Master

Optical study of breakdown phenomenology in metal halide lamps

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Optical Study of Breakdown Phenomenology in Metal Halide Lamps

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SUMMARY

The knowledge level with respect to breakdown in gas discharge lamps is far from ideal. Since the theory that can be used for designing these lamps is limited, in many cases the design is done by trial and error with some theoretical background to guide the direction. We try to build a bridge between all the knowledge from theory, numerical simulations and experiments under 'ideal' circumstances to a practical application. It is for instance not known when the high-pressure lamps ignite by a Townsend, fast ionisation wave or streamer mechanism.

The main objective of this traineeship is to gain more insight in the breakdown processes in metal halide lamps. This objective is pursued by the creation of an experimental set-up that follows the development of the discharge emission profile in time. In this way we can measure some important parameters and try to determine which mechanism is responsible for breakdown in the high pressure gas discharge lamps that are studied.

In our experiments we want to study the breakdown processes in a lamp by taking pictures of the discharges with an ICCD camera. The set-up consists of a high voltage generator, current probe, voltage probe, ICCD, controller and a function generator for triggering. The breakdown time can be as short as 20 nsec in some cases. Therefore an ICCD is needed with a very short (3 nsec) gate width. Furthermore timing is essential for this set-up. For our first measurements burners with an electrode distance of 0.7 cm filled with 300 mbar Argon are used. The applied voltage amplitude is varied from 2.5 kV till 4.0 kV. The breakdown phenomenology for both negative and positive voltage pulses is studied. To study the influence of important parameters like gas pressure, kind of gas and electrode distance, some special burners were created with gas pressures of 300 and 700 mbar, electrode distances of 1.5 and 2.7 cm and filled with Argon and Xenon.

We have succeeded in creating an experimental set-up capable of visualising the ignition processes that occur during tens of nsec with an accuracy of a few nsec. A large number of experiments have been carried out from which we gained more insight in the breakdown phenomena in HID burners. Those data consist mainly of pictures that were taken at different moments in time.

From experiments it seems that for all burners that are studied, the breakdown mechanism is never a Townsend breakdown for the voltage pulses we applied. The most important argument for this conclusion is that the ionisation front velocities are much higher than the electron drift velocities. So the breakdown mechanism seems to be fast ionisation wave, streamer or a combination of these two. This depends on the applied voltage, the amplitude but also the polarity, the pressure, the kind of gas that is used, the electrode separation and burner aspect ratio.

In case of a positive voltage pulse of 4 kV the ionisation region is a small channel and branching can occur, which implies a streamer mechanism. When a negative voltage pulse of the same amplitude is applied the high voltage electrode ionisation is much more diffuse, which is an indication for a fast ionisation wave mechanism. When the voltage amplitude is increased the breakdown mechanism shifts in the direction of the streamer mechanism. The ionisation front velocities increase significantly and the ionisation is less diffuse. An increase of pressure from 300 mbar to 700 mbar results in more branching and a decrease of the axial ionisation front velocity with approximately 40%. An increase of the electrode distance has a similar effect as an increase
of the pressure ($pd$ similarity). An increase of the electrode distance from 1.5 cm to 2.7 cm results in a 20% lower ionisation front velocity. The streamer velocities are approximately 10% higher in Argon than in Xenon. In Xenon more branching occurs than in Argon. In the high aspect ratio burners the wall is relatively closer to the electrodes. As a consequence the electric field is much more radially directed and the ionisation regions expand in the direction of the wall. For high aspect ratio burners the wall has a much more important influence on the breakdown processes. In case of positive voltages for instance, streamers always propagate along the wall in high aspect ratio burners and always through the gas in low aspect ratio burners.
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1 Introduction

1.1 General introduction

Streamers are a quite popular subject for research. Due to their complexity, there are still some open questions about streamers, like for instance the propagation mechanism of the streamer head. Most studies about streamers focus at observing streamers in ideal circumstances (no wall influences, very high electric fields). The main lamp-related applications of streamers within Philips Lighting are the ignition of high pressure lamps, where streamers exist in the first stages of breakdown, and high-voltage electronics where they try to avoid the development of streamers (spark breakdown). In this traineeship we are not interested in the fundamental questions about streamers, but more in the phenomenology of streamers in gas discharge lamps. The knowledge level with respect to breakdown in gas discharge lamps is far from ideal. Since the theory that can be used for designing these lamps is limited, in many cases the design is done by trial and error with some theoretical background to guide the direction. We try to build a bridge between all the knowledge from theory, numerical simulations and experiments under 'ideal' circumstances to a practical application. It is for instance not known when the high-pressure lamps ignite by a pure Townsend mechanism and when streamers do occur. This is one of the main objectives of this traineeship.

1.2 Objectives

The main objective of this traineeship is to gain more insight in the breakdown processes in high pressure gas discharge lamps. This objective is pursued by the creation of an experimental set-up that follows the development of the discharge emission profile in time. In this way we can measure some important parameters and try to determine which mechanism is responsible for breakdown in the lamps that are studied. Our main objective, to gain more insight, can be divided into the following secondary objectives:

- Creating an experimental set-up, that is capable of taking pictures of the discharge emission profile on a very short (nanosecond) time scale. This set-up can also be used to do measurements on other lamps, not only for research but also for solving starting problems.
- Determining which breakdown mechanism, Townsend, streamer of fast ionisation wave, occurs in high pressure lamps, and under which conditions.
- Determining the ionisation front velocity from measurements of the emission profile evolution and comparing this velocity with literature values.
- Varying multiple lamp parameters (kind of gas, gas pressure, applied voltage) to study their influences on the breakdown processes.
1.3 Different lamp types

We will divide the most important lamp types into five categories\(^1\). Each lamp type has its own weak and strong points, like price, dimensions and luminous flux. The luminous flux (in lumen) is defined as the spectral radiant flux (in Watt) multiplied by an eye-sensitivity function integrated over all wavelengths.

- **Incandescent lamps**: Due to its low price, small dimensions, simple dimming and excellent colour rendering the incandescent lamp holds a strong position in the world of lamps. The disadvantages are a relatively low efficacy (9-20 lm/W) and a limited lifetime (on average 1000 hours). The halogen lamp is a special case of an incandescent lamp. The halogen principle and the quartz envelope allow a higher filament temperature which causes a higher lm/W and allow a reduction of dimensions. This makes the halogen lamp very suitable for the creation of narrow beams of high luminous intensity. This is the only lamp type on this overview that is not based on a gas discharge.

- **Fluorescent lamps**: Due to its high luminous efficacy (45-105 lm/W) and good lifetime (10,000 – 60,000 hours) the fluorescent lamp is a very suitable light source for diffuse, functional lighting. Another advantage of this lamp is the large choice in colour temperatures, dimensions and power. The most used fluorescent lamp is the TL. In a TL-lamp the mercury atoms emit resonance radiation with a wavelength of 253.7 and 184.9 nm. This is ultraviolet radiation, which is converted by a fluorescent powder on the inside of the TL-tube into visible radiation.

- **Sodium lamps**: Its luminous flux and colour properties are entirely determined by the pressure of the sodium in the discharge. The well known yellow 589 nm Sodium-line is the only strong line of the low pressure Sodium (SOX) lamp. The high luminous efficacy (100-200 lm/W) and the long lifetime (up to 10,000 hours) make the lamp very suitable for applications where cost-of-ownership factors play an important role, such as road and security lighting. The development of transparent ceramic material (PCA) that is resistant to attack by sodium has made it possible to increase the pressure in the discharge lamp significantly (from 1 Pa to \(10^4\) Pa). The resulting widening of the Sodium-line gives the high pressure Sodium (SON) lamp a somewhat whiter colour and better colour rendition than the SOX lamp, though at a lower efficacy.

- **Mercury lamps**: The visible spectrum of a mercury discharge consists of four lines, violet (405 nm), blue (436 nm), green (546 nm) and yellow (579 nm) resulting in a blue/greenish colour. This makes the medium pressure mercury lamp not very suitable for general lighting purposes. The medium pressure mercury lamps are therefore mainly employed for special purposes, such as photo-chemical processes and disinfection. The high pressure mercury lamps on the contrary can and are used for lighting applications.

- **Metal halide lamps**: By adding various metal atoms to a mercury discharge lamp the colour properties can be significantly increased, making the lamps better suitable for general lighting purposes. In order to ensure that sufficient metals are present in the discharge, these metals are added in the form of halides, which in general have a higher vapour pressure than pure metals. The combination of high efficacy, higher colour
rendering index and large luminous flux make the HPI (addition of sodium, thallium and indium iodides) lamp very suitable for the lighting of high spaces, building exteriors, storage and sorting areas, sports halls and gas stations. The CDM (Ceramic Discharge Metal halide), with a ceramic tube instead of quartz, offers major improvements of the colour stability and colour rendering, making it more suitable for indoor applications.

In this traineeship we are interested in HID lamps, which stand for High Intensity Discharge lamps. It is the generic term of all high pressure lamps (high pressure sodium, mercury and metal halide lamps). The term "high pressure" is appropriate when the pressure is above 300 mbar.

1.4 Working of a HID-lamp

A schematic drawing of the cross-section of an HID-lamp is shown in figure 1.1. Not all HID-lamps have the same construction, but in general they resemble the construction shown in figure 1.1. The most important component of the lamp is the burner, consisting of a discharge tube (1) and two electrodes (6).

![Schematic view of a high-pressure lamp](image)

**Figure 1.1:** Schematic view of a high-pressure lamp[1,1]. The various components are: discharge tube (1), outer bulb (2), lamp cap (3), lead wires (4), getter (5), electrodes (6).

