The role of photo electrical effect in sustaining the preionization process in Plasma Focus device.

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Abstract. In the present work an estimation shows that the photo effect on the cathode near the insulator has significant role in the breakdown of the Plasma Focus device. An analysis is made to establish the number of the emitted photons from the exited molecules and respectively the number of ejected electrons from the cathode due to the photo effect.

1. Introduction
In our previous works we investigated the development of electron avalanche in the Plasma Focus (PF) \cite{1, 2}. The model used so far shows that at low pressure (1–3 Torr) in the time interval 16–20 ns after the beginning of the process most of the electrons born by direct ionization in the device chamber go to the wall and the ionization growth of the charged particles stops due to the diffusion losses. In the real experiments at the same pressure range the PF devices produce all the required elements for a good pinch–homogeneous current sheet and then acceleration and compression of the plasma \cite{3}. A solution of this disagreement can be pursued by accounting for additional ionization sources besides the electron impact ionization of the ground state molecule, i.e. applying a more adequate physical model that takes them into account. Such a source may be ejection of secondary electrons by a photo effect.

2. Results and discussion
In the time range in which we have obtained the description of the ionization process, namely from the moment of applying the electric field up to 20 ns, the ions and the metastable molecules are too slow and cannot reach the cathode. Thus the process of secondary electron emission from the cathode due to impinging of the cathode by these species can be neglected. However at that time a considerable number of electron excited levels of the hydrogen molecules appears in the volume. These excited levels emit photons in the UV region which are capable of electron ejection. This effect is known for a long time. For example R. R. Newton \cite{4} made estimations for the time delay of electron ejection from the cathode due to the ions, metastable states and excited radiative states. He uses flat geometry with 1 cm length of the gap and pressure 1 Torr of the filling gas. According to his estimations the average time for excitation of a molecule with subsequent radiation and then ejecting an electron by the cathode is $10^{-8}$ s. Much slower is the ejection of electrons, caused by the ions and metastable atoms ($10^{-6}$ and $10^{-3}$ s respectively). The experimental data \cite{5, 6} concerning the formation of the current sheath...
exclude the participation of the heavy particles in the electron ejection since the current sheath appears a few hundred nanoseconds after the beginning.

![Schematic representation of the Plasma Focus coaxial electrodes](image1)

**Figure 1.** Schematic representation of the Plasma Focus coaxial electrodes

Our geometry (figure 1) is more complicated than that in [4] but electric field distribution (see figure 2) near the cathode and dielectric is quite similar to the conditions in the work of Newton. There is a strong electric field, concentrated within a range of 1 cm close to the bottom part of the cathode.

![Equipotential lines at pressure p = 3 Torr](image2)

**Figure 2.** Equipotential lines at pressure $p = 3$ Torr

Due to this form of the field the ionization rate is highest in the vicinity of the cathode. Figure 3 shows considerable values of electron number density near the cathode so we could

![Electron number density at pressure p = 3 Torr](image3)

**Figure 3.** Electron number density at pressure $p = 3$ Torr
also expect intensive excitation of molecules in the same region. Therefore an intensive flux of radiation will originate there.

Let us denote the creation rate of excited molecules from a given type \( s \) in the whole volume with:

\[
f(t) = \frac{dN_s^+}{dt},
\]

where \( dN_s^+ \) is the number of collisions creating the exited molecules from type \( s \) in the time interval \((t, t + dt)\).

**Figure 4.** Excitation rate at pressure \( p = 3 \) Torr

The function \( f(t) \) is a result of our simulation (see figure 4). Knowing the \( f(t) \) one can obtain the number of photons emitted in the entire volume as a function of time. If the number of excited molecules is \( N_s \) in the beginning of the time interval, then at the interval end the number of exited molecules will decrease by \( dN_s^- \) due to the radiation losses:

\[
dN_s^- = N_s(1 - e^{-\frac{dt}{\tau_s}}) \approx N_s \frac{dt}{\tau_s}.
\]

Here \( \tau_s \) is the lifetime of the corresponding level \( s \), and it is given in table 1 [7].

**Table 1.** Lifetimes of some H

| Excited levels | Lifetime - \( \tau_s \) |
|---------------|-----------------|
| \( B^1\Sigma_u^+ \) | 0.8 ns |
| \( C^1\Pi_u \) | 0.6 ns |
| \( a^3\Sigma_g^+ \) | 11.1 ns |
| \( d^3\Pi_u \) | 68 ns |
| \( e^3\Pi_u \) | 1 ms |
Using (1) and (2) we can write the balance equation:

\[ dN_s = dN_s^+ - dN_s^- . \]  

(3)

Substituting (1) and (2) in (3) we have:

\[ \frac{dN_s}{dt} = f(t) - \frac{1}{\tau_s} N_s . \]  

(4)

Solving this differential equation we obtain the total number of excited molecules of given type as a function of time.

\[ N_s(t) = e^{-\frac{t}{\tau_s}} \int_0^t f(t') e^{\frac{t'}{\tau_s}} dt'. \]  

(5)

The result is given on figure 5.

