Axial light emission and Ar metastable densities in a parallel plate dc microdischarge in the steady state and transient regimes

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Abstract

Axial emission profiles in a parallel plate dc microdischarge (feedgas: argon; discharge gap \(d = 1\) mm; pressure \(p = 10\) Torr) were studied by means of time-resolved imaging with a fast ICCD camera. Additionally, volt–ampere (\(V–A\)) characteristics were recorded and Ar\(^+\) metastable densities were measured by tunable diode laser absorption spectroscopy (TDLAS). Axial emission profiles in the steady-state regime are similar to corresponding profiles in standard size discharges \((d \approx 1\) cm, \(p \approx 1\) Torr). For some discharge conditions relaxation oscillations are present when the microdischarge switches periodically between the low current Townsend-like mode and the normal glow. At the same time the axial emission profile shows transient behavior, starting with peak distribution at the anode, which gradually moves toward the cathode during the normal glow. The development of argon metastable densities highly correlates with the oscillating discharge current. Gas temperatures in the low current Townsend-like mode \((T_g \approx 320–400\) K) and the high current glow mode \((T_g \approx 469–526\) K) were determined by the broadening of the recorded spectral profiles as a function of the discharge current.

(Some figures may appear in colour only in the online journal)

1. Introduction

Microplasmas have recently become a focus of research due to their wide range of possible applications [1]. Different kinds of microplasma sources have been proposed: microatmospheric pressure plasma jets (\(\mu\)-APPJ) [2], microhollow cathodes [3], and large arrays of microdischarges with dielectric barriers [4] are some of the most popular. However, very few studies of parallel plate microdischarges exist at all [5–7]. Due to their simple geometry, parallel plate microdischarges can be used as an ideal benchmark for different plasma models and for testing the similarities between large-scale low-pressure discharges and microdischarges.

Reproducible and stable discharge conditions are of high importance to realize reliable applications. However, these conditions are usually not achievable over the full operation range. Observations of self-pulsing regimes were amongst others reported in microhollow cathode discharges [8], microthin-cathode discharges [9], microplasma jets [10] and recently in parallel plate microdischarges [11]. Numerous experiments in standard size parallel plate dc discharges \((d \approx 1\) cm, \(p \approx 1\) Torr) have shown that different instabilities may occur [12–15] and the discharge does not operate in a stable regime but moves through a transient phase, switching repetitively from low to high current mode. With the development of ICCD cameras, time-resolved measurements of discharge transients became possible [16, 17]. In our previous work we have shown the first 2D time integrated recordings of the axial light emission in a parallel plate dc microdischarge [18].
In this paper we continue our research and show time resolved 2D recordings of a parallel plate dc microdischarge \((d = 1 \text{ mm}, p = 10 \text{ Torr})\) during relaxation oscillations. ICCD camera images are correlated with current and voltage measurements to gain a better understanding of the formation of space charge effects and the cathode fall formation. Axial light distributions under steady-state conditions (static volt–ampere \((V–A)\) characteristics) have been measured and used to compare with discharge transients.

In addition we have applied tunable diode laser absorption spectroscopy (TDLAS) to record the spectral profiles of the lowest argon metastable state, deducing \(\text{Ar}^* (1s5)\) densities to compare with discharge transients. To calculate the displacement current, the capacity \(C_d\) of the discharge is determined from measurements of the current and voltage during a short voltage pulse in vacuum. With the knowledge of \(C_d\) the displacement current can be calculated:

\[
I_d = C_d \frac{dU_d}{dt},
\]

where \(U_d\) is the voltage drop over the discharge gap.

Prior to each experiment the discharge is sustained at low current (roughly \(10 \mu A\)) mode for around 15 min until stable discharge conditions are achieved. During the experiments the discharge is first ignited in a low current (a few \(\mu A\)) Townsend-like mode. Additionally, short voltage pulses (usually \(<3 \text{ ms}\)) are applied to change the discharge’s working point (intersection between a loading curve and microdischarge \(V–A\) characteristics) to higher currents, as described in [13]. Due to the short pulse length the discharge is running only for a short time in the high current mode, therefore significant gas heating and conditioning of the electrodes is avoided.

