

# High-voltage discharge in supersonic jet of plumbum vapor

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**Abstract.** During study of vacuum discharge in plumbum evaporating from molybdenum crucible in identical geometry of discharge gap and the same crucible temperature existence of two different discharge forms were observed. These two forms are vacuum arc with current above 10 A and voltage about 15 V and high-voltage discharge with current about 10 mA and voltage of 340 V. Plumbum was placed in heat-isolated crucible (cathode). Electron-beam heater was situated under the crucible. At the temperature of 1.25 kK that corresponds to plumbum saturated vapor pressure about 0.1 kPa voltage from power source (380 V, 200 A) was applied to anode and high-voltage discharge initiated with characteristics mentioned above. After a few seconds this discharge could turn into arc or could exist hundreds of seconds until total plumbum evaporation. Glow of discharge could take the form of a cone, harness or plasma bunch that hanged at the appreciable distance from the electrodes. The estimations of plasma parameters are presented.

## 1. Introduction

During the experiments with vacuum discharge in vapor of plumbum cathode at the same temperature and geometry of discharge gap the existence of two differ discharge forms was established. These two forms are a low-current discharge (LCD) with current about 10 mA and voltage  $U = 340$  V and vacuum arc with current about 20 A and voltage about  $U = 15$  V. Study of LCD is presented in this paper.

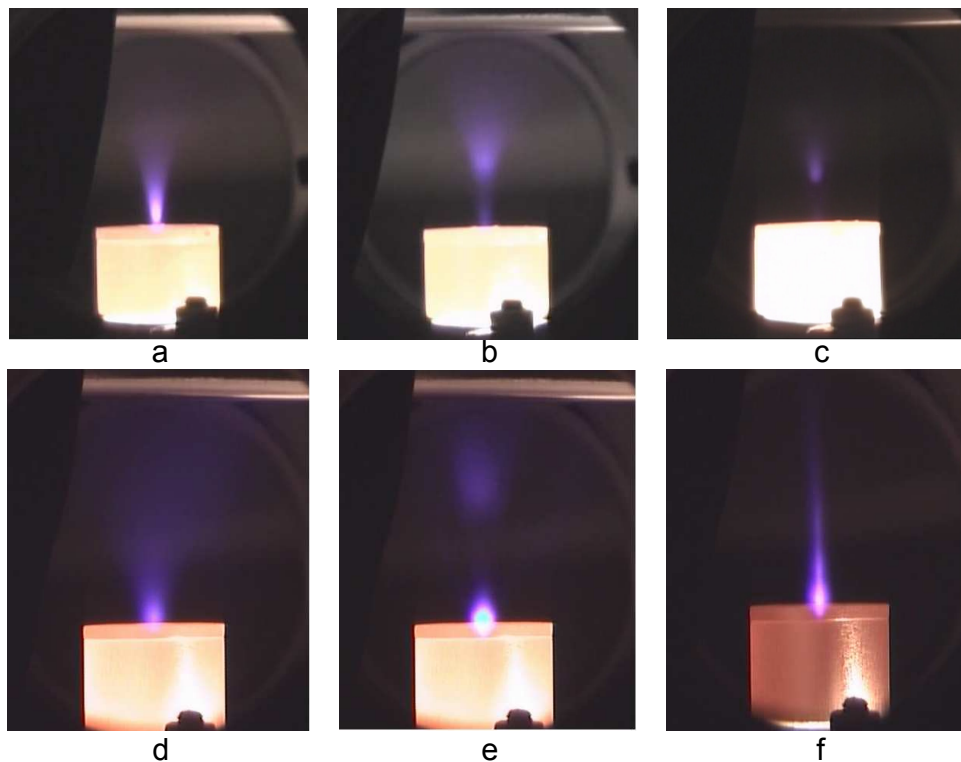
The discharge was initiated in vacuum chamber with residual gas pressures less than 10 mPa. Plumbum (Pb) with mass about 15 g was placed in molybdenum heat-insulated crucible (cathode) with external diameter 25 mm. Surface area of liquid Pb taking into account the meniscus was 3–5 cm<sup>2</sup>. The crucible was covered by molybdenum cap that has 6 mm hole. By estimations, it allowed us to decrease Pb evaporation rate approximately in five times. Electron-beam heater (EBH) was situated under the crucible. The water-cooled steel disc with central hole of 15 mm in diameter was used as the anode. The distance between electrodes was about 30 mm. Crucible temperature  $T_c$  was measured by brightness pyrometer. By estimations the difference between measured temperature and mean temperature of Pb surface due to temperature drop in crucible wall was less than 3%.



