Low-Voltage Discharge with a Self-Heating Hollow Cathode for Charged Particle Sources and Plasma Generators [1]

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Abstract – A new design of self-heating hollow cathode has been studied. Such hollow cathode operates with lower gas flow rates than conventional cathode and has a longer lifetime as well. So that the ignition of the discharge should be possible under low gas flow we have added to our hollow cathode design an igniting unit.

1. Introduction

Resent interest in the self-heating (or heat-insulated) cathode stems from the feasibility of an efficient steady-state high-current low-pressure discharge [1, 2]. The distinctive property of a self-heating-cathode discharge is a possibility to establish conditions wherein the plasma ions accelerated in the cathode potential fall region heat the cathode to thermoemission temperatures. As this takes place, the discharge operates self-consistently in the diffuse form at a considerably lower operating voltage and displays more uniform current distribution over the cathode surface. These factors provide a higher energy efficiency of the discharge chamber and lengthen the lifetime of the cathode.

A self-heating cathode can be made in the form of a rod [3, 4] or a hollow tube [5, 6]. In terms of the use in charged particle sources and plasma generators, a discharge system with a self-heating hollow cathode appears to be more preferable. In this case, the problem of heat insulation of the cathode is much easier to solve and the currents required of the discharge to pass into a stable self-heating mode are vastly smaller, compared to a rod cathode.

For any design of the self-heating cathode, the key problem is to realize the operating mode of the discharge. In a hollow-cathode system, the simplest way of switching the discharge to the self-heating mode is to heat the cavity by plasma ions [7]. However, this way is only seemingly simple, since the current and the pressure needed to realize the discharge in this case are relatively high. This problem can be solved in part by preheating the cathode up to the thermoemission temperatures [8]. However, this method complicates the device as a whole and decreases its energy efficiency.

The objective of this work was to realize and study the stable operation of a discharge with a self-heating hollow cathode whose parameters allow its efficient use as an alternative for "ordinary" hot cathodes employed in Bernas-type ion sources [9]. The self-heating hollow cathode can be used as well for additional electron emission in devices based on cold-electrode low-pressure discharges. The discharge system in question has two basic features. One of them is an auxiliary discharge over the ceramics surface which provides generation of plasma of density sufficient to initiate a hollow-cathode discharge at relatively low pressures corresponding to the operating pressure range of the above sources. The second peculiarity is that the fixed end of the hollow cathode with the holder, rather than the free (unfixed) end (as is the case with traditional discharge systems of this type), faces the anode (Fig. 1).

2. Experimental setup

Figure 1 shows schematically the experimental mockup of the discharge system with a self-heating hollow cathode. Hollow anode 1 was made in the form of a cylindrical glass of diameter 50 mm with a ∅5-mm hole at the bottom and was electrically insulated from the cathode unit by ceramic insulator 2. The cathode unit was a cavity of diameter 12 mm and length 27 mm into which trigger electrode 8 separated from the cathode cavity by ceramic insulator 9 was inserted at one of the faces. At the other face, the cavity was bridged with titanium holder 5, into which tantalum tube 6 was pressed. This tube was just the self-heating hollow cathode. The tube was flushed with the holder face presented to the anode. The distance from the end of the tube 6 to the face surface of the anode was several millimeters. The tube length was normally 24 mm and its inner and outer diameters were -2.3 mm and 3.2 mm, respectively. We also used tantalum tubes of outer diameter 4 mm. In the experiments, a possibility was provided to vary the tube wall thickness. In some experiments, a niobium tube with an outer diameter of 4 mm was employed. All the electrodes of the discharges system, other than the titanium holder and tantalum tube, were made of stainless steel.

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Water-cooled ring Sm-Co magnets produced a magnetic field of up to 0.1 T in the internal cavity of the cathode unit. The working gas was supplied directly into the internal cavity. The experimental mockup was mounted on the flange of the vacuum chamber which was preliminary pumped close to 10^{-6} Torr by a turbomolecular pump.

