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Spatially and temporally resolved electron density measurements in streamers in dielectric liquids

Peter Bårmann†, Stefan Kröll† and Anders Sunesson‡

† Department of Physics, Lund Institute of Technology, PO Box 118, S-221 00 Lund, Sweden
‡ ABB Corporate Research, Department H, S-721 78 Västerås, Sweden

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Abstract. Spatially and temporally resolved spectroscopic measurements of light emitted from positive streamers in transformer oil are presented. Analyses of the measurements performed with a DC needle–plane gap yield electron densities and indications of the atomic excitation temperatures in the streamers. The hydrogen emission reveals an electron density below 10^{16} cm^{-3} during the main part of the streamer propagation time (80–90%). Later the light is also characterized by emission from a high-density plasma with electron densities in the range 10^{18}–10^{19} cm^{-3}. The electron density during this time increases approximately linearly with distance from the initiation point and a density factor of four higher has been measured at the streamer tip than at the root. Measurements with high spectral resolution detect both high and low electron densities simultaneously. A tentative model of the interior of the streamer plasma, spatially resolved, is presented.

1. Introduction

The objective of the presented work is to investigate basic physical mechanisms of the initial stages of electric breakdown in liquids. Previous work important for this topic includes experimental studies using imaging, broad-band light emission measurements and current measurements [1–10]. Therefore, a lot is today known about the streamer's appearance, streamer initiation and streamer propagation. However, relatively few experimental studies have focused on the physical processes in the interior of the streamer channel. Pioneering experiments using emission spectroscopy [9–13] revealed decomposition products such as carbon radicals and hydrogen atoms during streamer propagation. Further spectroscopic work concentrating on analysis of the properties of the streamer plasma has been presented in [14].

The aim of the present work, which is a continuation of that in [14], is to achieve a more thorough physical understanding of the internal streamer processes. This is mainly done utilizing emission spectroscopy and applying atomic and molecular physics theory. Although the methods used are well known, they have not previously been applied fully to this field of research. Primarily, emission spectra from positive streamers are analysed to obtain the electron density and indications of the temperature in the streamers. The electron density is determined from the dynamic Stark broadening of the hydrogen Balmer α line. The theory has been presented in [15, 16]. Indications of the temperature are mainly obtained from the hydrogen line intensities, but also from the temperature-dependent rotational–vibrational emission of the C_2 radical.

The earlier measurements presented by our group on positive streamers yielded very high electron densities, of the order of 10^{18} or even 10^{19} cm^{-3} [14]. These values were obtained late in the propagation process but the experimental technique did not provide measurements of sufficient quality to allow one to study the earlier stages. The high electron densities obtained were incompatible with the available amount of energy under the assumption of a radially homogeneous charge distribution in the streamer filament. The energy supplied by the streamer current is simply not sufficient to ionize the whole streamer volume to the degree that was found. An earlier thorough theoretical estimation of the streamer electron density assuming homogeneous radial charge distribution is to be found in [17]. The energy-consuming processes, vaporization, decomposition, ionization and mechanical work, were taken into account and resulted in an electron density value of around 10^{16} cm^{-3} in positive streamers. Considering this together with the experimental results, it seemed that the streamer plasma must be inhomogeneously distributed at least shortly before breakdown and that it probably possess a radial structure. The present work tends to justify this assumption.

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In this paper the whole positive streamer process has been characterized with spatially and temporally resolved emission spectra for streamers in a needle–plane gap and with DC voltage. The measurements primarily yield the electron density and this quantity has been monitored for different positions along the needle axis and for different times before breakdown. The new results show emission also from a weakly ionized plasma, electron density $<10^{16}$ cm^{-3}, during the main part of propagation and, with increasing intensity, emission from a dense plasma, electron density $>10^{18}$ cm^{-3}, starting approximately 1 μs before breakdown. The electron density in the dense plasma is also shown to be dependent on the position along the streamer and the applied electrical field.