As discharge tube material usually quartz, PCA (Poly Crystalline Alumina) or YAG (Yttrium Aluminate Garnet) are used, since they are thermally and chemically resistant to the filling. For practical purposes PCA is preferred above YAG, since YAG burners are more expensive and have a shorter lifetime (1000 burning hours). In all lamps we studied YAG is used, since YAG is transparent in contrast with PCA (which is translucent). The electrodes are made of tungsten, due to its chemical resistance and in particular its high melting point. In normal HID-lamps the discharge tube contains a number of substances that can be divided into three categories:

- **Starting gas:** the most dominant gas present in a cold lamp. It determines the starting behaviour of the lamp until it is warm. For the starting gas a low ignition voltage, a high enough pressure to inhibit sputtering of the electrode and a small thermal conductivity to reduce the heat losses from the discharge to the tube wall are preferred. In practice the noble gases argon and xenon are mostly used.
• **Buffer gas**: the main constituent of the gas in the steady state. It largely determines the electrical and thermal properties of the discharge. The buffer gas usually has a low vapour pressure at room temperature. When the gas temperature increases its pressure increases and it will influence the behaviour of the lamp. The most common buffer gas is mercury vapour.

• **Radiation emitting substance**: In most cases, the buffer gas is also a radiation-emitting substance, as is the case in mercury for instance. Additionally, small amounts of elements can be brought into the gaseous state to take over the light-emitting function of the buffer gas. The elements Na, Sc, Tl, Dy and In are frequently used, due to their sufficiently high vapour pressure and because their emitted radiation is mainly in the visible spectrum.

The support wires provide the current through the discharge tube and keep the discharge tube in place. The outer bulb is sealed off gas tight. The lamp cap provides the electrical contact to the lamp fitting. The getter is used to keep the impurity level in the outer bulb low.

### 1.5 Starting of an HID-lamp

During the start of an HID-lamp the burner gas turns from an isolator into a conductor. A gas can only conduct a current when a large number of charged particles is present in the gas. These charged particles are created by applying a high voltage (few kV) to one of the electrodes for a short time (a few µs). The static V-I characteristic of a high pressure HID-lamp during its start is shown in figure 1.2.

![Figure 1.2: V-I characteristic for HID ignition](image)

In region (I) the voltage is not high enough for a self-sustaining discharge. Due to radioactive or cosmic radiation from the environment a small number of free electrons is created. When the applied voltage is increased to the breakdown voltage, the voltage is high enough for a
self-sustaining discharge and we arrive in region (II). According to a Townsend or a streamer mechanism the number of free electrons increases exponentially. When the current reaches a certain point, the voltage decreases due to the internal resistance of the circuit. This is called breakdown.

In literature a distinction is made between current breakdown and voltage breakdown. Current breakdown takes place when the current increases significantly at a constant voltage. This occurs at a very low current ($10^{-12}$ A). Since the sensitivity of the current probes we use is not high enough to measure such low currents, we just ignore this phase called current breakdown. From now on we will use the term breakdown for voltage breakdown.

As the current grows high enough, positive space charges are formed around the anode. This positive column grows towards the cathode. Since the positive column is a good conductor the voltage drop is mainly between the cathode and the positive column (cathode fall). We are now in region (V), which is called glow discharge because of the glow light that is visible around the cathode. Since the cathode fall causes a locally high electric field, the required glow discharge voltage is lower than the breakdown voltage. When the complete cathode is covered with a glow the voltage increases again, which is the transition zone to an arc discharge (anomalous glow discharge). Since the cathode fall also increases and ions are colliding with the cathode at higher velocities, the cathode is heating up. When the cathode temperature is sufficiently high thermoemission of free electrons from the cathode occurs. The required voltage to sustain the discharge then decreases. When the thermoemission is such high that it becomes the main source of free electrons we arrive in region (VII), the arc discharge.

We are only interested in the first part of the ignition, the (pre)breakdown phase (I and II). This is the part of the ignition before breakdown takes place (region III).

### 1.6 Outline of report

In chapter 2 the theory behind the Townsend, streamer and fast ionisation wave mechanisms is explained. In chapter 3 we give an overview of the experimental set-up we used for our experiments. During those experiments quite a large amount of data has been measured. To keep this report orderly, the structure of this report is slightly different from the usual structure in which first all results are represented followed by discussion and conclusion. The measurements are divided into two parts. The two lamp types we studied each have their own chapter. The low aspect ratio results are shown in chapter 4 and the high aspect ratio burner measurements in chapter 5. Each part consists of a representation of the results followed by a discussion. The differences between the low and high aspect ratio burners are discussed in a general discussion and conclusion (chapter 6).
2 Theory

In the beginning of the 20th century the research of gas breakdown could be divided into two branches. The first line of research was the study of lightning and laboratory sparks in air. The second line of research was the study of gas discharges in low pressure gases. The latter line made quick progress, leading to the avalanche theory by Townsend, which is described in paragraph 2.1. This Townsend theory was capable of describing the breakdown voltage as function of gas pressure and electrode distance of low pressure gases quite accurately. This theory, however, was unable to explain the fast breakdown at high pressures, e.g. lightning. It failed especially in long gaps with a strong field. A new theory that was able to explain the spark discharge was founded in the 1940s [2, 1]. This streamer breakdown theory is described in paragraph 2.2. A third breakdown mechanism, the fast ionisation wave, is discussed in paragraph 2.5.

2.1 Townsend mechanism and Paschen curves

A breakdown of a gas can be caused by different mechanisms. The first breakdown mechanism that is discussed, which is also the easiest to understand, is the Townsend mechanism. The other two are the streamer and the fast ionisation wave mechanism, which are discussed in paragraphs 2.2 and 2.5. Townsend occurs in cases of a low gas pressure and low over voltage. We will now discuss the Townsend mechanism in an idealised situation of two parallel plates at a distance $d$ and at a potential difference $V$. The volume between the plates is filled with a rare gas, argon or xenon for instance.

![Figure 2.1: Schematic of an electron avalanche.](image)

The size of the plates is much larger then the gap length $d$, so the electric field is uniform and the situation can be considered as one dimensional. Suppose that, for some reason, a free electron is formed between the plates. This can be caused by ionisation of a gas atom or emission of an electron from the cathode due to cosmic rays or due to radioactive or ultraviolet radiation (see paragraph 2.8 for more information about the creation of initial electrons). This initial electron is accelerated to the anode and its energy increases. When this electron has
gained enough energy it can ionise an atom by an inelastic collision. Due to this ionisation one new electron is created. The two electrons will be accelerated to the anode and each will create one new free electron by ionisation. This way the number of free electrons increases exponentially, forming a so called electron avalanche. The number of free electrons \( N_{\text{free}} \) as function of the distance \( x \) from the cathode is described by an ionisation coefficient \( \alpha \) \(^{[2,1-2,3]}\), also called the first Townsend coefficient. \( \alpha \) is defined as the number of ionisation acts per unit length executed by one electron when moving opposite to the electric field:

\[
dN = N_{(x)} \alpha dx.
\]  

When we start with \( N_0 \) free electrons at the cathode this number increases exponentially with the distance from the cathode

\[
N_{(x)} = N_0 \exp(\alpha x).
\]  

These free electron move towards the anode where they are absorbed and disappear from the gas. For a self-sustaining discharge to occur an additional electron emission source is necessary.

Secondary processes, like ion bombardment of the cathode and photo-emission generate secondary electrons at the cathode. This phenomenon is described by a \( \gamma \)-coefficient, which is defined as the number of secondary electrons produced per incoming ion. If all ions that are produced end up at the cathode (i.e. a 1-D geometry and no volume recombination), the number of ions created by one single primary avalanche is equal to number of free electrons created by ionisation:

\[
N_{\text{ion}} = N_{(d)} - N_{(0)} = N_0 \left( \exp(\alpha d) - 1 \right).
\]  

These secondary electrons that appear on the cathode lead to the development of a new avalanche. When the number of secondary electrons created at the cathode is smaller than the initial number of free electrons, the breakdown will decay. The criterion for a self-sustaining discharge is that the number of secondary electrons \( \gamma N_{\text{ion}} \) per avalanche is larger then the initial number electrons \( N_0 \), which is the case when

\[
\gamma \left( \exp(\alpha d) - 1 \right) > 1.
\]

This is called the Townsend criterion. If this criterion is fulfilled the number of charge-carriers in the discharge volume increases exponentially and eventually a significant current will flow between the plates. This increase in current, due to an increase of conductance of the gas is what we call breakdown.

Characteristic for the Townsend mechanism is that succeeding avalanches eventually lead to a breakdown. Due to these succeeding avalanches the current through the gas has a wave form. This has been experimentally verified by Doran\(^{[2,4]}\). Doran has studied a nitrogen
discharge in a 2 cm gap at a gas pressure of 300 Torr and an applied voltage of 27.72 kV. The intensity of the light radiated by the discharge was measured by a photomultiplier and is under the chosen experimental conditions proportional to the avalanche current (a constant electric field and no significant electric field disturbances due to space charges). The current evolution is shown in figure 2.2.

![Figure 2.2: Current evolution for a series of succeeding avalanches in nitrogen. The solid curve corresponds to experimental results from Doran\(^{[2,4]}\) and the dashed curve represents a numerical simulation of Davies\(^{[2,5]}\).](image)

The time between the succeeding avalanches is approximately 140 nsec. Each 140 nsec an electron is released from the cathode and originates a new avalanche. The freeing of an electron from the cathode is in this case caused by ions colliding with the cathode and is called secondary emission (paragraph 2.8).