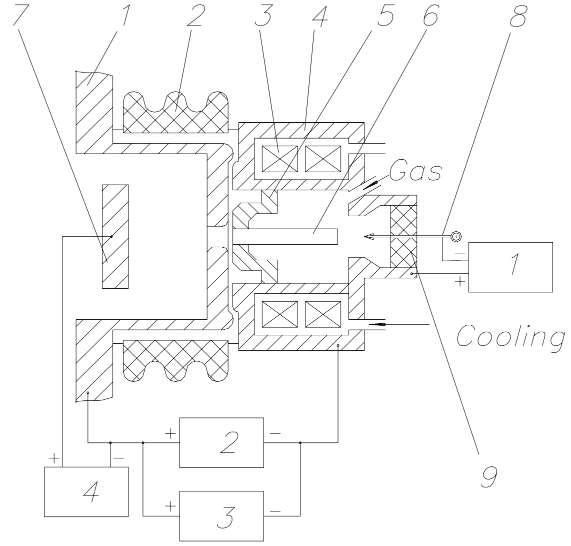

Fig. 1. Discharge system with a self-heating hollow cathode: 1 – hollow anode, 2 – ceramic insulator, 3 – ring Sm-Co magnets, 4 – case, 5 – holder, 6 – tantalum tube, 7 – electron collector, 8 – trigger electrode, 9 – ceramic. The power supply: 1 – discharge trigger unit, 2 – power supply of the hollow-cathode glow discharge, 3 – power supply of the self-heating discharge, 4 – power supply for electron extraction

Figure 1 is also illustrative of the principle of the source operation. A voltage from power supply 2 (500 V, 5 A) was applied between the anode and the cathode. On application of a trigger pulse from power supply 1 (5 kV, 30 A, 30 μs), a surface discharge occurred over ceramics 9 between the trigger electrode 8 and case 4. The thus produced plasma filled the internal cavity and reached the anode vie the tube 6. The penetrating plasma of the auxiliary discharge initiated a glow discharge between the anode 1 and cathode cavity 4. The operating voltage of this discharge was of the order of 300 V and its current ranged to over 0.5 A. The magnetic field present in the discharge gap led to sever radial inhomogeneity of the plasma density distribution with the maximum lying on the system axis, and the necessity of completing the discharge current through the tube insert governed the formation of a double electric layer. Ions from the glow discharge plasma were accelerated in the double layer and, bombarding the tube 6, ensured its heating. With the parameters of the glow discharge realized in the experiment, the tube was heated to the thermoemission temperature in a few second. When the conditions for efficient thermoemission were attained, the discharge switched to the self-heating mode of operation, which showed up as an abrupt decrease in discharge operating voltage. The degree to which the voltage drops depends on the material of the cathode tube 6 and on the pressure and kind of the working gas and is no greater than several tens of volts. The stable operation of the discharge in the self-heating mode is possible only when the voltage drop involves a corresponding increase in discharge current. In the experiment, this was attained with the use of additional discharge power supply 3 (see Fig.1) which provided the required discharge current (up to 10 A) at relatively low discharge operating voltage.

3. Experimental results

Figure 2 shows the operating voltage of the self-heating hollow-cathode discharge versus the pressure of the working gas (argon) for different cathode tubes. In the experiments, the discharge current was kept constant and was 8.5 A. It can be seen in this figure that the discharge operating voltage for the niobium cathode is lower than that for the tantalum cathode. An increase in pressure causes the operating voltage to decrease. The smaller the cathode tube diameter, the more pronounced this effect is.

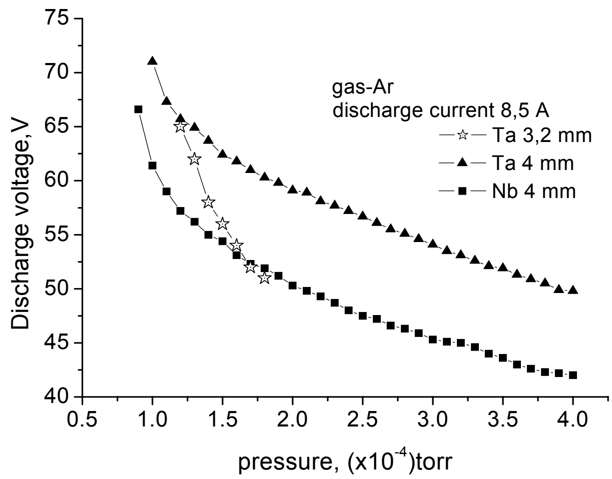

Fig.2. Voltage across the discharge gap versus the pressure in the vacuum chamber

The decrease in operating voltage is associated not only with an increase in the efficiency of ionization processes, but also with a shift of the so-called "active" zone to the fixed end of the tube. The active zone is a region inside the self-heating hollow cathode in which the temperature reaches values sufficient for thermoemission to occur. The shift of the active zone reduces the length of the current-carrying plasma region inside the tube and, hence, decreases the voltage drop across this internal region. The same effect is observed with decreasing inner diameter of the cathode.