## 2. Experimental results

The experiments were carried out by following scheme. With the help of EBH crucible was heated to the temperature  $T_c \cong 1.15$  kK where plumbum saturated vapor pressure is  $p_s \cong 30$  Pa [1]. Above the crucible a weak purple glow was observed at this temperature. Its intensity and shape changed over time. Apparently this glow appears as a result of vapor ionization by electrons leaking from EBH. Isolated anode was charged by leakage current to potential about 10 V. At crucible temperature  $T_c \cong 1.25$  kK ( $p_s \cong 0.13$  kPa, saturated vapor density  $n_s \cong 7.7 \times 10^{15} \text{ cm}^{-3}$ ) voltage ( $\approx 380$  V) from power supply was applied to discharge gap. Then either LCD or vacuum arc was initiated. LCD could exist tens of seconds and after that could convert to arc. All LCD regimes had voltage  $U = 340$  V.

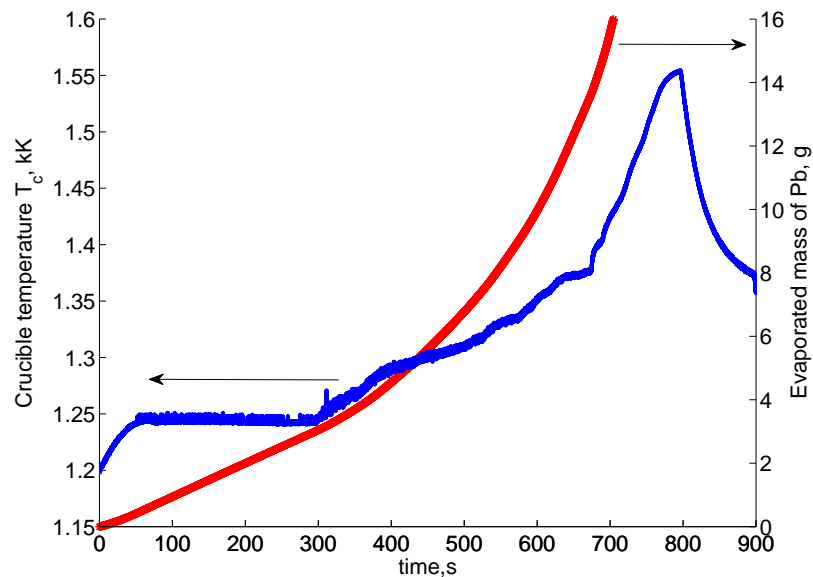
Character of LCD glow was able to significantly change. Discharge with cone form was observed more frequently (figure 1a). On the short time interval (1–3 s) clamped cone form could appear (figure 1b). Also single plasma bunch was observed (figure 1c). Glow irregularities from figures 1b and 1c could move along discharge axis with the velocity of 3–10 mm/s. After EBH switching off discharge lost cone form and glow intensity considerably increased near crucible hole (from figures 1d to 1e). Apparently electrons leaking from EBH influence on glow shape. Last discharge shape existed several seconds. During the process of crucible cooling discharge took form of a needle (figure 1f). At the temperature  $T_c \cong 1.17$  kK the discharge faded. Minimum crucible temperature when LCD initiated was about  $T_c \cong 1.19$  kK (saturated vapor density  $n_s \cong 3.3 \times 10^{15} \text{ cm}^{-3}$ ).



**Figure 1.** Forms of low-current discharge: (a)  $T_c = 1.27$  kK; (b)  $T_c = 1.29$  kK; (c)  $T_c = 1.43$  kK; (d)  $T_c = 1.33$  kK; (e)  $T_c = 1.33$  kK; (f)  $T_c = 1.19$  kK.