To determine under what circumstances the criterion (2.4) is fulfilled, we need to know the value of \(\gamma\) and \(\alpha\) and their dependence on the electric field and gas pressure. The secondary emission coefficient depends mainly on the cathode material, cathode geometry and kind of gas and is independent of \(p\) and \(E\). In general, one assumes that \(\gamma\) is between \(10^{-3}\) and \(10^{-1}\)\(^{[2,1, 2,2]}\). There is quite some uncertainty about the value of \(\gamma\), but fortunately in most formulas the logarithm of \(\gamma\) is used. The primary ionisation coefficient depends on the kind of gas, the gas pressure \(p\) and the electric field strength \(E\). Experimentally it is found that the relation for the ionisation coefficient \(^{[2,2, 2,8]}\),

\[
\alpha = pA \exp(-Bp/E),
\]

(2.5)

is valid for many gases. \(A\) and \(B\) are constant parameters determined by the gas. For Xenon with \(E/p\) between 200 and 800 Vcm\(^{-1}\)Torr\(^{-1}\), \(A = 26\) cm\(^{-1}\)Torr\(^{-1}\) and \(B = 350\) Vcm\(^{-1}\)Torr\(^{-1}\)\(^{[2,7, 2,8]}\). Let us assume that the electric field is not distorted by the created free electrons and ions, so
the electric field is equal to the applied voltage $V$ divided by the electrode separation $d$. The breakdown voltage $V_{br}$ is defined as the minimum voltage that has to be applied for breakdown to occur and therefore to satisfy the Townsend criterion. When (2.5) is substituted in (2.4) it follows that

$$V_{br} = \frac{Bpd}{\ln(Apd) - \ln \ln(1 + 1/\gamma)}.$$  \hfill (2.6)

The breakdown voltage is related to the product of $pd$ by this similarity law that was experimentally first discovered by Paschen. This similarity law is therefore named the Paschen's law for static breakdown and a plot of the breakdown voltage as function of $pd$ is called a Paschen curve. Some experimentally determined Paschen curves for various gases are shown in figure 2.3.

![Paschen Curves](image)

Figure 2.3: Experimentally determined Paschen curves for various gases on a double logarithmic scale according to Vollrath [2,9].

These Paschen curves always have a minimum, which is located at $(pd)_{\text{min}} = (e/A) \cdot \ln(1 + 1/\gamma)$. The part of the curve for $pd < (pd)_{\text{min}}$ is called the left-branch and the other part is called the right-branch of the Paschen curve. The lamps we studied in our experiments are all located on the right branch, far away from the minimum.

According to ref [2,10-2,11] in case of argon the ionisation coefficient can be better described by

$$\alpha = pC \exp\left(- \frac{D}{\sqrt{E/p}} \right),$$  \hfill (2.7)
with \( C = 33 \text{Torr}^{-1}\text{cm}^{-1} \) and \( D = 22.7 \text{V}^2\text{cm}^{-1}\text{Torr}^{-1/2} \) [2.10, 2.11]. Formula (2.7) is used for most inert gases, since it gives a better fit to experimental data than (2.5). In this case the breakdown voltage can be calculated by

\[
V_{br} = \frac{D^2pd}{(\ln(Cpd) - \ln(1 + 1/\gamma))^2}.
\]  

(2.8)

Drift velocity

The drift velocity of electrons depends in good approximation linearly of the applied electric field\([2.1]\):

\[
\bar{v}_{e,\text{drift}} = -\frac{e\vec{E}}{m_e} = -\mu_e \vec{E},
\]

(2.9)

where \( \nu_m \) represents the effective collision frequency for momentum transfer and \( \mu_e \) is called the electron mobility. For the drift velocity of ions, which is much smaller than the electron drift velocity, a similar equation is applicable:

\[
\bar{v}_{i,\text{drift}} = -\mu_i \vec{E}.
\]

(2.10)

The diffusion coefficient of electrons is related to the electron mobility by the Einstein relation:

\[
\frac{D_e}{\mu_e} = \frac{mv^2}{3e} = \frac{2 \bar{e}}{3} \frac{kT_e}{e}.
\]

(2.11)

In figure 2.4 the electron and Ar⁺ drift velocities in argon and Xenon are plotted as function of the reduced electric field strength \( E/p \).

![Figure 2.4: Electron drift velocities (left) and ion drift velocities (right) of Argon and Xenon](image)

2.2 Streamer mechanism

The multiplying of avalanches, which is essential for the Townsend mechanism, is a relative slow process. The propagation velocity of the avalanche is limited by the drift velocity of the electrons. A considerable time is necessary for the succeeding avalanches to cross the gap and cause sufficient ionisation for breakdown. For breakdown to occur it is required that an
avalanche crosses the electrode distance at least once. In experiments it is shown that under certain conditions the discharge occurs much faster than that the Townsend theory predicts. The delay time are significant smaller (sometimes more than 100 times as small) than the time needed for one avalanche to cross the gap according to Townsend theory. This significant difference in velocities is not the only diversion from the Townsend theory. The possibility of a spark breakdown in a large gap with a strongly non-uniform electric field with an applied voltage much lower than the breakdown voltage predicted by the Townsend theory, was also unexplainable by the Townsend mechanism. The foundation of a new breakdown mechanism, the so called streamer mechanism, was laid by Loeb, Meek en Raether\textsuperscript{2-13-2-17}. This theory is based on the concept of a streamer, a thin ionized channel, that forces its way between the electrodes.

The main difference with the Townsend mechanism is that space charges are not neglected and even are demanded for the existence of a streamer. The electron drift velocity is much higher and also in the opposite direction of the ion drift velocity. The ion drift velocity can be neglected in comparison to the electron drift velocity. The free electrons in an avalanche move away from the ions and in this way a charge separation originates (figure 2.5). In front of the avalanche the free electrons are moving and on the tail are the ions that are left behind. These space charges form a sort of a dipole and produce their own electric field $E'$ that distorts the external field $E_0$. As long as the external field is only slightly distorted, $\alpha$ only depends on the external field intensity: $\alpha = \alpha(E_0)$. This is one of the assumptions made for the Townsend theory. In an avalanche with a high amplification factor, $\exp(\alpha d) \gg 1$, $\alpha$ becomes dependent on the resulting electric field $E$ ($E = E_0 + E'$) and the Townsend theory is no longer valid.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.5.png}
\caption{The uniform electric field between the plates $E_0$ and the electric field of the streamer head $E'$ add up to at total electric field $E$ that is concentrated near the streamer head.}
\end{figure}
The electric field intensity $E'$ is highest in front of the streamer, very close to the streamer tip. When the radius of curvature of the streamer tip is small, the electric field intensity $E'$ can become very high, much higher than the external field intensity $E_0$. For an anode-directed streamer, as is the case in figure 2.5, $E'$ and $E_0$ have the same direction in front of the streamer. For cathode-directed streamers $E'$ and $E_0$ are oppositely directed. The fields $E'$ and $E_0$ in front of the avalanche head add up (right side of figure 2.5) to create an electric field stronger than the external field $E_0$. This leads to transition of the avalanche into a streamer.

For the dipole field in front of the avalanche to exceed the applied electric field ($E' > E_0$), it is required that the avalanche size reaches a certain number of free electrons. In the next paragraph we will make an estimation of this critical number $N_{cr}$ at which an avalanche-to-streamer transition occurs.

When electrodes with a small curvature radius are used, the electric field nearby these electrodes is significantly enhanced locally. Since $\alpha$ depends exponentially on the electric field, an avalanche nearby an electrode will experience a huge increase of free electrons. Therefore, the avalanche-to-streamer transition will mostly occur nearby one of the electrodes as is shown in figure 2.6.

![Figure 2.6: A schematic illustration of the development and propagation of a streamer at a sharp electrode which is at a high negative voltage in the left column (a) and at a high positive voltage at the right column (b) [2.18].](image)

Due to a well conducting ionised channel that is left behind by the streamer head, the potential of the streamer head is almost as high as that of the electrode. This high potential of the streamer head in combination with the small curvature radius (typically between $10^{-2}$ and $10^{-1}$ cm [2.18, 2.19]) causes a high electric field in front of the streamer head. Due to this high electric field induced by the streamer itself, the streamer can maintain itself in weak applied electric fields and propagate with very high velocities (typically between $10^6$ an $10^8$ m/s) by creating
new free electrons. The high electric field of the streamer is also the cause that streamers are not only anode-directed but can also be cathode directed. The mechanism behind the propagation of streamers is a popular discussion subject in literature. A streamer is capable of creating secondary electrons in front of the streamer head by photo-ionisation. The secondary electrons create avalanches of free electrons that will join the streamer. This way the streamer can reach such high propagation velocities.

2.3 Avalanche to streamer transition

For a streamer to form, the electric field of the space charges must become higher than, or at least comparable to, the applied electric field. To determine under which conditions this will occur, let us consider one single avalanche that starts at the cathode from a single free electron. The number of free electrons can be calculated by $N = \exp(\alpha x)$. To estimate the electric field due to the free electrons in the avalanche we need to determine a characteristic length scale. For this the diffusion radius of the avalanche could be used.

All the new electrons in the avalanche move in a group towards the anode with a drift velocity $v_d = \mu_e E_0$. Diffusion makes the electron cloud spread around to the central point $x_0 = v_d t$ (figure 2.7).

![Figure 2.7: A single avalanche developing from a single electron in a uniform field. Due to a higher drift velocity of the electrons the avalanche has a negatively charged front and a positive charged tail. The broadening of the avalanche is caused by diffusion.](image)

The total flux densities of electrons consists of drift and diffusion components

$$\Gamma_e = \pm n_e \mu_e \vec{E} - D_e \nabla n_e,$$  

(2.12)

where $\mu_e$ is the electron mobility and $D_e$ the electron diffusion coefficient, that are related by the Einstein relation $D_e \mu_e = kT \mu_e e$. Using the diffusion equation, the continuity equation and the definition of the primary ionisation coefficient one can derive the electron density as function of the position along the field axis $x$, the radial distance to the axis $r$ and time $t$ [2,13]
\[ n(x, r, t) = (4\pi D_e t)^{-3/2} \exp \left[ -\frac{(x-x_0)^2 + r^2}{4D_e t} \right] \exp(\alpha x_0). \] (2.13)

\( x_0 \) is the \( x \)-position of the centre of the avalanche and is equal to \( v_d t \).