2. The experimental arrangement

The experimental arrangement used, figure 1, includes a high-voltage supply ($\pm$0–65 kV) connected to a test cell with a needle–plane gap filled with Nynäs Nytro 10x transformer oil. The needle radius is about 30 μm. Two optical fibres collect the streamer light emission and transfer it to two detectors. A photo-multiplier tube (PMT) detects the light from a 10 m long fibre, and a spectrograph with an intensified and cooled diode array detector detects the light from a longer (70 m) fibre bundle. The optical fibre bundle was specially designed for the detection system to achieve a high optical throughput together with high spectral resolution and a necessary propagation time delay of 300 ns. The minimum gate time of the detector is 100 ns. Synchronization of the system is handled by a dual input gate generator and a pulse amplifier. One gate generator input is fed a streamer start pulse from the oscilloscope and the other input receives a pulse from a photodiode, viewing the electrode gap, when a breakdown occurs. The detector gate can be specified with an arbitrary length and delay with respect to the streamer start pulse. If the gate is ‘on’ when the photodiode breakdown pulse arrives, the gate pulse is shut off. Since the gate is turned off within 250 ns and the very strong light emission from the breakdown arc takes 300 ns to travel through the fibre, the detector is protected from the breakdown emission. This light could otherwise destroy the intensifier in front of the detector. The broadband light emission that is detected by the PMT is recorded on a 1 G s/s digital oscilloscope (Tektronix TDS 540) together with the current induced in the gap. The current is detected via a protection system that bypasses the current to earth in the event of a breakdown. The bandwidth of the protection system is more than 700 MHz and the oscilloscope bandwidth is 250 MHz. The spectrograph and the fibre are wavelength- and intensity-calibrated for correct spectral response using a mercury lamp and a calibration lamp. Possible absorption of the oil can be disregarded in this procedure since the oil has negligible absorption in the wavelength region of interest (400–700 nm).

The needle in the presented experiments was directly coupled to the DC HV supply output via a 150 MΩ resistor. This generates positive streamers from the needle [8] with a frequency set by the applied voltage to be around 20 Hz. Due to the current limitation by the resistor the breakdown arc following each streamer growth is weak and growth of a new streamer can start shortly thereafter. The technique is discussed further in [18]. Its great advantages are savings in data acquisition time and, since many spectra can be averaged in a short time, a high signal-to-noise ratio. In fact, without this technique, measurements on the early phase of streamer propagation would not have been possible with our equipment, due to the low light intensity. A possible error source in this measurement is that the liquid will have ‘remembered’ the previous discharge occurring 50 ms earlier. However, the spectra recorded in this work look the same as the spectra of the pre-breakdown events in the case of a single isolated laser-initiated breakdown process [14] or spectra from a single high-voltage pulse-initiated breakdown process in the needle–plane gap, although the signal-to-noise ratio in those cases was insufficient for a more detailed analysis. Thus there is no indication of a significant influence due to the short rest time between the discharges.

3. Results

3.1. Time and position of measurements

Measurements were performed for different locations and different propagation times to characterize the electron density during the whole streamer process. In figure 2 the times and locations of the streamer spectra presented in this paper are indicated. The detector gate times are shown below the streamer current and PMT light traces. For the locations further from the needle, such as location C in figure 2, it may be noticed that both the stem of a streamer and the tip of other streamers can be detected at the same time. Especially the locations far away from the needle must therefore be considered as being an average of several different stages in the streamer process. For the spectra shown in this paper, the integration time was 60–90 s and each spectrum shown is the average of 1000–2000 streamers.

3.2. Time-resolved measurements

Figure 3 shows a typical (averaged) spectrum of positive streamers at the beginning of propagation, time 1 (figure 2), which was recorded at the streamer root, position A. In the spectrum narrow Hα and Hβ hydrogen emission lines of the Balmer series can be seen, as can several emission bands from the C_2 Swan band system. Narrow hydrogen lines are typical of the early part of the streamer propagation.