2. Experimental setup

A sketch of the dc microdischarge chamber is shown in figure 1(a). The plane parallel stainless steel electrodes are mounted within a tight fitting Plexiglas tube to avoid long-path breakdown [5]. The gas inlet and outlet are mounted at opposite sides of the discharge tube. A flux of argon (typically 25 sccm) is used as feed gas to minimize the influence of impurities. The outer and inner walls of the Plexiglas tube are polished to improve the optical access to the plasma volume. The area between each electrode end and the Plexiglas tube is shrouded by a Teflon insulator as indicated in figure 1(b). The discharge gap can be changed by a micropositioning linear stage, but was fixed at \(d = 1 \text{ mm}\) during the experiments. Electrodes with a diameter of 8 mm were used. The experiments were performed close to the Paschen minimum at \(pd = 1 \text{ Torr cm}\).

The electrical circuit is shown in figure 1(c) and is similar to the one presented in [30]. The voltage is monitored with a high voltage probe. The current is determined from the voltage drop over a monitoring resistor and corrected for the displacement current. To calculate the displacement current, the capacity \(C_d\) of the discharge is determined from measurements of the current and voltage during a short voltage pulse in vacuum.
image because of the low light emission intensity. Therefore, the charge gathered on the CCD chip is accumulated within a single pulse each time the discharge is running under identical conditions (the same current and voltage). An external delay generator is triggered on the signal of the discharge current each time the signal passes the falling slope of the set threshold voltage. The delay generator controls the gate position and gate width of the ICCD camera.

2.2. TDLAS setup

The small dimensions of microdischarges and their operation at high pressures are a challenge for optical diagnostics, since high sensitivity and high spatial resolution are required. For the TDLAS measurements a diode laser with an external cavity in Littrow configuration is used. The linewidth of the laser (<10 MHz) is much smaller than the width of the absorption line. Figure 2 shows a schematic of the TDLAS experimental setup. The laser beam from the DL passes through two beam splitters. Part of the beam is guided to a Fabry–Perot interferometer (1 GHz free spectral range) and another part through a low-pressure reference cell, both necessary to calibrate the system. The part of the beam transmitted through the beam splitters into the discharge is attenuated by neutral density filters with an optical density in the order of 3, and guided into the discharge with a beam power of the order of a few µW, to avoid any saturation effects. After passing the discharge the beam is guided through a set of apertures and filters to suppress the emission from the plasma by reducing the collection angle and blocking wavelengths different than the observed transitions. The transmitted beam intensity is measured by a fast photodiode that provides a time resolution of a few hundred nanoseconds. The wavelength is tuned to the 1s5 → 2p9 transition of Ar* at around 811.5 nm. After recording the spectral profile of the absorption line, the metastable density \( N_I \) is given by

\[
\int_0^\infty \ln \left( \frac{I_0(\nu)}{I(\nu)} \right) d\nu = S = \frac{e^2 f_{ik} I}{4\epsilon_0 m_e c} \cdot N_I,
\]

where \( I(\nu) \) and \( I_0(\nu) \) are the intensities of transmitted radiation with and without the presence of absorbing species, \( I \) is the path length through the absorbing medium, \( S \) is the area under the absorption curve that provides the line-averaged density of the absorbing species, \( f_{ik} \) is the oscillator strength of the line and \( N_I \) is the density of the lower level [31]. All constants and oscillator strengths were taken from the NIST Atomic Spectra Database. Details about the calculation of metastable densities from the spectral profile are described in a previous publication [32].

Due to the cylindrical geometry of the Plexiglas tube, the optical path through the discharge can only be retraced coarsely. For this reason the laser beam was intentionally set up with poor spatial resolution to cover the complete active region of the discharge with a spot size of about 0.5 × 2 mm², providing the discharge integrated metastable density. Taking the vertical divergence of the beam into account, the mean absorption length \( l \) through the plasma was approximated to be 7 mm.

3. Results and discussion

3.1. Steady-state V–A characteristics and axial light emission

Figure 3 shows the V–A characteristics recorded under steady-state discharge conditions. Between the low-current Townsend-like discharge and the normal glow discharge a region of currents and voltages exists where no steady-state regime can be reached for any discharge conditions. These instabilities were detected in standard size discharges and described through a combined effect of the external circuit and the effective negative differential resistance that may be observed in V–A characteristics [12–15, 33]. The cause of negative differential resistance is the slightly increased electric
Figure 4. 2D images of the axial light emission profile of steady-state discharge. Labels (1)–(4) correspond to the conditions indicated in figure 3. The cathode and anode are located at $-0.5\text{ cm}$ and $+0.5\text{ cm}$ respectively. Dotted lines mark the central axes of the discharge chamber, while solid lines mark the position of the peak of emission. The discharge current is shown in the bottom lefthand corner of each image. The bar on top of each image indicates the discharge intensity recorded by the ICCD camera. (1) Townsend-like discharge. (2)–(3) Normal glow discharge. (4) Abnormal glow.