The sphere radius \( r_0 \) is defined as the radius on which the intensity is exactly \( e \) times smaller than at the centre. The sphere radius increases with time by the diffusion law:

\[ r_0 = \sqrt{4D_e t} = \sqrt{\frac{4D_e x_0}{\mu_e E_0}} = \frac{4kT_e x_0}{eE_0}. \] (2.14)

Assume that \( N_e \) free electrons are within a sphere of radius \( r_0 \). The electric field caused by space charges is then \( E' = eN_e (4\pi\epsilon_0 r_0^2) \). Using (2.14) for \( r_0 \) we find

\[ E' = \frac{eN_e}{4\pi\epsilon_0 \cdot 4(kT_e/e)x_0} E_0. \] (2.15)

The criterion for an avalanche to turn into a streamer is that the electric field distortion must be at least equal to the external electric field, \( E' \approx E_0 \). To fulfill this criterion a critical number \( N_{cr} \) of free electron is needed. When we take \( E' = E_0 \) in (2.15) we find that \( N_{cr} \approx (3 \cdot 10^7 / \text{cmV}) \cdot (kT/e) \cdot x_0 \). In a gas with an electron temperature of a few eV and \( x \approx 1 \text{ cm} \), we find that \( N_{cr} \approx 10^9 \). This critical number is equal to \( \exp(\alpha x_0) \). In literature one assumes that \( \alpha x_{cr} \) is between 18 and 20 \cite{2.2, 2.3, 2.16}.

When the number of free electrons in the primary avalanche has reached the critical number, a weakly ionised thin channel can be formed from the avalanche, which is called a streamer.

### 2.4 Townsend to streamer transition

So far we have discussed two completely different breakdown mechanism, Townsend and streamer. In this paragraph we want to answer the question under which conditions each mechanism does occur. In the early days it was assumed that breakdown is originated by a Townsend mechanism when \( pd < 200 \text{ cmTorr} \) and by a streamer mechanism when \( pd > 200 \text{ cmTorr} \) \cite{2, 13}. This is only true for low over voltages, \( K < 10\% \). \( (K = (V-V_{br}) / V_0) \). When the voltage is increased very slowly, breakdown will occur just after the applied voltage exceeds the breakdown voltage, so the over voltage will be very low.

When a high voltage pulse with a very short rise time (much smaller than the delay time) is applied, very high over voltages can be created. A gap with \( pd < 200 \text{ cmTorr} \) is also capable to breakdown in accordance with a streamer mechanism when the applied over voltage is high enough \cite{2, 20}. Kunhardt\cite{2, 21} observed that the delay times depend very strongly on the applied voltage. He discovered a discontinuity in the curves of the delay time as function of the applied voltage. This observation lead to the theory that the over voltage \( K \) was the critical parameter.
rather than \( pd \). As a criterion it was proposed is that Townsend is valid for \( K < 20\% \) and the streamer mechanism for \( K > 20\% \). Later it was established \(^2\) that the critical value of \( K \) was dependent on \( pd \), as is shown in figure 2.8.

![Graph showing the relationship between \( K \) and \( pd \).](image)

**Figure 2.8:** The curve representing the boundary between the Townsend (below) and the streamer (above) in atmospheric air. \(^2\)

The region above the curve represents the streamer mechanism and the region below represents Townsend. For high values of the \( pd \) (> 300) the Townsend region becomes very small, so only a very small over voltage is enough to get a streamer mechanism.

Rodges et al.\(^3\) proved by statistical analysis of the delay times that a transition area exists between the Townsend and streamer regions. In this transition area the mechanism is a combination of Townsend and streamer. In this regime the space charge does play an important role but is not high enough to create a streamer. They also proposed the number of free electrons \( N \) in an avalanche as the critical parameter. For \( N << N_{\text{critical}} \) the Townsend mechanism is valid and for \( N >> N_{\text{critical}} \) the streamer mechanism is valid, where \( N_{\text{critical}} \approx 10^8 \). In the transition regime fast ionisation waves occur, which are described in the next section.

### 2.5 Ionisation waves

The term ionisation wave is used for a lot of breakdown phenomena in which an ionisation region propagates in a gap. Ionisation waves travelling a relatively low propagation velocities of \( 10^3 \) – \( 10^5 \) m/s frequently appear in gaps where the electric field is homogeneous and the velocity of the ionisation front is determined by the electron drift. Ionisation waves travelling at higher velocities of \( 10^6 \) – \( 10^8 \) m/s (fast ionisation waves) frequently appear in the final stages of electrical breakdown when usually a plasma already exists in a discharge gap. \(^3\) Once an ionisation front has reached the opposite side of the gap, the subsequent increase in current is accompanied by ionisation waves propagating in the gap. \(^2\) In this master thesis the focus is more on the bridging of the gap than the phenomena that occur after the bridging. Under
certain conditions it is possible to generate fast ionisation waves (FIWs) also during the initial stages of electrical breakdown as a mechanism for the bridging of the gap. The most important factor is a short rise time of a high voltage pulse applied to the discharge gap and the occurrence of preliminary ionisation (preionisation) in the gap. As a rule, the shorter the rise time of the applied voltage pulse and the stronger the preionisation of the discharge gap, the higher the velocities of FIWs starting from the high voltage electrode. The electric field intensity behind the FIW front, where a high-conductivity channel is formed, is zero in the ideal case and therefore all the ionisation processes occur in the region of the voltage drop in front of the wave.

In theoretical discussions of FIWs practical difficulties arise from the problem of the formation of a sufficient number of initiating electrons ahead of the FIW front and the high propagation velocity. Early investigations have already established \(^\text{[2.24, 2.25]}\) that direct photoionisation, which can explain the motion of streamers, cannot account for the occurrence of FIWs. In particular at low gas densities photoionisation is ineffective.

The most likely mechanisms of preionisation are runaway electrons and radiation (only at high pressures). At pressures lower than 200 Torr (\(\approx 267\) mbar) the intensity of the electric field in the front of a wave is so high that the front becomes a moving source of a beam of high-energy electrons in which the current can reach several kiloamperes \(^\text{[2.23]}\). The electric fields at the FIW front are usually so high that the electrons go over to the runaway regime \(^\text{[2.26]}\). The influence of such runaway electrons may be decisive in relation to the formation of free electrons ahead of the front. Runaway electrons are electrons that gain energy from an applied electrical field at a faster rate than they lose it through collisions with other particles. These electrons tend to run away, because the collision cross-section decreases as the particle's velocity increases, so that the faster the particle goes, the less likely it is to be stopped. The high-energy electrons in the wave front overtake the front and cause preliminary ionisation of the gas ahead of the front. At pressures higher than 200 Torr the main source of such preionisation is the transport of radiation emitted by the front followed by associative ionisation of excited molecules or atoms \(^\text{[2.25, 2.27]}\).

Now all three relevant breakdown mechanisms have been discussed we give an overview of their appearances and criteria in table 2.1. A Townsend mechanism is attended with a relatively low propagation velocity, a diffuse ionisation region which can only propagate in the direction of the anode. In case of higher velocities the breakdown mechanism can be FIW as well as streamer. When (small) channels are demonstrable, the mechanism is defined as a streamer and when the ionisation region(s) is diffuse, it is called a FIW in this master thesis. The FIW mechanism is in the transition regime between Townsend and streamer.

Streamers need a small tip, so the electric field in front of them is strongly concentrated. Streamers therefore are always small channels. In case of FIWs, small channels are not
required and are therefore more diffuse. FIWs are usually anode-directed, just like Townsend, but in literature\textsuperscript{[2,23]} also examples of cathode directed FIWs are known.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|}
\hline
 & Townsend & FIW & streamer \\
\hline
ionisation front velocity: & not higher than the electron drift velocity & much higher than the electron drift velocity & much higher than the electron drift velocity (typically between $10^5$ \text{ an} $10^7$ m/s) \\
\hline
shape of ionisation region: & diffuse & diffuse & small channels, usually some branching occurs \\
\hline
possible directions: & only anode-directed & both directions are possible, but mainly anode-directed & both directions are possible, but more often cathode-directed \\
\hline
\end{tabular}
\caption{The criteria for the three relevant breakdown mechanisms: Townsend, Fast Ionisation Wave, streamer.}
\end{table}

\section{2.6 Influence of the wall}

When the inside diameter of the burner is of the same size of even smaller than the electrode distance $d$, the wall has a huge influence on the gas breakdown behaviour. This is mainly attributed to the changing of the electric field, wherefore two reasons can be distinguished:

1. the wall is a dielectric and therefore due to polarisation not only influences the electric field in the dielectric itself, but also the electric field in the gap,

2. the wall charges up because of charged particles from the gas attaching to the wall and UV-radiation causing free electrons by photoemission.