Single-shot measurements from later stages of propagation showing strongly broadened hydrogen lines, as a result of the Stark broadening, have previously been presented [14]. The width of a Stark-broadened line depends on the electron density and a higher electron density leads to a more pronounced Stark broadening. In [14] the broadening was thus used to determine the electron density in the streamer plasma by fitting theoretical Stark profiles to measured spectra. The experimental profiles were in good agreement with theoretical profiles. The hydrogen line width in figure 3 is limited by the resolution of the

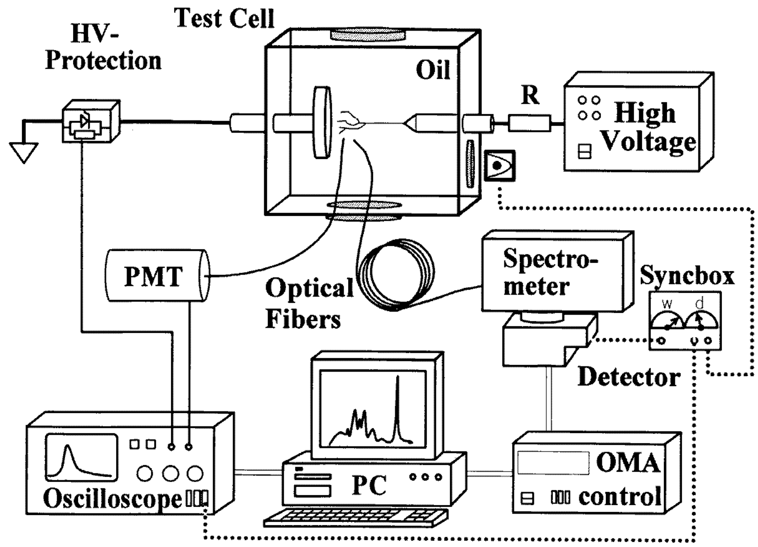

Figure 1. The experimental arrangement.

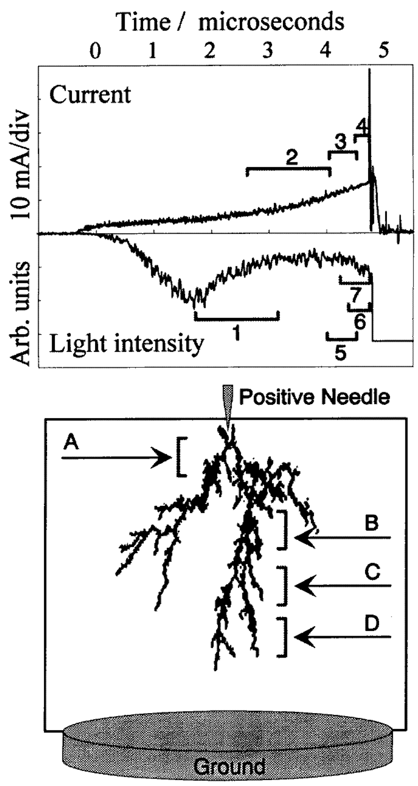

Figure 2. Light and current measurements and a schematic picture of positive streamers. The times and positions of presented spectra are indicated.

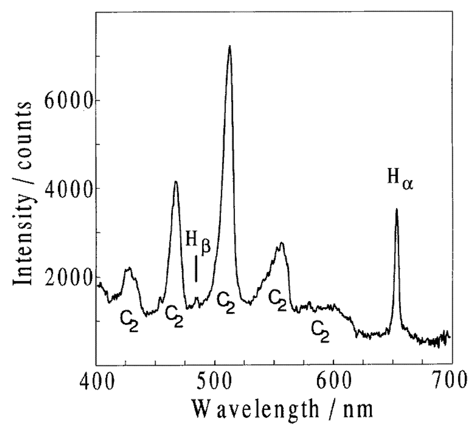

Figure 3. A positive streamer spectrum from the early stages in the streamer propagation, (period 1, position A in figure 2).

spectrometer and the electron density can therefore only be determined to be below a certain value (see the next section). A sequence of measurements such as those in figure 4 visualizes the change in time of the streamer emission. The measurements are from position A in a 10 mm point–plane electrode gap. For the first and largest part of the propagation time, figure 4(a), the streamers have a lower electron density than can be determined with the available spectral resolution. During the last microsecond before breakdown the average electron density is increased by more than two orders of magnitude, figures 4(b) and (c), up to above 10^{18} cm^{-3} (5×10^{18} in figure 4(c)).