In the low-current diffuse Townsend-like mode (label (1)) the discharge emission is growing exponentially from the cathode to the anode where it reaches its maximum. The discharge current is low enough so that the space charge effect cannot change the homogeneous external field significantly. The discharge spreads over the full electrode diameter and has the profile of a Bessel function. By the increase in discharge current the discharge changes to the normal glow (label (2)). The peak of the axial distribution moves toward the cathode, indicating the formation of the cathode fall. In the radial direction the discharge is highly constricted. The constrictions are shifted away from the center toward the electrode edge. The position of the constrictions is stable and is the result of the local variation of the secondary electron yield which seems not to be affected further by the discharge current. As current is further increasing (from 2 to 3) the current density stays constant and the discharge is spreading in the radial direction. Between points (2) and (3) in figure 3, the discharge is operating in the normal glow, similar to low pressure, large scale discharges [16]. At point (3), the discharge occupies the whole electrode diameter, which marks the ending point of the normal glow. From this point the discharge runs in abnormal glow (label (4)). The current increase leads to a higher light intensity. The peak intensity shifts closer to the cathode and marks the cathode fall edge. All of these observations in our microdischarge are also typical for standard size discharges [16, 34].

3.2. Time resolved 2D emission distributions of discharge transients

As noted in the previous section, there is a region of instabilities where the discharge is not stable. This oscillatory behavior is described through dynamic $V$–$A$ characteristics (figure 3, circular blue line). The characteristic hysteresis, previously reported for hollow cathode discharges [35] and parallel plate standard size discharges [16, 17] for relaxation oscillations, is present: the discharge current starts from the low-current regime and runs through the upper branch to the maximum current value and turns again to the low current. The time
Figure 5. Discharge voltage (with subtracted breakdown voltage $V_b = 224$ V) and current as a function of time during oscillations ($pd = 1$ Torr cm). The corresponding $V-A$ characteristic is presented in figure 3. The solid dots (a)–(h) indicate the conditions of the 2D images shown in figure 6 and the corresponding axial emission profiles at the peak of emission shown in figure 7. Dashed lines mark the positions of the maximum of each current peak while solid lines indicate the (positive) maximum of each voltage peak.

resolved voltage and current waveforms of transients are presented in figure 5. Both the dynamic $V-A$ characteristics in figure 3 and the waveforms in figure 5 show the same transient behavior of voltage and current except for the first transition from low to high current. The first transition is different because the voltage first follows the shape as expected for operation under conditions of pristine gas without free charged particles, as seen in [16]. During later transitions the charged species and excited atoms from the previous discharge remain, and thus reduce the breakdown voltage. Therefore, the discharge switches to self-sustained oscillations and the shape of the current and voltage signal is necessarily different. The periodic behavior allowed us to accumulate light signals from different transients within a single voltage pulse to record reliable images, as described in section 2.1.

Figure 6 shows 2D images of the axial light emission recorded by the ICCD camera at different discharge voltages and current values, as indicated by the labels (a)–(h) in figure 5. The corresponding axial light emission profiles at the peak of emission are presented in figure 7. In the transient regime the discharge develops from the low current Townsend-like diffuse mode to the high current normal glow mode. It should be pointed out that images during the oscillations (figure 6) and in steady state (figure 4) have been recorded with different exposure times, therefore absolute intensities between these two measurements cannot be compared directly.

During the transient Townsend-like mode (label (a)) the discharge is diffuse and the peak of emission is close to the anode. The discharge occupies the full electrode diameter. The light emission increases exponentially from the cathode to the anode, which is characteristic for a homogeneous electric field with negligible space charge effects. The current rises and space charge builds up slowly, leading to a small drop of the voltage (label (b)). At the same time the light emission of the discharge increases and the peak of emission moves away from the anode. The cathode fall develops as the discharge current is rising further (label (c)). The peak of emission is shifted to the cathode and the discharge is highly constricted. Comparing the current values and the emission profile with the steady-state conditions (figure 4(2)) we conclude that the discharge is operating in the normal glow. At the current maximum (label (d)) the light emission has reached its highest value and the peak of emission is located almost at the middle of the discharge gap. The discharge is less constricted in the radial direction than in the previous state (label (c)), again characteristic of the normal glow. As current drops (labels (e) and (f)), the peak of emission moves back from the center toward the anode, while the profile becomes more Bessel-like. Finally at low currents the discharge operates in the Townsend-like mode again (label (g) and (h)) as indicated by the diffuse discharge spread over the discharge diameter (figure 6) as well as the exponential increase in the light emission from the cathode to the anode (figure 7). Afterwards, this process repeats.