First we will discuss the influence of the wall as a dielectric. If an electric field is applied to a medium containing a large number of atoms or molecules, the charges bound in each molecule will respond to the applied field and the motions will be disturbed. The atoms or molecules will become induced dipoles. This effect occurs almost instantly. An electric field that is applied to a dielectric causes an electric polarization $\vec{P}$, which is defined as the dipole moment per unit volume: \textsuperscript{[2,28]}:

\begin{equation}
\vec{P} = \frac{\sum \vec{p}}{\Delta t} ,
\end{equation}

with $\Delta t$ a small volume and $\sum \vec{p}$ the total dipole moment in that volume. In an isotropic medium the induced polarization is parallel and proportional to the electric field:

\begin{equation}
\vec{P} = \varepsilon_0 \chi \vec{E} ,
\end{equation}

where $\chi$ is the electric susceptibility of the medium. Since the electric susceptibility of the wall is positive the polarization is in the same direction as the electric field. The polarization of a dielectric can be interpreted as a displacement of bound charges, resulting in a polarization
charge. One can derive that the polarization space charge density is equal to the divergence of the electric polarization and that the surface charge density is equal to the normal component of the polarization field:

\[ \rho_{\text{pol}} = -\nabla \cdot \vec{P} \quad \text{and} \quad \sigma_{\text{pol}} = \vec{P} \cdot \vec{n}, \]  

(2.18)

where \( \vec{n} \) represents the normal of the surface. This polarization charge influences the electric field just outside the dielectric. The electric field outside the dielectric tends to concentrate near the dielectric. The polarity wall charges enhance the electric field nearby the electrodes in the direction of the wall. A higher the electric susceptibility of the wall, a larger wall thickness or a smaller wall diameter result in a higher electric field enhancement.

Before breakdown occurs, charged particles (electrons and ions) are formed in the gap. These charge particles (mainly electrons, since ions are to slow) can collide with the wall and attach to it. Due to electron-attachment a negative charge accumulates at the wall with its own electric field. At the end of a voltage pulse some charged particles stay behind attached to the wall. The wall charges from a prior discharge can influence the initial electric field in the gap. Since the wall is slightly conducting the wall uncharges at a slow rate. To make sure that no significant amount of wall charges is present, one has to wait some time (~10 sec typically in this case) between each discharge in order to get reproducible results.

### 2.7 Delay times

When a high voltage is applied to one of the electrodes, it takes some time before breakdown occurs. The time difference between the moment at which the voltage is applied and the moment of breakdown is what we call the delay time.

![Figure 2.10: Schematic of the voltage waveform.](image)

The voltage applied on the lamp is never a perfect step function. Therefore we define a rise-time \( t_{\text{rise}} \) as the time period in which the voltage increases from 10% of \( V_0 \) to 90% of \( V_0 \). \( t_1 \) is the moment at which the voltage exceeds the breakdown voltage and \( t_2 \) is the breakdown
moment at which a significant voltage drop is observed. The delay time $t_{delay}$ is the time period between $t_1$ and $t_2$. The delay time is the sum of a statistical delay time and a formation time: $t_{delay} = t_s + t_t$. The statistical delay time $t_s$ is the time measured from $t_1$ until the first ionisation emission becomes visible as a consequence of an electron avalanche. The formation time $t_t$ is the time period from the first visible ionisation emission until breakdown. For this traineeship we are only interested in the formation time. The formation time shows only small statistical variations (< 1 nsec) in contrast with the statistical delay time that depends on the number and the position of free electrons in the gap. The statistical delay time can be decreased by irradiating the gap with a UV-lamp. The UV-radiation causes photo-emission of electrons from the cathode, resulting in $t_s << t_t$. The delay time is quite easy to measure and gives valuable information about the breakdown mechanism.

2.8 Initial electrons and secondary emission

In order to start an avalanche at least one initial free electron needs to be present at the gap. We will discuss some primary electron initiation mechanisms and their relevance for our experiments.

- Due to natural ionizing radiation, i.e. natural radioactivity of materials, cosmic rays, etc., from 10 to 100 $^{[2,2]}$ electrons per cubic centimetre per second appear in the air at atmospheric pressure. On the moment a voltage is applied it is very likely that a certain amount of free electrons is present at the gap thanks to this natural radiation.

- Thermionic emission: This occurs when a metal is at a relatively high temperature. Electrons acquire sufficient energy to escape from the potential well that the work function of the metal represents for them. Thermoionic emission depends strongly on the temperature. At room temperature this effect is negligible.

- Field electron emission: A field that pulls electrons away transforms the potential well of a metal into a barrier of a finite width. As a result, electrons can escape from the metal by tunnelling. The electric field, and therefore also the field electron emission, is enhanced dramatic at microscopic protrusions that always exist on metal surfaces. In practice this effect becomes significant when the applied electric field is approximately $10^6$ V/cm.

- UV-radiation: In some experiments the number of free electrons in the gap due to natural radiation is not high enough for reproducible measurements. The delay time has a large statistical variation or breakdown does not occur at all. In those situations a UV-lamp is used to help the discharge getting started. When an electrode is radiated by UV, free electrons are produced. These free electrons are in the vicinity of the electrodes. Close to the electrode on which a voltage is applied, the electric field is strongest. So the free electrons created by UV radiation are on the right place to start an avalanche.
Secondary emission plays an important role in the Townsend mechanism. For a streamer secondary emission is not relevant, since photo-ionisation is a much faster way of creating free electrons. Two types of secondary emission can be distinguished [2,1]:

- Ion-electron emission: Positive ions colliding with the cathode and freeing an electron by an Auger process. An Auger process starts with the removal of an inner shell atomic electron (using the ionisation energy of an incoming ion in this case) to form a vacancy. The inner shell is filled by a second atomic electron from a higher shell, releasing an amount of energy. A third electron, the Auger electron, escapes carrying the excess energy in a radiationless process. Each ion created in the gap knocks out $\chi$ electrons from the cathode.

- Photo-emission: Photons that are produces in the avalanche, coinciding with the cathode, can also be a source of secondary electrons. The secondary photo-emission coefficient $\chi_0$ is defined as the number of electrons released from the cathode per positive ion.

The former process is on the long term dominant ($\chi >> \chi_0$), but at small time scales ($< 1 \mu s$) the latter process is more relevant. Let us consider the time required for the first ion that is created to travel back to the cathode. The distance from the cathode at which this ion is created can be approximated by the mean free path for ionisation: $\lambda_{\text{ionisation}} = 1 / \alpha$. This ion needs a time $\tau = 1 / (\alpha \nu_{\text{ion}})$ to travel back to the cathode. For $E/p = 40 \text{ V/(cmTorr)}$ in Argon this corresponds to $\tau = 0.1 \mu s$. To created 1 secondary electron on average 10-100 ions have to collide with the cathode. From this we conclude that ion-electron emission is only relevant at time-scales longer than 1 $\mu s$. 


3 Experimental Set-up

3.1 Overview of experimental set-up

In our experiments we want to study the breakdown processes in a lamp by taking pictures of the discharges with an ICCD camera (paragraph 3.3). We are only interested in the pre-breakdown phase, i.e. from the first ionisation until the breakdown moment. The duration of this phase varies from a few tens of nsec to a few µsec, depending on which lamp is used and on the applied voltage. The amplitude of the applied voltage pulse is typically a few kV. The width of the pulse is configurable and is chosen such that it is just long enough for breakdown. It is no use to apply a longer pulse, since we are not interested in the post-breakdown phase. The post-breakdown processes can only have a negative effect by affecting the lamp conditions for the next measurement, for instance due to wall charges, heating up of gas and electrodes or sputtering. As a high voltage generator the Velonex is used, which is described in paragraph 3.2. To synchronise the camera with the applied voltage, the Velonex is triggered by a function generator.

To measure the applied voltage over the lamp, a voltage probe is used (figure 3.1). This voltage probe permits the use of an oscilloscope for the registration of high voltage pulses. This probe is essentially a calibrated voltage divider with a voltage ratio of 1:1000.

Due to the length of the probe wire and a time constant of the probe, the scope signal has a delay of 15 nsec compared to the lamp voltage. The propagation velocity in a solid Polyethylene coax-cable is equal to $2 \cdot 10^8$ m/s, which corresponds to 5 nsec per meter.

For the measurement of the current through the lamp a Rogovsky coil is used as current probe. A Rogovsky coil makes use of the magnetic field of a current wire. Its main component is a solenoid coil. A current through the probe creates a magnetic flux that induces a voltage in the solenoid coil. The time integral of the induced voltage in the coil is proportional to the current through the wire.

Figure 3.1: Schematic drawing of the experimental set-up.
To study the ionisation evolution during the pre-breakdown phase, we want to take two dimensional pictures of the light intensity at various time periods before breakdown. For this purpose a normal camera does not fulfil. Since the breakdown delay time of the lamps we studied is very small (tens of nsec in some cases), the shutter time of our camera needs to be very short (3 ns). This cannot be achieved by a mechanical shutter. As a consequence of the short shutter time, the measured light intensity is also very small. To get a decent picture of the ionisation front in the lamp, an intensifier is required (see paragraph 3.3, for details).

### 3.2 Velonex

The Velonex is a high voltage pulse generator. The amplitude and pulse width of the output can be varied. When the direct output of the Velonex is used, a negative pulse with a maximum amplitude of 4 kV and a rise time of 40 nsec is generated, as is shown in figure 3.2. To create a higher voltage or a positive voltage the output of the Velonex is connected to an output unit that transforms the direct output of the Velonex into a higher and/or positive voltage. A higher amplitude however can only be created at the expense of a longer rise time.

![Figure 3.2: Velonex output voltage measured by a voltage probe connected to an oscilloscope. a) Negative amplified output, b) Positive amplified output, c) Direct output.](image)

The details of the different output units we used are shown in table 3.1.