3.3. Measurements with high spectral resolution

In measurements with higher resolution and an instrumental line width of 0.5 nm, figure 5, the narrow Hα line is still resolution-limited. The electron density in the emitting plasma during earlier stages of streamer propagation can therefore only be determined to be below 10^{16} cm^{-3}. The spectrum in figure 5 was recorded during period 1 and

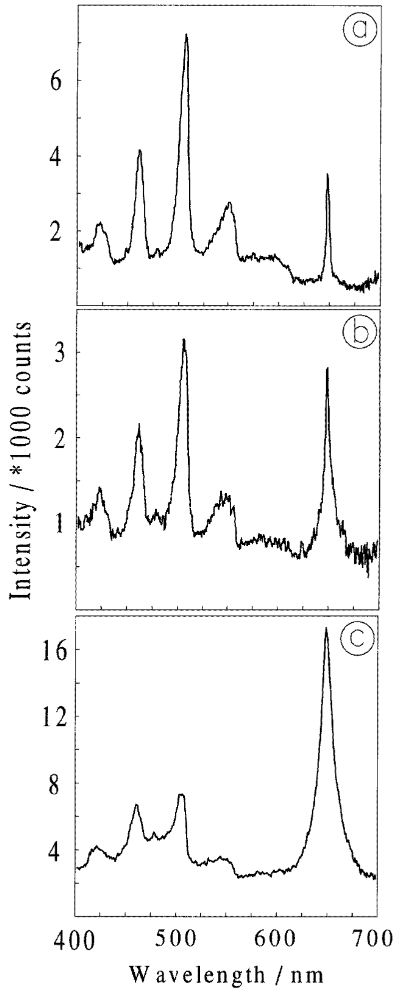

Figure 4. Streamer spectra from three different time periods before breakdown: (a) 1.7–0.7 μs (period 2); (b) 0.7–0.2 μs (period 3) and (c) 0.3–0 μs (period 4).

position B (see figure 2). The measurements also show that, during approximately the last 1 μs of propagation, the Hα emission consists of two components simultaneously, one narrow and one wide, figure 6. Figure 6 is an example of measurements at two spatial positions B and D (3 and 8 mm from the needle), during the periods 5, 6 and 7. The width of the narrow component is resolution-limited and has approximately the same intensity in all spectra. The width of the wide component is constant over time at one position but is higher closer to the streamer tip and the intensity increases with time.

3.4. High temporal resolution at later stages

The majority of the recorded spectra are of lower resolution (line width $>$ 2 nm). It was shown in high-resolution spectra that the narrow component is present for all propagation times with approximately the same intensity and for all positions in the streamer. When evaluating the electron density from the wide Hα component in low-resolution spectra, the narrow resolution-limited component was therefore subtracted before fitting a theoretical Stark profile. The last part of the propagation, during which,

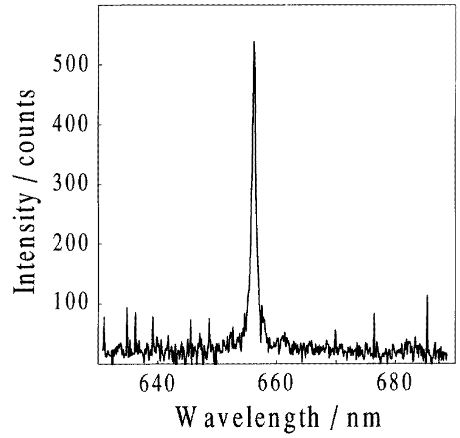

Figure 5. The Hα line in a positive streamer spectrum recorded in the early stages of propagation (period 1, position A in figure 2).

