Spatiotemporal Development of Low-Pressure Gas Discharges

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Abstract. We present an analysis of time and space resolved development of all typical regimes of low-pressure DC discharge in argon – low current Townsend discharge, oscillations and constrictions of discharge and high current glow discharges. Our work is based on time-resolved ICCD recordings of the discharge structure, synchronized with current and voltage measurements. Special care is given to radial effects and influence of dielectric walls during development of the glow discharge structure.

1. Introduction
Time resolved development of gas discharge structure is related to kinetics of basic processes that participate to low-pressure breakdown and discharge maintenance. Our aim was to extend our earlier studies of the development of breakdown and Volt-Ampere characteristics of low pressure discharges [1,2] to include temporal development of different modes. This work represents a continuation of extensive studies of electrical properties of low-pressure DC discharges and their spatial structure, started by Phelps and coworkers [3-7].

Recently, studies similar to ours have been reported [7,8]. Jelenković and Phelps [7] studied spatiotemporal development of cathode-fall dominated DC discharges in argon. However, they have used a box-car integrator to record discharge emission intensity as a function of time so they could not follow radial effects in the discharge. Wagenaars and coworkers [8] investigated ignition of high current glow discharge in complex parabolic geometry. Our goal was to extend the studies to different modes of low-pressure low-current discharges and to extend the knowledge of kinetics of formation and maintenance of these discharges in a simple geometry. The basic idea is to follow time resolved structures of the discharge in order to gain a better understanding of processes leading to the development of space charge effects, formation of constricted regime of discharge, cathode fall and other features of glow discharges. In addition, the idea is to provide the experimental data that may be modelled by 2D models, which will provide further information on basic kinetic processes in the discharge. These models would have to include radial effects in discharges and influence of the walls.

2. Experimental setup
The schematic of the experimental set-up is shown in figure 1. The discharge chamber used in our experiment consists of parallel plane electrodes tightly fitting inside a quartz cylinder which prevents long-path breakdown. The cathode (C) is made of copper and the anode (A) of quartz, with a transparent yet conductive thin film of platinum deposited on its surface. The diameter of the...
electrodes \((2r)\) is 5.4 cm. The distance between the two electrodes \((d)\) may be adjusted by fixed electrode supports at three different values – 1.1, 2.1 and 3.1 cm.

The system is pumped down to a base pressure of below \(10^{-6}\) Torr and a very small flow of gas (argon in this case) is used to reduce the accumulation of impurities. Prior to the measurements, the surface of the cathode is treated by a relatively high current discharge in hydrogen (30 µA) until a stable breakdown voltage is achieved (approximately 30 minutes). Cathode surface treatment provides stable and reproducible results of measurements.

The discharge is established at very small DC current (typically 1-2 µA). The Volt-Ampere characteristic of the discharge and transient behaviour of discharge are scanned by applying a voltage pulse to a DC voltage \([1,2]\). The voltage is measured by two probes, one at the cathode and the other in the anode circuit. The second probe is used only when a relatively high monitoring resistor is connected into the low-voltage anode circuit to determine the current. Pulses of higher current usually last only long enough \((\Delta t < 2\) ms\) to make a reliable recording of voltage and current transients. The emission profiles recorded by the ICCD camera correspond to the conditions of the pulse in the observed time interval. Keeping the pulses short enough enables us to avoid heating and significant conditioning of the cathode surface during the measurements.

Development of discharge structure is traced down in time by use of fast ICCD camera (Andor, iStar DH720-18U-03). Both radial and axial emission profiles are recorded. The camera has \(18 \times 6.7\) mm\(^2\) active area that consists of \(690 \times 256\) pixels. Minimum optical gate width is 2 ns. The spectral range of the photocathode is \(180 – 850\) nm. However, camera lens (Nikkor 50 mm f/1.4) limits recorded emission to the visible part of the spectra. The delay generator built into the ICCD camera enables us to synchronize recording of the light emission with pulse development and voltage-current measurements. Delay between gating of the camera and start of the voltage pulse is varied to record emission from the discharge in different time intervals. Gate width for recording was determined according to the rate of change of discharge current and emission intensity. Time interval had to be short enough to avoid integration of rapidly changing profiles of emission. On the other hand it had to be long enough to record reliably low intensity discharge emission. Single shot mode of recording was utilized whenever it was possible – in order to avoid changes in discharge conditions over long periods of discharge operation. Otherwise, accumulation mode of operation was used - emission from repetitive shots was summed up. It was sufficient to use \(5 – 50\) shots, in dependence of discharge emission intensity. While we do not measure absolute values of the intensity, relative relationships between the emission profiles at different currents are established. In principle, it is
possible to make absolute calibration by normalizing the profiles in the low current Townsend regime to the excitation coefficients at the anode.