Figure 5. Total number of excited molecules at pressure \( p = 3 \) Torr

As it can be seen from table 1, the state \( c^3 \Pi_u \) is metastable so it has no role in photon radiation in the first several tens of nanoseconds. In table 2 are given the most important electron excited levels and their transition to the lower levels. The transitions in the triplet states, \( a^3 \Sigma_g^+ \rightarrow b^3 \Sigma_g^+ \), ...

| Transition | Photon energy |
|------------|---------------|
| \( B^1 \Sigma_u^+ (v = 0) \rightarrow X^1 \Sigma_u^+ (v = 0) \) | 11.3 eV |
| \( C^1 \Pi_u (v = 0) \rightarrow X^1 \Sigma_u^+ (v = 0) \) | 12.4 eV |
| \( a^3 \Sigma_g^+ (v = 0) \rightarrow b^3 \Sigma_g^+ (v = 0) \) | 0.53 eV |
| \( d^3 \Pi_u (v = 0) \rightarrow a^3 \Sigma_g^+ (v = 0) \) | 2 eV |
| \( c^3 \Pi_u (v = 0) \rightarrow X^1 \Sigma_g^+ (v = 0) \) | 11.75 eV |
and \( \text{d}^3\Pi_u \rightarrow a^3\Sigma_g^+ \) bear low-energy photons that are not capable of electron ejection from the cathode, but these transitions lead to dissociation of the hydrogen molecule. The photons, born in transitions to the ground levels \( B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+ \) and \( C^1\Pi_u \rightarrow X^1\Sigma_g^+ \), can eject electrons by photo effect.

Using the result for the total number of excited molecules \( N_s(t) \) of the levels \( B^1\Sigma_u^+ \) and \( C^1\Pi_u \) and relying on the fact that the most probable transition of these states is to the ground state, then the number of emitted photons per unit time is given by the approximate expression:

\[
N_{ph}(t) = \frac{N_s(t)}{\tau_s}.
\]  

(6)

Having in mind that the bulk of charged particles are concentrated near the cathode (see figure 3), we can expect that a considerable part of excitations have been done in the same region. Then assuming \( \pi/4 \) geometry, approximately 1/4 from the emitted photons reach the plate cathode. To be more accurate the geometry used in our model (which is the bottom part of PF device) is almost completely closed cavity. Therefore the photons emitted in an arbitrary point of the volume will reach either the electrode or dielectric surface and will produce photo electrons. However, the cathode area which is near the biggest field gradient is most important. In these estimations the possible photo effect from the insulator is not taken into account either. On the basis of these assumptions, the number of electrons ejected per unit time from the cathode is given by:

\[
n_{eject}(t) = \frac{\gamma_{ph}N_{ph}(t)}{4},
\]

(7)

where \( \gamma_{ph} \) is the quantum yield from a clean copper surface given for photons with the corresponding energies (see table 2). According to the [8] these values are above 0.01. For the purpose of the estimation the exact value can be used.

The total number of photo electrons ejected, calculated using (7), is given on figure 6.

**Figure 6.** Photoelectrons emitted by the cathode.

The figure 6 shows the ionization rate at different gas pressures as well as the rate of creation of photo electrons. It is seen that the electron ejection rate values are substantially lower than the corresponding ionization rate for the whole volume in the same time interval till 15 ns. But
these photo electrons are born in the space where the electric field has significant value, so they can start new electron avalanches. The results in [1, 2] were obtained, assuming that there is a homogeneous distribution of the initial number of electrons existing in the neutral gas (seed electrons), about 1 electron in 2 cm$^{-3}$. When the electric field is applied this number rapidly increases but at low pressures the diffusion losses prevailed in the charged particle balance and the ionization multiplication is stopped or it is hampered at high pressure. The limitation of the model used is that we did not take into account the new-born electrons from the cathode by the UV photons. In practice in the first 30 - 40 nanoseconds the cathode works in Townsend mode with a second coefficient $\gamma$ determined by the photo effect. The photo electrons, emitted by the cathode enter the discharge gap in the most sensitive region. Since their number is considerable this fraction may significantly influence the ionization multiplication. As a result we expect that the exponential increase of the charge particles will not be suppressed as it can be seen now in figure 6 after the 20$^{th}$ nanosecond. The correct treatment of the problem requires simultaneous consideration of several plasma particles ensembles e.g. charged particles, various excited molecules, their spatial distributions as well as the emitted photons. Another ionization factor is the stepwise ionization from the triplet states which a heavily populated (see figure 5) which also should be taken into account. Such tasks are beyond the scope of this work.

3. Conclusions
Using the numerical results for the electron energy distribution function and excitation rate of different molecule states obtained in [2] an estimation is derived for the number of photoelectrons ejected by the cathode.

Acknowledgments
This work was supported by the contract VUF 03/2005 of the Bulgarian National Scientific Research Fund and European Commission contract G4MA-CT-2002 with IFPILM, Warsaw.

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