with the available resolution, a spectral change is only observable for the broad component, has been studied with high temporal resolution. Evaluation of low-resolution measurements for different time periods during the last 500 ns of propagation and at different positions relative to the needle tip is shown in figure 7. The measurements were obtained using a 200 m long fibre delay and triggering the detector with the breakdown event. The last 500 ns of the delayed light was then analysed with gate times down to 100 ns. It is clear from figure 7 that the electron density is higher closer to the streamer tip and is constant for one position during the last 0.5 μs. The intensity of the wide Hα emission increases rapidly with time before breakdown. Between 500 ns and up to some tens of nanoseconds before breakdown the intensity increases approximately tenfold. After that the intensity increases even faster and once again increases approximately tenfold before the breakdown occurs. The detected light intensity is generally higher at the streamer root (position A) than it is at the streamer tip (position D), but it increases faster closer to the streamer tip.

The electron density calculated from the wide component is found to increase with the applied electrode voltage. A presentation of the electron density variation with electrode voltage when emission both from the wide and from the narrow component in low-resolution spectra is included is shown in figure 8. The measurements were recorded from the three streamer positions A, B and C and include light from the whole propagation time.

Spectra from the beginning of the breakdown arc are different from streamer spectra with new emerging spectral components and have a very rapidly increasing intensity. This fact verifies that the presented streamer measurements are not influenced by breakdown arc radiation.

3.5. The streamer temperature

The temperature during the later parts of the streamer propagation was discussed in [14] in terms of the population

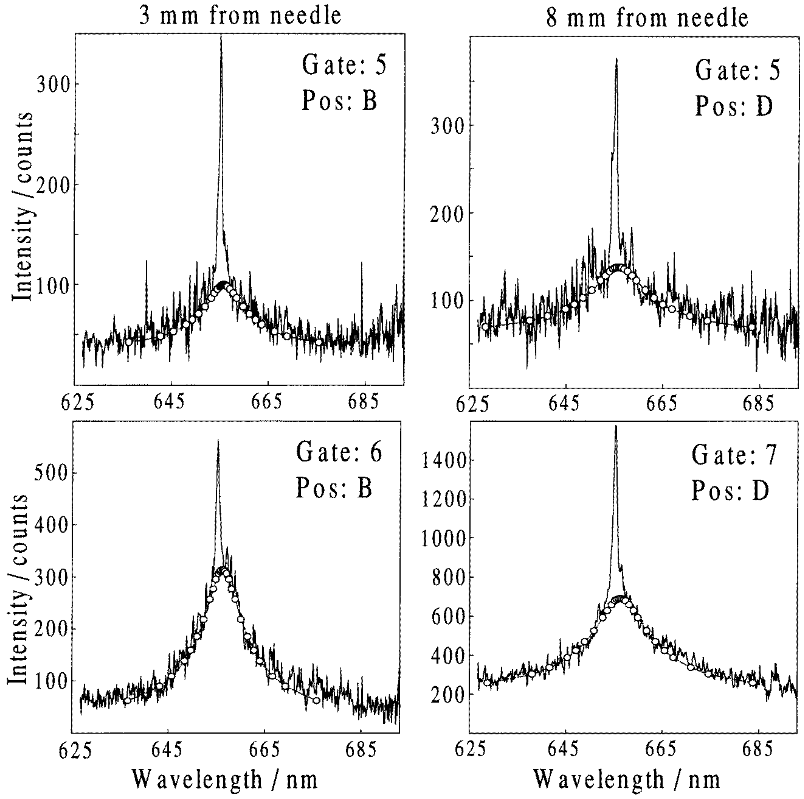

Figure 6. Spectra from two streamer positions and different times in a 10 mm gap. Corresponding positions and gate times, according to figure 2, are indicated. The electrode voltage was 55 kV. A theoretical Stark profile is fitted to each spectrum.

