Computer simulation of the breakdown phase in a plasma focus device including photoeffect

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Abstract. The aim of this paper is to reveal the influence of the photoeffect on the initial phase of the electrical breakdown. The results of a two-dimensional computer simulation of the breakdown phase in a plasma focus (PF) device are presented. The spatial and temporal developments of the electron and ion densities are calculated by solving numerically the continuity equations together with the Poisson equation. We assume that any swarm of charged particles comes almost instantaneously in dynamic equilibrium by way of various ionisation, transport and electrode processes that depend on the local value of the electric field/gas number (E/N) ratio. To reveal the influence of the photoeffect on the breakdown development process, it was assumed that electrons are emitted from the cathode as a result of positive ions bombardment and photoemission.

1. Introduction
The reason why plasma focus (PF) discharges have been studied for many years is their high efficiency of X-ray generation, high-energy electrons and ions acceleration and neutron production (if one uses deuterium as a filling gas). This initial discharge phase is very important because it influences essentially the next discharge stages, i.e. the acceleration and radial compression. Quantitative evidence in terms of neutron and X-ray output shows that the successful sheath generation depends on the electric field applied and on the electrodes and insulator configuration. The thickness and length of the insulator and the anode-cathode distance influence the photoeffect and the breakdown character. The experiments show different types of discharges depending on the hydrogen pressure, the insulator length and type of insulating material [1], the distance between the electrodes [2] and on the electrode design [3].

A computer simulation of electrical breakdown in a large device with a coaxial electrode system without photoeffect is presented in [4]. The influence of the insulator dielectric constant is reported in [5]. The discharge evolution and its different character depending on the gas pressure are given in [6].

One would expect that the photoeffect plays an important role in small as well as in large devices. This paper presents the results of a computer simulation of the electrical breakdown phase in a coaxial electrode system in a small (case 1) and a large (case 2) PF device. These devices are equipped with a Mather type insulator-electrodes system. Figure 1 shows schematically the electrode-insulator
geometry. The insulator is made of Al$_2$O$_3$. The voltage rise is \( \frac{dU}{dt} = 2.10^{11} \text{ V/s} \). The working gas is deuterium with pressure \( p = 3 \text{ Torr} \). The initial electron and ion density is \( 10^2 \text{ cm}^{-3} \).

![Simplified presentation of plasma focus electrodes.](image)

**Figure 1.** Simplified presentation of plasma focus electrodes.

The parameters of electrode-insulator system in two variants are presented in table 1.

| Variant | \( R_k \) (cm) | \( R_d \) (cm) | \( R_a \) (cm) | \( Z_k \) (cm) | \( Z_3 \) (cm) | \( Z_e \) (cm) | \( Z_1 \) (cm) |
|---------|----------------|----------------|----------------|---------------|---------------|---------------|---------------|
| 1       | 16             | 11.6           | 10.7           | 20            | 13.8          | 1.5           | 1             |
| 2       | 6.4            | 3              | 2.5            | 16            | 9.2           | 2.4           | 1             |

2. **Theoretical model**

A model of the breakdown consists of the particle conservation equations for electrons, ions and excited atoms and has the following form:

\[
\begin{align*}
\frac{\partial n_{e,i}}{\partial t} + \nabla \cdot \left( n_{e,i} \vec{V}_{e,i} \right) &= \alpha n_e |\vec{V}_e| + D_{e,i} \nabla^2 n_{e,i} \\
\frac{\partial n_{e,*}}{\partial t} &= \alpha^* n_e |\vec{V}_e| - \frac{n_e}{\tau_e} + D_{e,*} \nabla^2 n_{e,*}
\end{align*}
\]

where \( n \) is the density of particles, \( \vec{V} \) is the drift velocity, \( D \) is the diffusion coefficient, \( \alpha \) is the Townsend preliminary ionization coefficient, \( \alpha^* \) is the excitation coefficient, \( \tau_e \) is the lifetime of an excited atom and the indices \( e, i, * \) refer to electrons, ions and exited atoms, respectively. For ionization coefficient we used the Townsend preliminary ionization coefficient, which is empirically determined as a function of the electric field and particle density.