There was an experiment when LCD existed until total Pb evaporation. Figure 2 shows the crucible thermogram in this experiment. Change of  $T_c$  was caused by increase of EBH power  $N$  and energy loss by plumbum evaporation. Before applying voltage from power supply  $N = 70$  W

and  $T_c = 1.24$  kK. At the time  $t = 300$  s EBH power was increased to 90 W. Supply voltage was applied at  $t = 320$  s when crucible temperature equaled 1.26 kK. After that  $N$  was gradually increased to 150 W that caused rise of  $T_c$  but LCD did not turn into arc. Discharge faded at  $t = 715$  s when  $T_c = 1.44$  kK. By this time plumbum totally evaporated. Note that arc with current about 20 A and average cathode current density about 10 A/cm<sup>2</sup> existed at crucible temperature 1.25–1.45 kK.



**Figure 2.** Crucible thermogram and evaporated mass of Pb.

Figure 2 also presents the values of evaporated mass of Pb calculated at measured crucible temperature. These calculations were carried out by method [2]; the influence of discharge on evaporation rate was neglected. According to the calculations full mass of Pb (15.1 g) had to evaporate by the experiment time  $t = 695$  s. By the actual end of the evaporation ( $t = 715$  s) it had to evaporate 17 g of Pb. Thus calculation error of evaporation rate is about 10%. According to estimations the energy loss caused by Pb evaporation at the temperature 1.38 kK equals 50 W. This value is in a good agreement with the experiment. Significant rise of  $T_c$  after  $t = 680$  s in figure 2 is explained by absence of evaporation energy loss. LCD glow intensity in this experiment also significantly changed and by the end of evaporation it took form of thin jet with diameter about 1 mm and height of 5 mm.

With the rise of crucible temperature from 1.27 to 1.32 kK current of LCD also increased approximately from 15 to 20 mA. At these conditions LCD is rather sustainable to conversion in arc. At one of the experiments LCD appeared at temperature 1.19 kK ( $n_s \cong 3.3 \times 10^{15} \text{ cm}^{-3}$ ) and converted into arc at  $T_c = 1.35$  kK ( $n_s \cong 2.6 \times 10^{16} \text{ cm}^{-3}$ ).

Plumbum vapor density and velocity change significantly on discharge gap length. Close to fluid surface vapor speed is much less than sound speed and at the outlet of the crucible they are equal. On the basis of data from [2] it can be shown that for using crucible atom density  $n_0$  at cathode surface is  $0.95n_s$ . At crucible outlet it equals to  $n_m \approx 0.6n_s$  and near anode  $n_a \approx 0.005n_s$ . Vapor speed at cathode surface is  $u_0 \approx 20$  m/s, at minimum crucible section  $u_m \approx 250$  m/s and near anode  $u_a \approx 500$  m/s. Intense gradients of vapor parameters along discharge axis lead to irregularities of plasma that reveals in the pictures of glow.

### 3. Conclusion

Studied low-current discharge could be classified as glow discharge [3] by its current ( $\approx 10$  mA), voltage (340 V) and media pressure (0.05–1 kPa). Appearance of described LCD in Pb vapor in some regimes also similar to glow discharge. However these discharges have significant difference in cathode processes. In glow discharge charge transferred to cathode mainly by ions. Electron emission current caused by ion bombardment of cathode is about 10% of discharge current [3]. This relatively small electron current initiates particles multiplication processes. In studied LCD singly ionized Pb ions can't cause electron emission from the cathode. Work function of Pb equals 4 eV [1], than thermionic current density from cathode  $J_e$  is 4–5 orders less than discharge current (at  $T_c \cong 1.3$  kK it is  $J_e \cong 0.1$  mA/cm<sup>2</sup>). Therefore production mechanism of “primary” electrons in cathode layer is not clear.

It is useful to compare characteristics of studied discharge with glow discharge in mercury vapor [3]. Depending on cathode material (mercury, copper, graphite) value of normal cathode drop changes in range 340–480 V that is close to total voltage drop in studied discharge in Pb vapor. Also there is a data on normal value of current density on cathode for glow discharge in paper [3]. At vapor density  $1.4 \times 10^{16}$  cm<sup>-3</sup> normal current density in mercury vapor is about 3  $\mu$ A/cm<sup>2</sup> that is by three orders less than in our experiments. Note that mercury ions in contrast to plumbum ions cause electron emission from cathode. Value of this emission can amount to 1–3% of discharge current.

Studied discharge in plumbum vapor is sustainable to arc mode conversion. Reasons of it are not clear.

### Acknowledgments

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