3. Steady-state measurements

We have performed measurements at pressure ($p$) × electrode gap ($d$) products 250 Pa cm, 150 Pa cm and 45 Pa cm and $d = 1.1$ cm, 2.1 cm and 3.1 cm, that covered formation and maintenance of different modes of discharges – low current diffuse (Townsend) discharge, normal glow and abnormal glow discharge. Steady-state voltage-current characteristics are shown in figure 2. In section 4, temporal development of discharge is described for selected steady-state conditions. These conditions are indicated by arrows in figure 2.

![Figure 2. Voltage current characteristics for different discharge conditions: (a) $pd = 250$ Pa cm; $d = 1.1$ cm; (b) $pd = 150$ Pa cm; $d = 1.1$ cm; (c) $pd = 45$ Pa cm; $d = 3.1$ cm. Here $V_b$ is the breakdown voltage and $V$ is the operating voltage.](image1)

Pressure $\times$ electrode gap values that are close to Paschen curve minimum ($pd = 150$ Pa cm) were used as a test case. Higher $pd$-s were interesting to observe significantly constricted modes of a discharge, and lower $pd$-s to study contribution of heavy particles to discharge operation. A special care was taken in recording of the spatiotemporal development of discharge oscillations and constrictions. The development of glow and abnormal glow discharges was recorded in end-on and side-on view, revealing radial dependence of the discharge and showing radial development of constrictions.

4. Time-resolved measurements

4.1. Townsend discharge

We have selected operating conditions – $pd = 150$ Pa cm, $d = 1.1$ cm to describe temporal development of Townsend discharge. Voltage and current waveforms are shown in figure 3. Labels 1-5 indicate the moments at which the images were taken. Corresponding axial emission profiles are shown in figure 4.

After the application of a low voltage pulse, the discharge first oscillates for a while, until a steady state is established. Steady-state voltage and current are indicated by an arrow in figure 2(b). Discharge voltage initially follows the shape of the pulse that would be expected in vacuum, which is indicated by the dashed line in figure 3. Initial increase in voltage is followed by the discharge current increase. As the circuit capacitance starts loosing the charge through the discharge, voltage starts decreasing, while the current still increases. This kind of behaviour is typical for the decreasing part of the voltage-current characteristics at low currents. Throughout the development of the discharge, axial emission profile exhibits exponential increase from the cathode towards the anode (figure 4), which is characteristic of low current Townsend discharge in a homogeneous field. The emission intensity
follows the intensity of the discharge current, while the slope of the profile in semi-logarithmic scale remains the same. Only at the highest currents, small decrease of intensity near the anode can be observed. This indicates the onset of space charge induced deviation from homogeneous electric field [9].

![Figure 3. Discharge voltage and current waveforms for development of Townsend discharge. (pd = 150 Pa·cm, d = 1.1 cm).](image)

![Figure 4. Axial profiles of emission that correspond to labels 1-5 in figure 3.](image)

4.2. Oscillations

Oscillatory behaviour of low-pressure low-current discharges, at the transition from the Townsend (dark-diffuse) discharge to the constricted normal glow discharge, has been studied by several authors, e.g. [1,5,6,9]. These studies included well defined systematic measurements of discharge voltage and current, detailed analysis of the effect of circuit elements on oscillations and influence of discharge current on frequency and damping of oscillations. We present first time-resolved measurements of the 2D discharge structure throughout oscillations that included broad range of discharge conditions and different regimes of oscillations.

Figure 5 shows voltage and current waveforms of free running oscillations. Labels 1-11 indicate the times at which the images were taken. Corresponding axial emission profiles are shown in figure 6 (for moments labelled by 1-6). 2D images of the discharge, taken in side-on view, are presented in figure 7.

