Evaluation of plasma pressure of high current low inductance vacuum spark on cathode surface

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Abstract. This paper presents evaluation of the plasma pressure in a high current, low inductance vacuum spark on the cathode surface (the electrode material is steel). Calculations are provided for the first half period of the discharge, wherein the cathode surface is subjected to the most severe impacts (micropinches are created resulting in high-energy plasma beams). The evaluations were made using the experimental data obtained on the Pion device. The data of electrical measurements of the discharge current, the average plasma flow values obtained with the multi-grid probe and the data from a cathode macrostructure study were used. The results are given for different values of the discharge current.

1. Introduction
Pulsed electrical discharges, where the micropinch mode occurs, have been the subject of intense research for quite a long time due to a wide range of applied science missions ranging from the controlled thermonuclear fusion (CTF) to the development of selective shortwave radiation sources: ultra-violet (UV), vacuum ultra-violet (VUV) and soft X-ray (SXR). The micropinch phenomenon is quite common for all types of Z-pinches. The low inductance vacuum spark (LIVS) [1-5] belongs to this class of discharges.

Many practical applications of such a plasma discharge require data on the plasma decay mechanisms (in the inter-electrode spacing and beyond) and the parameters of the plasma and corpuscular flows from the high intensity, low inductance vacuum spark discharge area. Among these applications is an effective source of the VUV and SXR radiation for the X-ray lithography and X-ray microscopy. Plasma fluxes from the discharge area can be characterized by the value of the gas-kinetic pressure. The data on the pressure in the plasma fluxes from the micropinch discharge allow to estimate the thermodynamic parameters and the plasma flows.

This paper presents the study of the plasma pressure on the cathode surface in the high intensity, low inductance vacuum spark discharge area. For the evaluation, the experimental data obtained on the Pion device [6] of the Department of Plasma Physics of MEPhI are used.

2. Evaluation of plasma pressure on the cathode surface
The electrical characteristics of the discharge are the oscillatory circuit characteristics, where the energy is transformed from the electric to the magnetic form and back. With time, the energy decays...
because of the Ohmic losses, radiation losses and losses associated with the particle escape from the inter-electrode spacing. Figure 1 shows the energy evolution in the high intensity, low inductance vacuum spark discharge for different values of the charging voltage. The stored energy decreases by more than a factor of two during the first half-period. A micropinch is formed during this time interval and hence the accelerated particle fluxes are formed. Their intense interaction with the electrode surface leads to electrode spraying and melting. Some part of the melt layer is forced by the plasma pressure out of the area of direct interaction with the plasma. This area is marked in figure 2.

One can see that outside this area, the material eruptions in the form of thin solidified metal jets are generated. In the assessment, it is assumed that the impact of the plasma pressure on the cathode is limited to the direct interaction area. The diameter of this area decreases as the battery voltage decreases (figure 3).

![Figure 1](image1.png)

**Figure 1.** Decay of the discharge energy $E(t)$ for different voltages across the inter-electrode gap.

![Figure 2](image2.png)

**Figure 2.** Macroscopic structure on the cathode surface formed after 50 discharges at a charging voltage of 15 kV (the thin circular line marks the area of the direct interaction with the plasma).

![Figure 3](image3.png)

**Figure 3.** The diameter of the cathode area subjected to the direct interaction with the plasma flows depending on the voltage across the inter-electrode gap.

![Figure 4](image4.png)

**Figure 4.** Example of distribution of the flow of ions bombarding the cathode over the electrode surface (Gaussian distribution) for the voltage of 15 kV.
The distribution of the flow of ions bombarding the cathode is not uniform over the electrode surface. The highest density of the incident plasma flow is on the central area of the cathode. For the evaluation, we can take the Gaussian distribution (figure 4) for the distribution of the total number of particles falling on the cathode $D(x,y)$:

$$D(x, y) = D_0 \cdot e^{-\frac{(x-x_0)^2}{2\sigma^2}} \cdot e^{-\frac{(y-y_0)^2}{2\sigma^2}}$$  \hspace{2cm} (1)

Here $D_0$ is the peak value (the number of ions arriving at the centre of the cathode), $x_0$ and $y_0$ the cathode centre coordinates and $\sigma$ the parameter of the normal distribution.

Distribution parameters $x_0$, $y_0$, $D_0$ and $\sigma$ are determined as follows. After 50 discharges, the working part of the electrode is identified visually, and $x_0$, $y_0$ are taken as one half of its diameter $d_i$, table 2.

The $\sigma$ value is determined according to the rule of ‘two sigma’, so that all the values of the variables $x$ and $y$ with a probability of 95% fall within the area of the diameter $d_i$. The peak value of distribution $D_0$ is set to make the total number of particles coming to the cathode $N_\Sigma$ equal to the integral of $D(x,y)$ over the area of the diameter $d_i$.