#### Table 3.1: The different output units

<table>
<thead>
<tr>
<th></th>
<th>Maximum amplitude</th>
<th>Rise time</th>
<th>Impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct output</td>
<td>-4 kV</td>
<td>20 ns</td>
<td>-</td>
</tr>
<tr>
<td>Positive amplified output</td>
<td>+6 kV</td>
<td>100 ns</td>
<td>2 kΩ</td>
</tr>
<tr>
<td>Negative amplified a</td>
<td>-8 kV</td>
<td>0.85 μs</td>
<td>13.3 kΩ</td>
</tr>
<tr>
<td>Negative amplified b</td>
<td>-12 kV</td>
<td>2 μs</td>
<td>30 kΩ</td>
</tr>
</tbody>
</table>
3.3 Camera

The camera used in our set-up is an ICCD, Intensified Charged Coupled Device, of Princeton Instruments (PI-MAX, 512). The studied lamp is focussed on a photo-cathode by a zoom lens. The photons that collide with the photo-cathode generate photoelectrons that are accelerated across a 200 µm gap towards a microchannel plate (figure 3.3). The electrons enter one of the channels, are accelerated by a huge electric field and are multiplied by successive collisions with the channel wall. This way a pixel-by-pixel amplification is accomplished. The electrons exiting the microchannel are pulled towards a fluorescent phosphor screen. The electrons colliding with this fluorescent screen are converted to visible photons that travel through a fibre optic coupler towards a CCD. In this CDD array the photons are transduced to electrons, which are stored, integrated and finally read out. The CDD is a 512x512 imaging matrix that is kept at a constant temperature of -20 °C by a thermoelectric (Peltier-effect) cooler. The combination of the photocathode, multichannel plate and phosphor screen form an image intensifier. The electric gain of this intensifier can be set as high as 10,000. The use of an intensifier in front of the CCD has two major advantages:

1. it allows a faint optical signal to be amplified over the read noise of the CCD and makes it possible to detect the signal of a single photoelectron leaving the photocathode.
2. the photocathode gating and the multichannel plate gating can electronically be set on and off. This allows a very short (up to 3 ns) shutter time, much shorter than can be accomplished by a mechanical shutter.

Figure 3.3: Schematic drawing of the ICCD camera.

The ICCD is operated with an ST-133 Controller in combination with a Programmable Timing Generator. The controller is connected to a PC and is operated with WinSpec/32 software. The Programmable Timing Generator determines the time delay between an external trigger and the opening and closing of the intensifier gate. This is explained further in the next paragraph.
3.4 Timing

When trying to create a series of pictures at various moments, several problems are encountered. These problems are a consequence of the short duration of the pre-breakdown phase. Since the maximum repetition rate of the intensifier is 5 kHz, only one picture per ignition can be taken. To create a complete series of pictures a number of individual measurements are required. Furthermore it is only possible to make such a series if the ionisation in the lamp is reproducible. So let us assume that this reproducibility is indeed the case (later we will confirm this experimentally).

When the output of the function generator has a negative slope it triggers both the Velonex and the ICCD controller. At the end of a fixed time period after the Velonex receives a trigger, its output voltage increases. This fixed time period is called the Velonex delay time and its standard deviation is called jitter.

In a measurement series the gate delay time is linearly increased from the first visible ionisation to the breakdown moment. The chosen gate width depends on the breakdown delay time and the amount of light that is measured. When the breakdown delay time is very small (<20 ns), the gate width is set to its minimum value (3 ns). For longer breakdown delay times the measurement is less time critical and therefore longer gate width can be used to get more counts.

Since the spread in the breakdown delay time is not negligible, we can not exactly predict at what time breakdown occurs and therefore do not know the exact value of $\Delta t$. To determine $\Delta t$ the lamp voltage and the monitor signal are connected to an oscilloscope, which is read out by a PC. Afterwards $\Delta t$ can be determined by comparing analysing the oscilloscope data (figure 3.5) and calculating the time difference between the breakdown moment and the negative slope of the monitor signal.
Figure 3.5: The current through the lamp, the voltage over the lamp and monitor signal. At \( t = t_{\text{breakdown}} \) the current magnitude through the lamp increases.

### 3.5 Used lamps

The lamps that are used for our measurements are shown in figure 3.6a. The low aspect ratio YAG burner within this lamp is magnified in figure 3.6b. The yellow dots are metal-halide grains that are added to the lamp. The burner is filled with 300 mbar (at room temperature) Argon and the electrode is 0.7 cm.

Figure 3.6: Pictures of the lamp types that were used for measurements. a – low aspect ratio lamp, b – low aspect ratio burner, c – short high aspect ratio burner (\( d = 1.5 \) cm), d – long high aspect ratio burner (\( d = 2.7 \) cm). Pictures b, c and d all have the same scale.

To study the influence of pressure, electrode distance and kind of fill gas, some special lamps have been constructed. To distinguish the two burner types from each other we use the terms low aspect ratio burners (b) and high aspect ratio burners (c and d). Since the lamps are not burnt, only ignited, the outer bulb is not required for our research. Therefore only burners (figure 3.6 c and d) are created instead of complete lamps. These newly created burners have a cylindrical shape and a inner diameter of 4.0 mm as is shown in figure 3.7.
This series of high aspect ratio burners has three different pressures (0.3, 0.7), two different fill gases (Argon and Xenon) and two different electrode distances (1.5 and 2.7 cm). The different combinations of parameters for the burners are shown in Table 3.2.

### Table 3.2: An overview of the lamps that have been studied.

<table>
<thead>
<tr>
<th>pressure [bar]</th>
<th>electrode distance [cm]</th>
<th>fill gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>1.5</td>
<td>Argon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Xenon</td>
</tr>
<tr>
<td>0.3</td>
<td>2.7</td>
<td>Argon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Xenon</td>
</tr>
<tr>
<td>0.7</td>
<td>1.5</td>
<td>Argon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Xenon</td>
</tr>
<tr>
<td>0.7</td>
<td>2.7</td>
<td>Argon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Xenon</td>
</tr>
</tbody>
</table>

In total we have 10 different high aspect ratio burner types and of each burner type, 3 burners are created to demonstrate that our measurements are reproducible. This makes a total of 24 high aspect ratio burners. In Figure 3.8 an X-ray picture of a part of a high aspect ratio burner with one electrode is shown.

**Figure 3.7:** Schematic of cylindrical YAG-burner geometry.

**Figure 3.11:** X-ray picture of a part of a cylindrical burner with one of the electrodes.
4 Low aspect ratio burner results

For our first measurements low aspect ratio burners (figure 3.6a and b) were used. Initially we used them to get our experimental set-up working and to test it. Next, we optimised our set-up and the timing in particular. The electromagnetic interference, as a consequence of the breakdown of a burner, had a disturbing effect on the functioning of the ICCD and its controller and therefore had to be suppressed. Then we measured the delay time of one burner 40 times, to determine its reproducibility (paragraph 4.1). In paragraph 4.2 and 4.3 the evolution of the discharge emission profiles for different negative voltages is shown and in paragraph 4.4 the positive voltage results. The ionisation front velocity of the discharges is discussed in paragraph 4.5. Since the large aspect ratio burners behave different (due to a larger wall influence) their results are in a separate chapter (chapter 5).

4.1 Time delay statistics

For a good measurement it is essential that the output of our high voltage pulse generator is highly reproducible, both in form and starting moment. When there is a large statistical spread in the delay between the Velonex triggering and the Velonex output for instance, it is difficult to configure the camera such that the gate is opened on the right moment (during the pre-breakdown phase). To check this reproducibility the output voltage of the Velonex and at the same time the output of the function generator are registered with an oscilloscope. This measurement is repeated 100 times. The shape of the output voltage (figure 3.2) is each time the same. The Velonex delay is determined by measuring the time duration between a trigger from the function generator and the moment at which the voltage exceeded 2 kV. The spread in the Velonex delay time is called jitter and is approximately 1 nsec. For our purposes the reproducibility of the Velonex output is sufficient.

The breakdown delay time is the time duration from the applying of the high voltage pulse and the breakdown of the gap. To determine this breakdown delay time, the lamp voltage and the lamp current are measured with a voltage and a current probe. In this report the delay time is defined as the time period between the moment at which the lamp voltage exceeds 2 kV and the first moment at which a significant increase of the lamp current (10% of its maximum value, see figure 3.5) is observed. We repeat this measurement 40 times, with 2 sec between each measurement. The spread in this breakdown delay time is called lamp jitter.

In figure 4.1a the breakdown delay times of all 40 succeeding measurements are represented in a bar chart. We discovered that when we increase the time period between each individual measurement, the jitter decreases. The bar charts for 10 sec, 30 sec and 60 sec between each individual measurement are shown in figure 4.1b, c and d. When increasing the time period from 2 sec to 10 sec the decrease of lamp jitter is obvious. The difference between the
two measurements can be explained by wall charges. During a discharge free electrons or ions will attach to the wall. The remaining wall charges will influence the succeeding ignition by disturbing the electric field. When the time period between the measurements is increased from 2 sec to 10 sec, the wall charges have more time to disappear out of the burner. When the time period between the succeeding measurements is increased further to 30 sec and to 60 sec, no significant decrease of lamp jitter is observed.

The time between the applied pulses is therefore chosen to be 10 sec for all measurement of these low aspect ratio lamps. In case of the high aspect ratio burners (chapter 6) the wall diameter is smaller, resulting in a larger wall influence, and therefore 20 sec are required between the individual measurements.

Figure 4.1: Bar charts of the delay times of 40 succeeding measurements. The applied voltage is -4 kV and a low aspect ratio lamp is used. The time between the individual measurements is respectively 2 sec, 10 sec, 30 sec and 60 sec.
4.2 Pictures of -4 kV measurements

In figure 4.2 some pictures of the pre-breakdown phase of a low aspect ratio lamp filled with 300 mbar Argon are shown. The applied negative voltage is -4.0 kV with a rise time of 40 nsec (figure 3.5). The ICCD gate width is equal to 3 nsec. The background signal due to dark current is subtracted from the measured signal. The colour of a pixel is a measure for its light intensity, which is measured as the number of counts per pixel. The colour bar on the right side indicates the translation between colour and number of counts. The result of this measurement is discussed in detail and will be used as a reference for all the other measurements.