The drift velocity for weakly ionized gases is given by \( \vec{V}_e = -\mu_e \vec{E} \), where \( \mu_e \) is the electron mobility. We further assumed that the particle diffusion effect on the field direction is small as compared to the effect due to the drift. For electron density of the order of \( 10^{13} \text{ cm}^{-3} \) or less, the effect of the volume recombination is relatively small.

The boundary condition on the cathode is based on the assumption that electrons are emitted by the impact of positive ions and by photons (photoeffect) so that the total electron flux from the cathode \( n_{ec} \vec{V}_e \) is equal to the flux generated by ion impact plus the electron flux caused by photoeffect:

\[
n_{ec} \vec{V}_e = \gamma_{ph} \vec{V}_{ph} + \gamma_e n_{i} \vec{V}_i ,
\]
where the coefficient \( \gamma_i \) is the probability of electron emission per incident ion (\( \gamma_i = 0.15 \)), \( \nu_{\text{ph}} \) is the photon flux per unit cathode surface and the coefficient \( \gamma_{\text{ph}} \) is the electron emission per incident photon (\( \gamma_{\text{ph}} = 0.01 \)). For a considerable number of metals \( \gamma_{\text{ph}} \) is in the range of 0.1 – 0.01 [7]. In our case the cathode is made of copper and the upper (horizontal part) of the cathode is a solid metallic wall. Furthermore, the anode surface is assumed to be perfectly absorbing.

The continuity equations are solved numerically simultaneously with the Poisson equation using the so called flux–corrected method. Our algorithm extends the work presented by McDonald et al. [8] and the flux-limiting algorithm developed by Zalesak [9].

3. Results and discussion

Comparison of the simulation results with and without photoeffect are presented in figures 2-3 for case 1 and figures 4-5 for case 2.

The calculated two-dimensional electron and ion densities are presented by constant density contours in the \((r, z)\) space. A logarithmic scale is used; thus, if the value of the constant density contour is 10, the real density is \(10^{10} \text{ cm}^{-3}\), and so on.

Figures 2 and 3 present the effect of the build-up of electron (a) and ion (b) density for large PF without and with the photoeffect included, respectively. It can be seen that with the photoeffect included the front of the density rise is thicker and propagates much faster towards the cathode than in the opposite case. Two discharge channels, separated by the region of low density (figure 3, \(r = 14\text{ cm}, z = 3.5\text{ cm}\)), can be easily distinguished while the character of the gliding discharge along the insulator is the same in both cases.

**Figure 2.** Electron (a) and ion (b) density contours for variant 1 without photoeffect.  
**Figure 3.** Electron (a) and ion (b) density contours for variant 1 with photoeffect.

Figure 4 presents the build-up of the electron (a) and ion (b) density for small PF at the moment \( t = 46.31 \text{ ns} \) without photoeffect from cathode, while figure 5 presents the same (for \( t = 41.27 \text{ ns} \)) but with photoeffect included. The same effect as in the case of large PF is observed (much faster propagation of the ionization front towards the cathode). Additionally, the photoeffect from the cathode increases the electron concentration at the end of the insulator (\(z \approx 9.5\text{ cm}\)).

Comparing the results for small and large device we can conclude that for the former one:
- gliding discharge is not observed
- only one streamer is formed.

One can also see that a low electron and ion density region appears near the horizontal cathode of the PF electrodes (for both plasma focus devices) when the photoeffect is included in the model.
4. Conclusion
The aim of this paper is to reveal the influence of the photoeffect on the initial phase of the electrical breakdown in the plasma focus device. The numerical calculations taking the photoeffect into account, we found:

- a faster growth of the electron and ion densities in both cases;
- the appearance of a low electron and ion density region near the horizontal cathode of the PF electrodes;
- for plasma-focus electrodes with a small anode-cathode gap, the photoeffect changes the character of the breakdown; a streamer is formed from the triple point to the cathode corner.

The general conclusion can be drawn that the photoeffect plays an important role in what concerns homogeneity of the breakdown development. In the case of a small device, it also changes the character of discharge. The photoeffect, therefore, cannot be neglected in the numerical simulation of such phenomena.

5. References
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