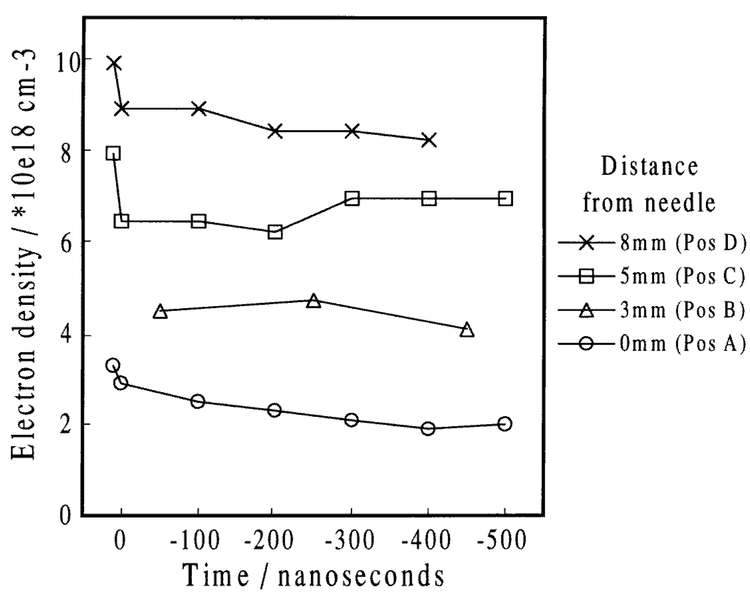

Figure 7. The electron density for four distances from the needle electrode, see also figure 2, as a function of time from breakdown.

difference in different electronic states. The temperature evaluation from the intensity ratio of Hα and Hβ in such spectra, figure 4(c) for instance, can only give an upper temperature limit of 10 000 K. This is due to the difficulty to determine the Hβ line intensity. Early in the propagation process with narrow hydrogen lines, figure 3, the determination of the Hα/Hβ intensity ratio is more precise. A temperature of 4000 K, for example, was

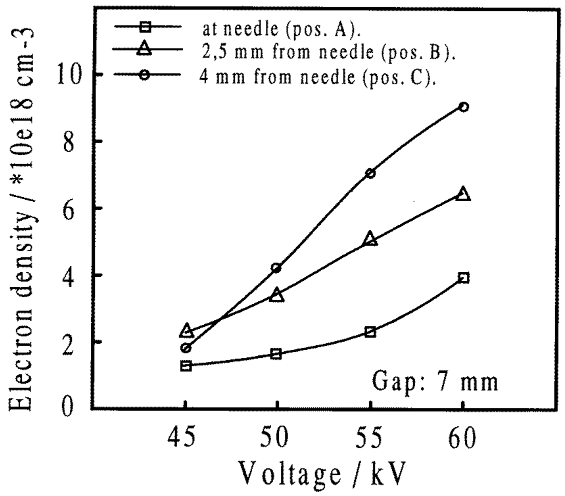

Figure 8. The average electron density as function of electrode voltage for three streamer positions.

found for the measurement in figure 3. The temperature obtained from the narrow hydrogen emission usually lies in the range 3500–6000 K, but much lower values have also been measured. In these measurements with low electron density, however, it is questionable whether there is a thermodynamic equilibrium. If not, the evaluated temperature does not correspond to the actual kinetic or gas temperature. Clearly the temperature determination as described above is very rough. Nevertheless, the range of temperatures present in the streamer processes is indicated and the technique can be used as an aid for comparing temperatures at different locations and at different times even if the absolute temperatures are unknown.

3.6. Radial electric fields

It has been found that radial electric fields from space charges in the streamers cannot have a major influence on the line shape [18]. The observed Stark broadening is therefore mainly a result of the high degree of ionization of the gas and thus the high electron density. Radial fields inside the streamer gas would accelerate ions, though, and might reach levels at which impact excitation and even ionization by the accelerated ions would be possible. This effect would increase the streamer temperature and also the intensity of the emitted light.

4. Discussion

To summarize the results of the streamer electron density (N_e) measurements for a 10 mm DC needle-plane gap we conclude the following.