3.3. Gas temperature under steady-state discharge conditions

The gas temperature and the metastable density have been determined from the Gaussian part of the line profile measured by TDLAS.

Figure 8 shows examples of the absorption profiles of the Ar* $\text{1s}_5 \rightarrow \text{2p}_9$ metastable transition for varying discharge currents in the low-current Townsend-like steady-state mode. Measurements have been taken at $pd = 1$ Torr cm.

The absorption line profiles are described by a Voigt-profile, a convolution of Gaussian and Lorentzian profiles, both having contributions in the same order of magnitude in this case. The area under the Voigt-profile is directly proportional to the absolute metastable density. The Lorentzian profile is primarily caused by pressure broadening and adds to the line profile with about 240 MHz for a pressure of 10 Torr. Stark
Figure 6. 2D images of the time development of the axial light emission during oscillations. Labels (a)–(h) correspond to the conditions indicated in figure 5. The cathode and anode are located at −0.5 cm and +0.5 cm, respectively. Dotted lines mark the central axes of the discharge chamber, while solid lines mark the position of the peak of emission. The discharge current is shown in the bottom lefthand corner of each image. The bar on top of each image indicates the discharge intensity recorded by the ICCD camera.

broadening can be neglected in this case due to the low electron density. The profile, determined by the Doppler broadening, is strongly temperature dependent, and varies between 750 and 850 MHz for typical discharge conditions. The Ar* 1s5 → 2p9 transition is commonly used to measure the gas temperature from the Doppler width of the absorption line, since these metastable levels are in quasi-equilibrium with the ground state atoms, due to equipartition of kinetic energy between particles with similar masses in elastic and metastability exchange collisions [36].

The widths of the Gaussian component $\Delta \nu_D$, caused by Doppler broadening, are described by

$$\Delta \nu_D = \frac{2}{\lambda_0} \left[ 2 \ln(2) \frac{k_b T}{M} \right]^{1/2},$$

where $T$ is the temperature of the absorbing species (here assumed equal to the gas temperature), $M$ the mass of the species and $\lambda_0$ the central wavelength of the observed transition [37]. For current spectra the temperature could be calculated with an uncertainty of less than 1%.

Measurements reveal that with increasing discharge current the gas temperature rises from around ambient temperature up to 400 K. As electron density and temperature correlate with the discharge current, metastable densities increase as well, because the main excitation source for metastable species is provided by direct electron collisions. Similar measurements have been performed in the high-current steady-state glow regime. The discharge current was varied between 186 µA (lowest possible current after oscillations) and 315 µA (maximum limit of the power supply). The gas temperature rises from 469 to 526 K and the metastable density from $2.1 \times 10^{10}$ cm$^{-3}$ to $3.2 \times 10^{10}$ cm$^{-3}$.

The dc results have somewhat greater but similar densities for the metastable atoms as the oscillating discharge transient (see figure 9). Thus the pulsed current peaking above 500 µA yields a density of $2.4 \times 10^{10}$ cm$^{-3}$ while the dc glow discharge at 315 µA leads to $3.2 \times 10^{10}$ cm$^{-3}$. As can be seen from the slope of the metastables’ density the majority of the metastables are produced at the peak of the current. The period when the current is above 50% of the peak value (4 µs) is
less than 50% of the duration of the metastables’ pulse. The effective current is thus around 270 µA while the effective metastables’ density is around 1.3 × 10^{10} cm^{-3}. Bearing in mind that the period of the metastables’ pulse is twice the duration of the current pulse, the effective excitation rates in steady-state and self-pulsed operation appear to be similar. Nevertheless it is evident that losses are high and thus in self-pulsed operation the losses would be twice as high as in dc operation which would require a more efficient production of metastables in the pulse. As the excitation coefficient increases rapidly with E/n [38] and instantaneous E/n also overshoots (see figure 3) the steady-state values, the results indicate an increased effective production of metastables in the oscillating mode as compared with the steady-state conditions.