At early times, after the application of the voltage pulse, emission intensity exponentially increases from the cathode towards the anode (label 1), which is typical for low current Townsend discharges. Further on, formation of the peak of emission, induced by the space charge, can be observed (label 2). This is consistent with the formation of the cathode fall, where position of the peak indicates the edge of the cathode fall [1,2]. The peak of emission rapidly moves towards the cathode (label 3). At this point, the discharge is centred and curved towards the cathode (figure 7 – label 3). This kind of behaviour is characteristic of rapid cathode fall development. The discharge profile then broadens radially and the peak intensity moves further towards the cathode (label 4). The peak intensity of emission is now somewhat decreased, indicating that the discharge has switched to a more economic regime due to the change in electric field profile. Following the decrease of current, the intensity of emission decreases and the peak of emission moves away from the cathode (label 5), until Townsend-like profile develops (label 6). In subsequent oscillation periods, axial behaviour of the discharge is
quite similar. However, radial behaviour gradually changes. In the lower set of images of figure 7, discharge, development in the third period of oscillations is shown. The discharge gets even more constricted and the peak of emission moves closer to the wall. In subsequent periods, the development remains the same.

![Graph](image)

**Figure 5.** Development of free running oscillations – voltage and current signals after the application of voltage pulse.

**Figure 6.** Axial emission profiles that correspond to labels 1-6 in figure 4.

![Graph](image)

**Figure 7.** 2D scans of discharge development. Labels 1-11 correspond to labels in figure 4. Dotted lines indicate positions of the cathode (left) and the anode (right). Intensity of emission in pictures labelled by 1, 6, 7, 10, and 11 is multiplied by factor 25, for a better visibility.
As we have shown, throughout the voltage and current oscillations, ionized gas oscillates both radially and axially. Furthermore, it takes several periods for the discharge to reach the final form which is sustained in subsequent oscillations.

4.3. Constrictions

Figure 8 shows current and voltage waveforms that correspond to development of the constricted regime of the discharge. 2D images of the discharge are presented in figure 9. Steady-state values of discharge voltage and current are indicated by an arrow in figure 2(a).

![Figure 8. Current and voltage waveforms during formation of discharge constriction.](image)

Starting from Townsend’s diffuse regime, the discharge gradually exhibits space charge effects. Formation of the peak of emission can be observed, which is consistent with the formation of the cathode fall (e.g. [2]). The peak of emission rapidly moves towards the cathode. At this point, the discharge is centred and curved towards the cathode (label 3 in figure 9), which is typical for rapid cathode fall development. Detailed analysis of this kind of discharge development will be analyzed in section 5. We have shown that during the cathode fall development the discharge can be observed as a group of parallel channels that operate independently.

As the discharge current reaches maximum, the discharge profile broadens radially and the peak intensity moves further towards the cathode (label 4). Following the decrease of the current, the intensity of emission decreases and the peak of emission moves away from the cathode (label 5), until Townsend-like profile develops (label 6). As the discharge approaches the steady state, formation of constriction can be observed. During this phase of discharge development, the peak of emission gradually moves axially towards the cathode and radially towards dielectric wall of the discharge chamber.
4.4. Abnormal glow

Finally, we will present the formation of abnormal glow with fully developed cathode fall. We selected the lowest pressure covered in this study and the widest electrode gap, in order to show influence of heavy particles, which is the most pronounced in our system, under these conditions. Figures 10 and 11 show current and voltage waveforms and selected axial emission profiles, respectively, for \( pd = 45 \text{ Pa}\cdot\text{cm} \) and \( d = 3.1 \text{ cm} \). Final steady-state voltage and current are indicated by an arrow in figure 2(c). Emission profile for initial moment is not shown in figure 11, because of too low signal-to-noise ratio. During the first \( \sim 40 \mu s \), the discharge is in Townsend regime, the emission profile exhibits typical exponential increase towards the anode due to electron induced excitation. Another peak of emission can be observed near the cathode, which is contributed to excitation by heavy particles – ions (\( \text{Ar}^+ \)) and fast atoms (\( \text{Ar}^0 \)). Further on, both contributions to excitation by electrons and by heavy particles increase. As the cathode fall develops, peak of emission moves away from the anode. At the current maximum, there is a small drop in peak of emission induced by the electrons, while the contribution of heavy particles rises due to a fast change in axial electric field distribution. This kind of “wave of excitation” can be expected for the rapid change in electric field distribution throughout formation of the cathode fall. As the discharge approaches the steady state, intensity of emission decreases, while the profile remains the same.
5. Formation of the cathode fall and constrictions

It has been observed that throughout the fast cathode fall formation (rapid decrease of voltage, followed by a current growth) a radial deformation of the spatial structure of emission occurs (Fig. 2-3). Our initial assumption was that this kind of behaviour is due to the space charge effects. The basic idea was that the discharge can be considered as a group of independent parallel channels. In order to check this assumption, we followed development of the spatial structure of the discharge in three different channels of the discharge. We have selected a channel of the discharge that corresponds to maximum intensity at maximal current (axes of discharge chamber) and channels that correspond to 90% and 70% of emission intensity at the axes. Emission transients in different channels have been analyzed by establishing relation between positions of the peak of emission $d_{\text{max}}$ in different channels (figure 12).

