hollow-cathode discharge, involving a decrease in operating voltage and in lower limiting pressure (see Fig. 1.3), only to the point determined by inequality (1.4). Further decrease of this ratio leads to the reverse effect because of the electrostatic double sheath formed in the anode region of the discharge.

For the optimal operating conditions of a hollow-cathode discharge, the lifetime of the electrons is sufficient for them to lose almost all their energy in ionization. Nevertheless, with a magnetic field produced in the cathode region, the discharge operating voltage decreases by 100–150 V [12, 18]. This clearly indicates that the addition of a magnetic field to the hollow-cathode configuration leads to enhanced ionization in the plasma. A drop in discharge operating volt-

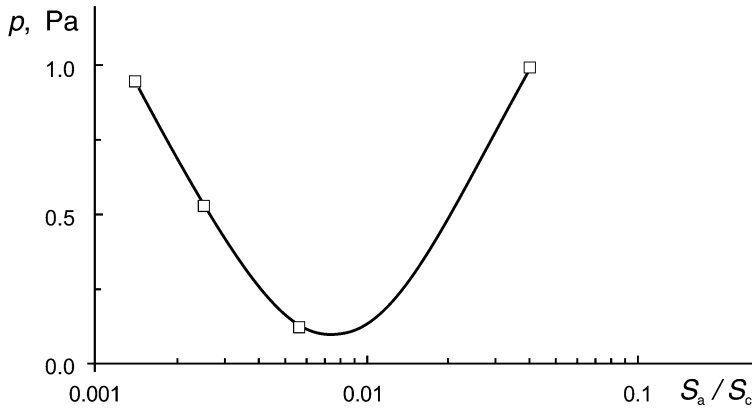


Fig. 1.3 Operating pressure of a hollow-cathode glow discharge versus the ratio of the area of the exit aperture to the area of the inner surface of the cathode [17]. Operating discharge voltage: 600 V.

age in this case is accompanied by fluctuations of the ion current density to a probe. The frequency of these fluctuations lies in the range 5–50 kHz, increasing with increasing magnetic field [18, 19]. The influence of a magnetic field on the operation of a hollow-cathode discharge may be associated with *collective instabilities* arising in the plasma [19]. However, this problem calls for further investigations.

In conclusion, it should be noted that, despite the wide use of the hollow-cathode glow discharge in plasma electron sources, the operating pressure of this type of discharge is somewhat higher than the pressure required for stable electron emission from the plasma. Therefore, a reduction of the operating pressure of a hollow-cathode discharge and its operating voltage is still an urgent problem whose solution is critical for the development of plasma-cathode electron sources based on this kind of discharge.

A number of other aspects of the operation of hollow-cathode discharges as applied to their use in plasma electron sources are considered in [20–23, 43–52].

1.2

Discharges in Crossed Electric and Magnetic Fields

Penning- [24] and *magnetron-type* [25] *discharges* qualify as glow discharges in crossed $E \times B$ fields. These types of discharge are well known and widely employed in various gas discharge devices (ion pumps, gas discharge pressure gauges, ion sources, sputtering systems, etc.). Although the electrode systems of Penning and magnetron discharges are different, the conditions for plasma generation and current passage are so much alike that they can be treated as two kinds of one and the same discharge in a magnetic field. Discharges in crossed