The pictures are selected out of a series of 40 measurements. During an individual measurement only one picture can be taken. By increasing the variable gate delay time (i.e. the time between the triggering of the Velonex and the opening of the ICCD gate) after each measurement it is possible to visualise the breakdown evolution. Under each picture a time $t$ in nsec is shown, representing the moment at which the ICCD gate was closed. In paragraph 3.4 it is explained how $t$ is determined by counting backwards from the breakdown moment towards the closing of the gate. To avoid getting negative values of $t$ an offset time is added to all values of $t$ in such a way that the picture in which the first light emission is visible corresponds to $t = 0$.

The electrode at which the voltage pulse is applied, which from now on will be called the high voltage electrode, is always chosen to be the left electrode. The grounded electrode, which functions as an anode in case of negative voltage pulses, is consequently the right electrode. The ionisation always starts at the electrodes, since the electric field is highest there, due to the small curvature radius of the electrode edges. The fact that the ionisation is more intense at the high voltage electrode than at the grounded electrode will be discussed later. An initial electron that is located near an electrode is accelerated due to the applied electric field and will create new electrons by ionisation. This way an electron avalanche originates near the electrode. The electric field enhancement near the sharp electrode has a huge influence, since the first ionisation coefficient $\alpha$ depends exponentially on the electric field strength.

Since the ionisation each time starts at the same moment with respect to the moment at which the voltage is applied ($\pm 5$ nsec), we can conclude that sufficient initial electrons are available in the gap when the voltage is applied, so that near each electrode always at least one initial electron is present. If for instance only one or two initial free electrons would be present in the gap, there would be a reasonable chance that none of them would be located close to the electrodes. In that situation some time would be required for the electrons to travel towards the electrodes. An electron moving at the electron drift velocity needs approximately 60 nsec to travel from the middle of the gap towards the anode.
Figure 4.2: Pictures of the light emission profile evolution before breakdown in a low aspect ratio burner. The applied voltage is -4.0 kV. Under each picture the time in nsec is shown. Time $t = 0$ is chosen to be the moment at which the first light emission is visible.
If only the electrodes would determine the electric field in the gap, the electric field would be perfectly symmetrical (figure 4.3a). In that case the ionisation is expected to start at both electrodes at the same time. In practice the ionisation begins at the electrode at which the voltage is applied. In this measurement the ionisation starts 3 nsec later at the grounded electrode than at the high voltage electrode (4.2b). This is probably caused by the influence of the burner wall. This burner wall, made of YAG, is slightly electrical conducting and therefore influences the electric field. At the moment that the voltage over the lamp increases, the burner wall is still at the earth potential. In figure 4.3b the burner wall is modelled as a conductor that is grounded. Since the grounded electrode is at the same potential as the burner wall, the electric field nearby the grounded electrode is very small. Figure 4.3b is only a simplified model. A real burner wall is only slightly conducting and therefore cannot be treated as a “hard” earth potential. The burner wall has a floating potential. The real situation is probably something in between the situations of 4.3a and 4.3b.

![Figure 4.3](image)

**Figure 4.3**: A simple schematic of the electric field lines in the gap when a negative voltage pulse is applied to the left electrode while keeping the right electrode grounded. The black bars represent electrodes and the ellipse represents the burner wall. In subfigure a the field lines are shown for a situation in which the wall influence has not been taken into account. In subfigure b the situation is shown if the burner wall would be a conductor connected to earth and isolated from the electrodes.

During the first 7 nsec the ionisation expands relatively quickly at both electrodes, but mainly at the high voltage electrode (figure 4.2d). From the left of the high voltage electrode some light is emitted (figure 4.4). This light can be explained as a wall reflection of the ionisation at the tip of the high voltage electrode or the light could be emitted by real ionisation on the spot close to the wall. The latter explanation is more likely, since wall reflections are not as sharp as in figure 4.4. Since at the concerning spot the high voltage electrode is close to the wall, its electric field intensity is relatively high (figure 4.3b), so it is not illogical that ionisation is started here.

![Figure 4.4](image)

**Figure 4.4**: An ICCD-picture of the ionisation and a schematic view of the burner wall and electrodes in white. The left electrode is the cathode and the right electrode is the anode.
During the next 7 nsec the ionisation keeps expanding but at a slower rate. After 16 nsec (figure 4.2j) both ionisation regions get connected and a conducting path between the electrodes is formed. This leads to a huge decrease of the gap resistance causing an enormous increase of the lamp current (figure 4.2k). This moment is defined as the breakdown moment. The increase of the lamp current involves a significant increase of the light emitted by the burner (figure 4.2l). Eventually the gap resistance becomes much lower than the internal resistance of the high voltage pulse generator, causing a decrease of the lamp voltage. The lamp current, determined by the internal resistance of the voltage source, grows as high as 2 A eventually.

The breakdown mechanism is probably streamer. This conclusion is based on two important observations:

1. The propagation velocity is significantly higher than the electron drift velocity. The propagation is approximately $4 \times 10^5$ m/s ($0.7$ cm in 17 nsec) and $v_{e,\text{drift}} = 0.6 \times 10^5$ m/s for $E/p = 25$ V cm$^{-1}$ Torr$^{-1}$. From this we conclude that the mechanism can be streamer or FIW, but definitely not Townsend. The propagation velocity is determined more accurate in paragraph 4.5.

2. The finger shape of the emission profile, which can be recognised in pictures e, g, i and j, is characteristic for streamer breakdown. In case of FIWs a uniform bulk ionisation is expected. This is not the case here, because some channels can be identified.

### 4.3 Pictures of other negative voltages

Now we want to study the breakdown phenomenology for negative voltage pulses of a lower amplitude (-3.0 and -2.5 kV). For each voltage 40 pictures are taken. In figure 4.5 only a representative selection of 6 pictures is shown for each voltage. To compare the three different applied voltages (-4.0, -3.0 and -2.5 kV) with each other the pictures are arranged in three columns. The numbers beneath the pictures represent the time in nsec at which the pictures are taken.

The pictures in column 1 are the same pictures as in figure 4.2. We will now discuss the -3.0 kV results and after that we will compare the different voltages. After 16 nsec (2b) the high voltage ionisation region has expanded spherical. No ionisation is visible at the grounded electrode, in contrast with the -4 kV results. At the left side of the high voltage electrode (2b-2d) the ionisation is also missing. In 2c the high voltage ionisation front has crossed approximately 75% of the gap. The radial ionisation expansion is limited by the burner wall. After 29 nsec (2d and 2e) the high voltage ionisation front hardly makes any progress towards the grounded electrode. The high voltage ionisation extents according to a large space angle, as if it doesn't feel the presence of the grounded electrode. As a results of the high voltage ionisation region being close to the grounded electrode after some time, the electric field intensity at the tip of the grounded electrode increases. As a consequence, an ionisation
region arises around the grounded electrode that quickly makes contact with the high voltage ionisation region (2d). Eventually this leads to breakdown (2f).

When the three columns are compared with each other, one can conclude that the breakdown mechanism is streamer for -4.0 kV and FIW for -3.0 kV and -2.5 kV. Thus a decrease of the applied voltage amplitude results in a shift of the breakdown mechanism in the direction of Townsend. This is just as expected from theory (paragraph 2.4). For our conclusion that the breakdown mechanism is streamer for -4 kV and FIW for -3.0 kV and -2.5 kV we have the following arguments:

• When comparing the different voltages it is obvious that the -3.0 kV and -2.5 kV discharges (2d and 3d) are much more diffuse than the -4 kV discharges (1d). In picture 1d some channels can be identified, while in pictures 2d an 3d the emission profile is a bulk ionisation, which is characteristic for a Townsend and FIW mechanism.

• In case of -4.0 kV an emission around the grounded electrode is visible. In case of -3.0 kV and -2.5 kV discharges no grounded electrode emission is visible (2a-2d and 3a-3d). A Townsend discharge can only be anode-directed and FIWs usually also are anode-directed. So the absence of ionisation around the grounded electrode is a clue that the breakdown mechanism shifts in the direction of Townsend for decreasing voltage amplitudes.

• The propagation velocities of the -3 kV and -2.5 kV discharges are lower than of a -4 kV discharge but still significantly higher than the electron drift velocity. From this we conclude that also for the lower voltage amplitudes the mechanism is not Townsend.

• The electron drift velocity depends in good approximation linearly on the reduced electric field $E/p$. Therefore in case of a Townsend mechanism the delay times would be reversely proportional to the applied voltage. In case of a streamer mechanism the delay times would be less dependent of the applied voltage.

As expected the breakdown delay times increase with increasing voltage amplitude. The delay times depend much stronger on the applied voltage than expected. The increase in delay times is much larger than the increase of the reduced electric field $E/p$. This is a clue that a shift in breakdown mechanism occurs when the applied voltage is decreased from -4.0 kV to -2.5 kV.
4.4 Pictures of positive voltages

To study the breakdown phenomena for positive streamers a positive voltage is applied to the left electrode. The right electrode is during all measurement at earth potential. The results of this measurement are shown in figure 4.6. The results of a +4.0 kV pulse are located in the middle column and the +2.5 kV pulse results are in the right column. To compare negative and positive voltage pulses with each other, in the left column the -4.0 kV results (which are the same as in paragraph 4.2) are shown.