Figure 12 shows $d_{\text{max}}$ (max. intensity) for selected channels of the discharge throughout the time interval indicated by the thick line in the current waveform (upper right inset). It can be observed that at specific times $d_{\text{max}}$ are different for different discharge channels. However, all the channels generally follow the same trend. Development of channels closer to the wall is delayed in comparison to the central channel. At the same time $d_{\text{max}}$ (max. intensity) dependency exhibits hysteresis. This indicates non-equilibrium processes that occur during fast cathode fall development.

Presented results confirm our initial assumption that during the cathode fall development the discharge can be observed as a group of parallel channels that operate independently coupled only by the radial diffusion.

In order to investigate further creation of constriction we will continue with the analysis of the development of the spatial structure of the discharge along the same current-voltage waveform. It has been observed that formation of constriction occurs during gradual establishment of the stationary state of the discharge (figures 8 and 9).
Figure 12. Position of the peak of emission in dependence on peak intensity during cathode fall formation.

Figure 13. Position of the peak of emission in dependence on peak intensity during formation of constriction.

Figure 13 shows $d_{\text{max}}$ for the three selected channels of the discharge in the time interval indicated in the upper right insert. We kept data obtained for cathode fall formation for comparison. It can be observed that during establishment of the stationary state, in the channel that corresponds to the highest emission intensity (solid squares) the discharge gradually develops from Townsend-like regime to normal glow regime of discharge operation. Peak of emission moves closer to the cathode, while intensity of emission increases. On the other hand, the remaining discharge channels retain Townsend-like behaviour with a gradual decrease of emission intensity.

Figure 14. Axial emission profiles of three selected discharge channels.

Throughout formation of the constricted regime of the discharge, different discharge channels become dependent. The current growth in one of the channels leads to turning off of the remaining channels due to the decreased operating voltage. Axial emission profiles of the three selected channels in the stationary state are shown in figure 14. Under the given operating conditions, electric field is too low for the discharge to operate in the Townsend regime. This mode of discharge clearly operates in the non-selfsustained mode thanks to diffusion of charged particles from the constricted channel. Having this in mind, broadening of constrictions with an increase of the discharge current in the
normal glow, can be explained. As the discharge current and correspondingly the charged particles
density increase in the conducting channel, the number of charged particles that diffuse to lateral
channels will also increase and lead to the redistribution of the electric field and formation of the
cathode fall. Eventually, the discharge will occupy the entire electrode diameter.

6. Summary
We presented spatiotemporal development of the characteristic modes of low-pressure low-current
discharges in argon.

During development of the Townsend regime, the emission intensity follows intensity of the
discharge current. Axial profile is typical for low current discharges in homogeneous field, with small
deviations at the highest currents

Throughout the voltage and current oscillations, ionized gas oscillates both radially and axially.
After several periods of oscillations, the spatial structure of the discharge adjusts itself to the more
stable state.

In the transition to the normal glow, analysis of spatial structure development in time enabled us to
follow kinetics of the cathode fall formation. Significantly constricted form of the discharge develops,
as the discharge approaches the steady state. We have shown that in this regime two (even three)
different modes of discharge can coexist at the same time.

Through the abnormal glow discharge formation, we were able to follow the kinetics of electron
and heavy particle induced excitation. Time resolved development of discharge structure has shown
that rapid redistribution of electric field through formation of the cathode fall initially leads to a
distinct increase of electron induced excitation. This is then followed by an increase of heavy particle
induced excitation. This kind of behaviour has been expected, but never experimentally confirmed.

Results shown here represent a necessary experimental basis for development of plasma models,
especially two-dimensional models that include radial effects and influence of dielectric walls. Due to
scaling laws, typical for space charge dominated discharges, these studies can also be very useful in
investigations of micro discharges. Ultimately, they can be extended to more complex systems used in
specific applications and even to transients in cathode dominated high frequency discharges.

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