(i) N_e is less than 10^{16} cm^{-3} for propagation times up to 1 μs before breakdown.

(ii) Emission occurs both from a low-density ($N_e < 10^{16}$ cm^{-3}) and from a high-density ($N_e > 10^{18}$ cm^{-3}) plasma region for propagation times from approximately 1 μs before breakdown until breakdown.

For the high-electron-density region during the last microsecond the measurements also show the following.

(i) N_e increases towards the streamer tip. A factor of four higher electron density at the streamer tip (position D) than at the root (position A) has been measured.

(ii) N_e is approximately constant over time for one spatial position.

(iii) N_e increases with higher electrode voltage.

(iv) The Hα emission intensity increases by several orders of magnitude during the last microsecond.

The two components of the electron density that have been found can give valuable information about the internal processes in the streamer during propagation. In an earlier publication [14] it was suggested that the streamer has a radial structure during the later stages of propagation. One reason to believe this is that the injected energy, as determined from the voltage applied and the measured current, is not sufficient to ionize the complete streamer plasma volume to the degree indicated by the electron density measurements. A possible explanation would be that only part of the streamer volume was ionized so that the conductivity was hardly affected. The idea that a dense plasma was situated at the centre of the streamer was put forward in the earlier work. It was then suggested that the streamer, like a gas discharge at high pressure, might experience a constriction of the conducting volume towards the centre of the discharge [14]. This intuitively seems a likely explanation. However, one could, in principle, also imagine other processes. A tentative picture of an internal streamer structure in which the dense plasma is concentrated around the rim of the streamer can also be made. In figure 9 the two cases are pictured schematically. A process that creates a dense plasma at the streamer rim would be the following.

During most of the propagation time, the electron density is low, corresponding to a low degree of ionization. The streamer current is mainly carried by the electrons while positive ions, created at the streamer tip due to field ionization [19] and in the filament due to impact ionization by the electron current, can be considered stationary in terms of their motion in the streamer propagation direction. A net charge of positive ions is thus accumulated in the filament. Due to the arising radial Coulomb field, the positive ions will drift towards the streamer–liquid boundary. As propagation continues, a positive space-charge layer at the streamer–liquid boundary is formed. This layer will also attract electrons to balance the high potential, and in this way it is conceivable that a denser plasma can be formed at the streamer–liquid boundary. Calculations indicate [18] that the radial electric field inside the streamer filament is not strong enough to cause the observed Stark broadening but may accelerate charges to energies sufficient to excite and ionize the streamer *gas* molecules. The broad Hα component could then be emitted from the more highly ionized space-charge layer at the plasma edge, while the narrow Hα component would be emitted from the bulk of the streamer which according to this model remains hardly affected also during the later stages of the pre-breakdown process.