**Table 1.** Parameters of the distribution functions of ions bombarding cathode.

| U (kV) | $x_0$, $y_0$ (mm) | $d_i$ (mm) | $\sigma$ (mm) | $K$ | $D_0$ ($\frac{\text{particles}}{\text{mm}^2}$) |
|-------|-----------------|-------------|--------------|-----|-------------------|
| 5     | 2.00            | 4.0±0.4     | 1.00         | 2.39| (1.3±0.2)$\times$10$^{17}$ |
| 7.5   | 2.50            | 5.0±0.3     | 1.25         | 2.99| (1.2±0.2)$\times$10$^{17}$ |
| 10    | 2.95            | 5.9±0.7     | 1.48         | 3.54| (1.0±0.3)$\times$10$^{17}$ |
| 12.5  | 3.40            | 6.8±0.6     | 1.70         | 4.07| (1.1±0.4)$\times$10$^{17}$ |
| 15    | 3.90            | 7.8±0.6     | 1.95         | 4.67| (1.0±0.4)$\times$10$^{17}$ |

The flux of ions bombarding the cathode may be represented through the current flowing through interelectrode gap, in assumption, that all ions are once ionized. The density of the flux of ions may be written as:

$$j(x, y, t) = j_0(t) \cdot e^{-\frac{(x-x_0)^2}{2\sigma^2}} \cdot e^{-\frac{(y-y_0)^2}{2\sigma^2}}$$ \hspace{2cm} (2)

$j_0(t)$ value may be calculated through particle flux, which is the integral over interaction domain (region with $d_i$ diameter) of the discharge current:

$$J(t) = \int \int j(x, y, t)dx\,dy = \int j_0(t) \cdot e^{-\frac{(x-x_0)^2}{2\sigma^2}} \cdot dx \cdot \int e^{-\frac{(y-y_0)^2}{2\sigma^2}} \,dy$$

Then $j_0(t)$ is:

$$j_0(t) = \frac{J(t)}{qK^2}$$ \hspace{2cm} (3)

Where substitution is made:

$$K = \int_0^d e^{-\frac{(x-x_0)^2}{2\sigma^2}} \,dx = \int_0^d e^{-\frac{(y-y_0)^2}{2\sigma^2}} \,dy.$$ \hspace{2cm} (4)

Then:
The ion energy component in the axial discharge direction measured with a multi-grid probe is used for the calculation of the average ion energy. The dependence of the average ion energy on the charging voltage is shown in figure 5. Using these data, the maximum pressure in the centre of the cathode (figure 6) is calculated. As an example, figure 7 shows the pressure in the plasma flow as a function of time and distance from the discharge axis for the charging voltage of 15 kV.

\[
j(x, y, t) = \frac{J_0 \cdot \sin(\omega t)}{qK^2} \cdot e^{-\frac{(x-x_0)^2}{2\sigma^2}} \cdot e^{-\frac{(y-y_0)^2}{2\sigma^2}} = 10^6 \frac{J_0 \cdot \sin(\omega t)}{qK^2} \cdot e^{-\frac{(x-x_0)^2}{2\sigma^2}} \cdot e^{-\frac{(y-y_0)^2}{2\sigma^2}} \left[ \frac{A}{\text{coulomb} \cdot \text{m}^2} \right] (5)
\]

where \( \omega \) is the frequency of the discharge current oscillation, \( J_0 \) – is its amplitude, \( q \) – is the ion charge (presumed single).

By expressing the pressure \( P \) as the flux density times the momentum \( p \) carried by a single particle to the cathode surface, it can be written as follows:

\[
P(x, y, t) = j(t) \cdot p = j(t) \cdot \sqrt{2m\langle E \rangle} = 10^6 \frac{J_0 \cdot \sqrt{2m\langle E \rangle}}{qK^2} \cdot e^{-\frac{(x-x_0)^2}{2\sigma^2}} \cdot e^{-\frac{(y-y_0)^2}{2\sigma^2}} \cdot \sin(\omega t),
\]

\[
P(r, t) = 10^6 \frac{J_0 \cdot \sqrt{2m\langle E \rangle}}{qK^2} \cdot e^{\frac{-r^2}{2\sigma^2}} \cdot \sin(\omega t) [Pa]
\]

The ion energy component in the axial discharge direction measured with a multi-grid probe is used for the calculation of the average ion energy. The dependence of the average ion energy on the charging voltage is shown in figure 5. Using these data, the maximum pressure in the centre of the cathode (figure 6) is calculated. As an example, figure 7 shows the pressure in the plasma flow as a function of time and distance from the discharge axis for the charging voltage of 15 kV.

**Figure 5.** The value of the average energy of ions depending on the voltage at the inter-electrode gap.

**Figure 6.** Maximum values of the plasma flow pressure on the cathode surface depending on the voltage at the inter-electrode gap.
3. Conclusions
The evaluation of the pressure of the plasma flows shows that the cathode surface is subjected to a considerable load that drives the molten cathode material outside the area of direct interaction with the plasma flow.

In [1], the radial component of the plasma pressure at the edge of the high intensity, low inductance vacuum spark was measured to be of several MPa. The evaluations presented here indicate that in the central part of the cathode exposed to the plasma flows, the plasma pressure exceeds these values by up to two orders of magnitude.

References
[1] Kuznetsov A P, Byalkovskii O A, Gubskii K L, Kozin G I, Protsenko E D, Dodulad E I and Savjolov A S 2014 Plasma Physics Reports 40 290-297
[2] Dodulad E I, Kostyushin V A and Savjolov S A S 2015 Physics Procedia 71 155-159
[3] Krasov V I, Paperny V L, Korobkin Yu V, Romanov I V, Rupasov A A and Shikanov A S 2007 Technical physics letters 33 941
[4] Bashutin O A, Alkhimova M A, Vovchenko E D, Dodulad E I, Savelov A S and Sarantsev S A 2013 Plasma Physics Reports 39 900-909
[5] Astrachantsev N V, Krasov V I and Paperny V L 1995 Journal of physics D: Applied physics, 8 2514
[6] Sarantsev S A, Dvoyeglazov Ya M and Raevskiy I F 2015 Physics Procedia 71 133-137