3.4. Time development of metastable densities during oscillations

The metastable densities presented in figure 8, which have been measured for low currents, already show that the species are a considerable source of potential energy in the system. The direct collisional electron excitation of Ar* from the ground state is a strong energy sink for electrons more energetic than the Ar* excitation threshold of 11.5 eV.

The temporal metastable evolution, as shown in figure 9, is highly correlated with the rise of discharge current. The maximum of each current peak (indicated by dashed lines) coincides with the highest metastable production rate, which is given by the maximum of the first derivative. This is in agreement with the fact that the metastable atoms are produced mainly by direct electron impact excitation. Absolute densities reach maximum values of about 2.4 × 10^{10} cm^{-3} (indicated by solid lines) 2.5 µs after the current peak, since the metastable excitation rate still exceeds the loss rate although the current is decreasing. The metastable decay during the decline of discharge current is a convolution of residual metastable production and the limited lifetime of the species. After the current ceases the decay is purely determined by the primary loss processes, namely diffusion, two- and three-body collisions with ground state atoms, and Penning ionization loss due to impurities.

Metastable lifetime measurements were performed in the constant low-current regime of the discharge, to exclude any influence of electrons on the de-excitation of the species. The lifetime values are given as the decay constant of an exponential function fitted to the density profile in the decaying tail. Under the given discharge conditions the metastable lifetime was measured to be 4.5 µs.

Assuming infinite purity of the argon gas, we can propose that the metastable lifetime is simply determined by diffusion to the walls and the two- and three-body collision processes with argon ground state atoms. For given discharge conditions metastable pooling can be neglected since their influence is about two orders of magnitude weaker. The dominant loss channels would therefore be

\[
\text{Ar}^* + \text{Ar} \rightarrow 2\text{Ar}
\]

\[
\text{Ar}^* + 2\text{Ar} \rightarrow \text{Ar}_2 + \text{Ar}
\]

\[
\text{Ar}^* + \text{wall} \rightarrow \text{Ar},
\]

leading to a calculated metastable lifetime in pure argon (p = 10 Torr; T = 300 K) of

\[
\tau = \left( K_2 \cdot N_{\text{Ar}} + K_3 \cdot N_{\text{Ar}}^2 + D_{\text{Ar}} \cdot \Lambda^{-2} \right)^{-1},
\]

where K_2 = 2.3 \times 10^{-15} \text{cm}^3 \text{s}^{-1} is the rate coefficient for two-body collisions, K_3 = 1.4 \times 10^{-32} \text{cm}^6 \text{s}^{-1} is the rate coefficient for three-body collisions, N_{\text{Ar}} = 3.3 \times 10^{17} \text{cm}^{-3} is the argon ground state density at room temperature, D_{\text{Ar}} = 7.28 \text{cm}^2 \text{s}^{-1} is the diffusion coefficient and \Lambda = [(\pi/\text{length})^2 + (2.405/\text{radius})^2]^{-1/2} is the characteristic diffusion length in the discharge chamber [39]. These coefficients produce rates at 10 Torr pressure of 700, 1500 and 7500 s^{-1} which leads to a calculated lifetime of 103 µs.
The calculated lifetime is clearly larger by a factor of more than 20 than the measured value (4.5 μs). One should note that Molnar and Phelps found smaller values for these rate coefficients ($K_2 = 1.2 \times 10^{-15} \text{ cm}^3 \text{s}^{-1}$ and $K_3 = 0.85 \times 10^{-32} \text{ cm}^6 \text{s}^{-1}$) and that other but similar values are often used in the literature [40–43], but none of those values would suffice to put this lifetime based on the ground state atom quenching and diffusion in line with the experiment.

As the measured lifetime values are much lower, the first instinct would be that the discrepancy can be attributed to the loss of metastable atoms by the excitation transfer to impurities. Assuming that the dominant impurity contribution is due to residual N$_2$ molecules (the O$_2$ quenching rate coefficient is in the same order of magnitude), the impurity level can be estimated:

$$N_{N_2} = \frac{k_{N_2}}{k_{N_2}} \cdot (\tau^{-1} - k_2 \cdot N_{Ar} = K_3 \cdot N_{Ar}^2 = D_{Ar} \cdot A_{Ar}^{-2}),$$

where $N_{N_2}$ is the molecular nitrogen density and $k_{N_2} = 3 \times 10^{-11} \text{ cm}^3 \text{s}^{-1}$ is the quenching rate coefficient of argon metastable atoms with nitrogen [44]. Taking the measured lifetime into account, the impurity intrusion is in the order of 2%. Taking the large surface-to-volume ratio and the low pressure of the discharge into account the estimated amount of impurities could be accepted, but it is still excessive.