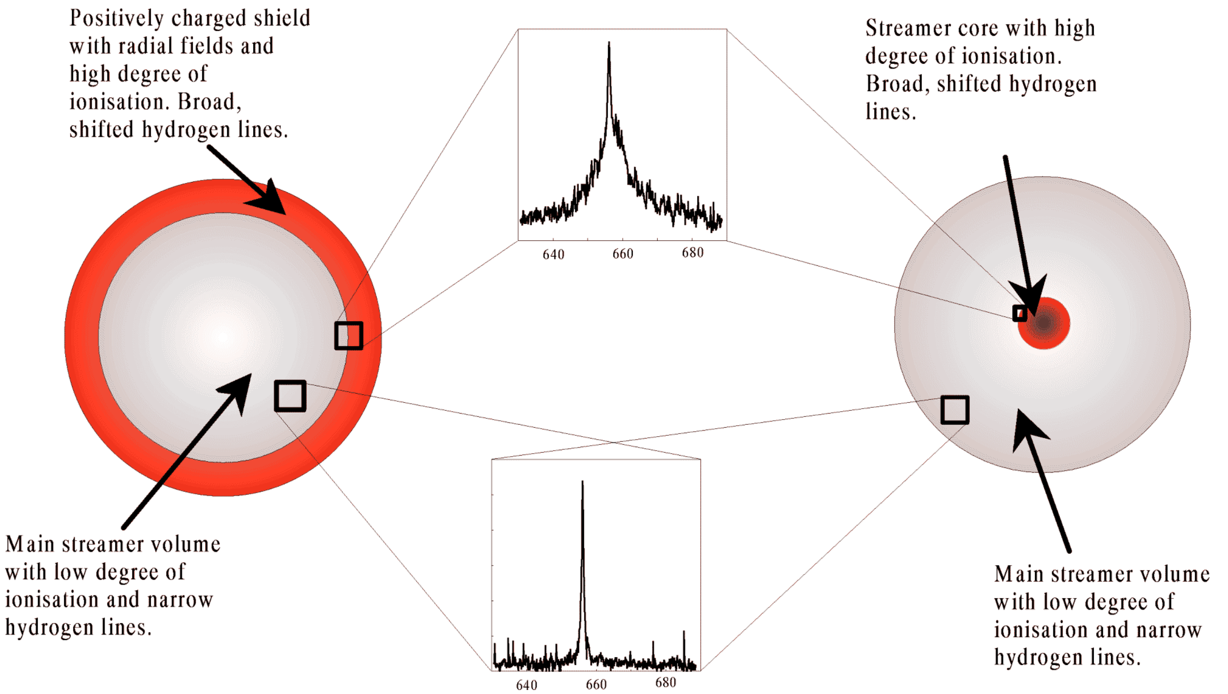

Figure 9. Possible models of the internal streamer structure. On the left; a dense plasma sheet in the outer parts surrounding a weaker, less ionized plasma. On the right; a weakly ionozed plasma surrounding a core with a higher degree of ionization.

It appears reasonable to explain the strong increase in light intensity with time from the dense plasma as being caused by an increased temperature. A larger degree of ionization does correspond to a higher effective temperature and a higher temperature also means a higher population of the emitting hydrogen 3p state. The upper state population according to the Boltzmann distribution will rise exponentially as a function of temperature, resulting in an exponential increase of emitted light intensity from the dense plasma region as a function of temperature. The temperature in the dense plasma region could actually be higher than the 10 000 K limit in, for example figure 4(c) since such a spectra could be an average of the high-ionization, high-temperature and small-volume plasma and the low-ionization, low-temperature and large-volume plasma. Furthermore, a conductivity increase in only a small volume will not affect the overall conductivity of the streamer too much, also keeping the current low during the later part of the pre-breakdown process (see figure 2).

That the C_2 emission at the same time does not show such a large intensity increase as does the Hα emission can be explained in terms of two possible processes. The temperature might reach values at which the C_2 molecule dissociates to a large extent. Also, the hydrogen emission may mainly originate from hydrogen ions, accelerated by the radial field, that recombine in the dense plasma sheet where they are de-excited through the Hα and Hβ transitions. A concurrent rise in C_2 emission would then not be seen.

Relevant parameters like conductivity, electron density and temperature are quite different in a dense and in a weak plasma. The two plasma types are for that reason in different conduction regimes such that the conductivity in the dense plasma is mainly determined by the temperature and not by the number density of charges, as it is for the weak plasma [20]. Calculations indicate that the dense plasma might have a one or two orders of magnitude higher conductivity. As has already been mentioned, the volume of this plasma should be small during the earlier stages and should then only have a limited influence on the streamer conduction and streamer current in this early phase. Later, when the dense plasma has increased in width and possibly also increased further in temperature, a rise in the streamer gas conduction should follow. This should occur during the last few nanoseconds of propagation in this set-up.

What does the detected rapid increase in electron density mean? It is possible that it is evidence of a phase change of the streamer, for which the pre-phase of a transition to a leader is one among other possibilities. An increase in temperature and thereby in the conductivity might lower the voltage drop over the streamer to make a transformation into a leader possible. In any case, we believe that the hydrogen emission can provide valuable information for understanding the processes occurring in a streamer.

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