Figure 3 shows current-voltage characteristics of the discharge at a constant Ar pressure of $1.8x10^{-4}$ Torr. As we might expect, a discharge of this type features a descending current-voltage characteristic in the range of relatively small currents. Note that it is possible to realize the stable operation of the self-heating hollow-cathode discharge with a current higher than 10 A. The form of a current-voltage characteristic depends largely on the discharge parameters, such as the pressure, the radius of the cathode tube, the flow rate of the plasma-forming gas, the magnetic field, and also the discharge chamber geometry.

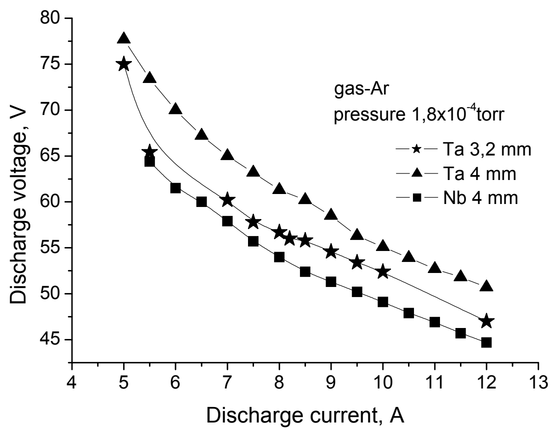

Fig. 3. Current-voltage characteristic of the discharge for different materials and diameters of the tube

Figure 4 shows current-voltage characteristics for a tantalum tube of diameter 3.2.mm at different pressures in the discharge chamber. Note that the current-voltage characteristic assumes radically different forms at different pressures. From the very beginning of the research on hollow cathode arcs it was noticed that the location of the maximum wall temperature moved farther from the open tip of the cathode when the gas-flow rate was reduced, increasing the cathode inside diameter for a given flow rate yields the same result. It is felt therefore, that the neutral gas pressure inside the cathode channel probably would be the determining parameter for the location of the maximum wall temperature. The pressure varies along the cathode channel due to the gas flowing through and the maximum temperature would occur at a distance where this pressure reaches an "optimum" value depending on the exact experimental condition [5].

At low pressures and at certain discharge currents, when the slop of the current-voltage characteristic is positive, the increase in discharge currents initially involves high-frequency modulation which increases in amplitude and is added with low-frequency modulation as the discharge current is further increased. Low-frequency modulation is an abrupt decrease in current to a certain value or to zero with its subsequent rise within 40 μs. A similar pattern was observed when the flow rate of the working gas was decreased at a constant discharge current.

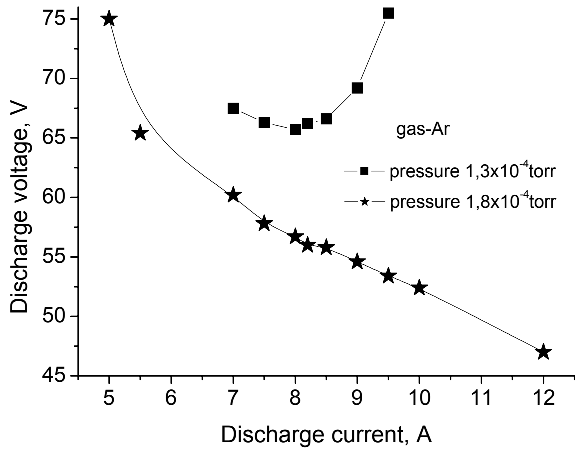

Fig. 4. Current-voltage characteristic of the discharge for different pressures in the vacuum chamber

3. Conclusion

The results of studies are unambiguously indicative of the promise held by a self-heating hollow cathode as a possible alternative for hot cathodes employed in discharge systems of ion sources and plasma generators. The use of an auxiliary surface discharge as the initiation system allows decreasing the operating pressure required for stable transition and operation of the self-heating hollow-cathode discharge. Despite the progress made in this work, further investigation needs to be conducted to accomplish the final goal.

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