In addition to the impurities, the large losses and therefore the short lifetime of the metastables may be explained by electron induced quenching, which has been established to be the main loss process in higher density plasmas, such as inductively coupled RF plasmas [24]. Taking the total current and the effective area into account, the electron density for an identical field distribution can be estimated as a function of $pz$ (where $z$ is the axial coordinate and $p$ is the pressure) by applying a hybrid calculation as used for the standard size discharge [45]. The estimated electron density is then in the order of $10^{12} \text{ cm}^{-3}$. This may be coupled with a reasonable value of the electron-induced quenching, which is in the order of $(2–5) \times 10^{-7} \text{ cm}^3 \text{s}^{-1}$ [46–48]. Thus the equivalent lifetime is roughly 4.8 μs. This lifetime is consistent with the experimental observations. Electron-induced quenching may proceed by collisional coupling of the metastables to the nearby radiative state (threshold less than 0.1 eV), collisional coupling to 2p states and ionization. It appears that electron-induced quenching may be the dominant loss channel for metastables during the early afterglow in microdischarges even when diffusion is quite high due to a larger surface-to-volume ratio.

Two further issues need to be resolved before making such a claim. The first is the maintenance of the electron density in the ‘afterglow’, and the second is the thermalization of the electron energy below the threshold required to realize electron induced transitions to higher excited states, which is in the order of 1–2 eV. Modeling of breakdown delay times in argon reveals that the period when diffusion is ambipolar (and the losses of electrons are consequently relatively small) is relatively long and for our conditions it exceeds the measured lifetime by almost an order of magnitude [49]. On the other hand we have performed a Monte Carlo simulation of the thermalization of the electron energy distribution function (EEDF) in the afterglow [50]. Starting from a typical EEDF with a mean energy of 4 eV, we have followed the time dependence of the electron population at different energies. The high-energy tail decays very rapidly for less than or around 1 μs. However the decay to 2 eV mean energy takes several microseconds and the decay to 100 meV would take 0.5 ms. In other words, during the period of decay of metastables there is a sufficient number density of electrons with a sufficient energy to maintain the electron-induced quenching of metastables.

4. Summary

We have shown time resolved axial light 2D images of a parallel plate dc microdischarge in steady state as well as during...
discharge transients. The static V–A characteristics are similar to large-scale, low-pressure discharges, with a distinct low current diffuse mode, and a normal and abnormal glow. The measured axial distributions support this similarity between microdischarges and large scale, low pressure discharges. The region of oscillations was found between the low-current mode and normal glow. During the relaxation oscillations the discharge develops from the low-current mode (several μA) to the high current normal glow mode (~600 μA), repetitively. With increasing current the discharge intensity rises and the peak of emission moves away from the anode as the cathode fall develops. The normal glow has a constant current density and shows characteristic constrictions of the conducting channel, which grows in diameter as the current increases.

The time development of the Ar metastable densities in the discharge has been measured by tunable diode laser absorption spectroscopy. The discharge current and the metastable density are highly correlated. At the current maximum the highest metastable production rate can be observed. During the operation of the discharge electron-induced excitation and eventually dissociative recombination produce a large population of metastables allowing stepwise processes that affect the ionization balance, but are also the dominant metastables’ quenching channel. It is possible that impurities contribute but excessive abundance of N2 of 2% is required to explain the results. During the effective afterglow (the decaying part of the current and the period when the current is at a constant low value) electron-induced quenching controls the rapid loss of metastables. Even though the high-energy tail of the EEDF decays rapidly, the mean energy decays slowly and it takes hundreds of microseconds to fall below the threshold for collisional coupling between metastables and resonant states.

In a recent paper published independently of this work a similar experiment was carried out with a more detailed model [51]. The higher pressure of that work favored three-body processes but in general they come to the same conclusions as we do: that the fast loss of metastables is dictated by the large electron-induced quenching in the early phases of the afterglow.

Gas temperatures and Ar metastable densities have been determined under steady-state discharge conditions from the line broadening of recorded absorption profiles for the low-current Townsend-like mode ($T_g = 320–400$ K, $N = (1,3–9,0) \times 10^{10}$ cm$^{-3}$) and the high-current glow mode ($T_g = (469–526)$ K, $N = (2,1–3,2) \times 10^{10}$ cm$^{-3}$).

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