First we discuss some positive breakdown phenomena by means of the +4.0 kV pictures. The ionisation starts at the high voltage electrode (2a). The ionisation region grows into the direction of the grounded electrode and forms one or two small channels (2a-2c). Once the ionisation region has expanded to approximately one third of the gap, an ionisation region at the grounded electrode becomes visible (2c). The grounded ionisation region is much more diffuse than the high voltage ionisation. From the 6th till the 8th nsec the grounded ionisation front also crosses one third of the gap, while the high voltage ionisation front hardly makes any progress (2d). Then the two ionisation regions come so close to each other that they begin to
interact. The closer the two ionisation fronts come to each other, the higher the electric field between them. A few nsec later the two ionisation regions make contact at the middle of the gap (2e). A conducting path is formed, resulting in a significant decrease of the gap resistance. The lamp current increases, leading to more ionisation and a higher light intensity (2f). The ionisation near the anode is still a small path compared to the cathode ionisation. 19 nsec after the first visible ionisation, a significant lamp current is measured, which we defined as the breakdown moment.
Figure 4.6: Pictures of the emission profile evolution from the first visible emission until breakdown occurs. The light emission when -4 kV (column 1), +4 kV (column 2) and +2.5 kV (column 3) are applied to the left electrode of a low aspect ratio burner. Under each picture the time in nsec is shown. Time $t = 0$ is chosen to be the moment at which the first light emission is visible.

The most important difference between positive and negative voltage breakdown is the shape of the ionisation regions. The positive voltage ionisation forms a narrow channel (2c) whereas the negative voltage ionisation is much more diffuse (1c). The same effect is observed when comparing the high voltage ionisation in 2d with the grounded ionisation in 2d. Note that when 2e is mirrored with respect to a vertical axis (flipped horizontally), it shows many similarities with 1e. Positive streamers seem to be narrower than negative ones. Positive streamers represent a charge conservative system: the heavy positive ions do practically not move during streamer advance, they stay at the place where they have been generated\cite{4.1}. On the opposite, the negative streamer tip charge is formed out of highly mobile electrons, which
have an increased tendency to diffuse out of the tip. Electrons in the ionisation region ahead of the negative streamer tip move away from the tip. Therefore, only electron avalanches that develop in the direction of the streamer channel supply a significant ion charge to the streamer. The more radially directed avalanches tend to diffuse the streamer tip charge. This may also explain the higher fields needed for a stable propagation of a negative streamer than of a positive one.

The breakdown delay times for negative and positive voltages are similar (19 and 17 nsec).

When the voltage amplitude is decreased to 2.5 kV the breakdown delay times increase significantly (almost 10 times as high). This decrease in ionisation front velocity implies a shift in the breakdown mechanism from streamer breakdown towards fast ionisation waves. The anode ionisation expands till 80% of the gap (3d). No cathode ionisation is visible yet. The anode ionisation has come so close to the cathode that the electric field between them increases. The electric field is now high enough to initiate a cathode ionisation that short after makes contact with the anode ionisation (3e). A conducting path between the electrodes is formed (3f) leading to breakdown.

### 4.5 Ionisation front velocities

From the measured delay times we can make an approximation of velocity at which an ionisation crosses a gap from one electrode to the other. A simple approximation of this velocity would be the electrode distance divided by the delay time. A more accurate description of the ionisation front velocity can be determined by combining the pictures of the discharge with the information about the time at which each picture is taken. This way we can determine the velocity at which an ionisation region expands in the axial direction and investigate whether this velocity is constant or depends on the axial position of the ionisation front. To determine the position of the ionisation from a picture, we plot the integrated intensity over y (number of counts summed for all 512 pixels in a column) as function of x (figure 4.7).

![Image of ionisation front velocities](image)

**Figure 4.7:** a: an arbitrary picture of an emission profile. b: a plot of the vertically integrated intensity of picture a as function of x.
The ionisation front is defined as the border between the region in which the number of counts is significantly above the background level and the region in which no signal is measured. The determination of the x-position of the ionisation front is shown in the graph in figure 4.7. The intensity is linearly fitted in the neighbourhood of a first guess of the ionisation front position. The ionisation front position is equal to the intersection of the linear fit of the intensity with the x-axis.

The axial positions of the ionisation front x are plotted in figure 4.8 versus the time t at which the pictures are taken. In figure 4.8a the applied voltage is -4.0 kV, in 4.8b -3.0 kV and in 4.8c -2.5 kV. The standard deviation in x is equal to 0.05 cm. In case of -4 kV x seems to depend linearly on t. A linear fit results in a propagation velocity of \((3.4 \pm 0.9) \cdot 10^5\) m/s. Linear fits of the -3 kV and -4 kV yield velocities of \((1.5 \pm 0.1) \cdot 10^5\) m/s and \((1.0 \pm 0.1) \cdot 10^5\) m/s respectively. The velocity in case of -3 kV and -2.5 kV is slightly lower near the electrodes than in the middle of the gap. The cause of the lower velocity near the high voltage electrode is probably that a critical number of electrons is needed for a FIW to originate. In figure 4.5 we already saw that the high voltage ionisation front does not propagate further than 75% of the gap, which is the reason for the lower velocity around the grounded electrode.

![Figure 4.8: The axial position of the ionisation front x plotted as function of t in nsec. x = 0 corresponds to the high voltage electrode and x = 0.7 cm to the grounded electrode. Each plot represents a different applied voltage (a: -4.0 kV, b: -3.0 kV and c: -2.5 kV). The straight lines are linear fits.](image-url)
5 High aspect ratio burner results

In chapter 4 the low aspect ratio burner results were presented. The only parameter that has been varied so far is the applied voltage. In this chapter we also study the influence of other important parameters (gas pressure, kind of gas and electrode distance). For this purpose we created a large number of different high aspect ratio burners. Two types of burner wall geometries are used: short and long burners. The short high aspect ratio burners have an electrode distance of 1.5 cm and are shown in figure 3.6c. The long aspect ratio burners have an electrode distance of 2.7 cm and are shown in figure 3.6d. The inner diameter of both short and long burners is 4.0 mm (figure 3.7). An overview of all high aspect ratio burners that are studied is shown in table 3.2. In paragraph 5.1 the positive voltage results are presented and in paragraph 5.2 the negative voltage results.

5.1 Positive voltages

40 voltage pulses of +4.0 kV are applied to the left electrode of a short (d = 1.5 cm) burner with 20 sec between each voltage pulse. The right electrode is grounded. This measurement is repeated for all different burner types (Ar and Xe, 300 and 700 mbar). In column 1 of figure 5.1a representative selection of the pictures of 300 mbar Argon is shown. The pictures in column 2 and 3 are 300 and 700 mbar Xenon burner results. Before comparing the different burners with each other, we want to discuss the breakdown phenomena of one burner in detail: the 300 mbar Argon burner in column 1.

As already seen in the low aspect ratio burners, the ionisation starts at the high voltage electrode (1a). In picture 1b the high voltage ionisation region expands mainly in the direction of the wall, since the wall is more or less still at the earth potential at t = 0. The electric field seems to be much more radially directed than in low aspect ratio burners. The main difference between high and low aspect ratio burners is the electrode-wall distance compared to the electrode-electrode distance. For high aspect ratio burners the electrode-wall distance is relatively much smaller, resulting in a much stronger wall influence. Once the high voltage ionisation region touches the wall, it propagates along the wall (1c-1f). Meanwhile some ionisation originates around the grounded electrode, which expands spherically. When the two ionisation regions come close to each other, the high voltage ionisation front appears to move away from the wall. At t = 110 nsec at approximately 80% of the electrode distance, the two ionisation regions unite (1g). 10 nsec later the current increases significantly (1h), leading to breakdown.

The breakdown of a burner filled with 300 mbar Xenon is presented in column 2. The main difference between Xenon and Argon is that Xenon shows even more branching. The light intensity from Xenon that is registered by the ICCD is lower than that of Argon, but this says
nothing about the number of ionisations. Argon has a different spectrum than Xenon and the ICCD sensitivity is wavelength dependent.

<table>
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**Figure 5.1**: Pictures of breakdown evolution of high aspect ratio burners. The electrode distance is 1.5 cm and the applied voltage is +4.0 kV. In column 1 (left column) 300 mbar Ar, in column 2 (middle column) 300 mbar Xe and in column 3 (right column) 700 mbar Xe. Under each picture the time \( t \) in nsec and a picture reference is shown. The time \( t = 0 \) is chosen to be the moment at which the first emission is visible.

Similar as in Argon the ionisation region initially expands radially towards the wall (2b). The streamers that propagate towards the grounded electrode in picture 2c are in the middle of the picture. Since this is a 2-dimensional picture it is not always easy to see whether the streamer
propagates along the wall or in the middle of the burner. Other measurements have shown that cathode-directed streamers in high aspect ratio burners always propagate along the burner wall. The branching of the streamers is clearly visible (2c-2f). The breakdown time, which is defined as the period from the start of the voltage pulse until a significant current rise, is approximately 130 nsec in both Xenon and Argon.

An increase of the pressure to 700 mbar (column 3) leads to even more branching, a longer breakdown time and a lower emission intensity.

The breakdown mechanism in the high aspect ratio burners with a electrode distance of 1.5 cm and an applied voltage of +4.0 kV is streamer (for both Argon and Xenon and both 300 and 700 mbar). This conclusion is drawn from the following observations:

- The ionisation front velocities are much higher than the electron drift velocities.
- Small channels and branching (especially for Xenon and for 700 mbar).

To study the influence of the electrode distance, longer burners with an electrode distance of 2.7 cm are used (figure 3.6d). They have the same inner wall radius as the shorter burners. In the second column of figure 5.2 a representative selection of the pictures of a 300 mbar Argon burner with an electrode separation of 2.7 cm is shown. The pictures of an electrode distance of 1.5 cm (which are the same as in column 1 of figure 5.1) are shown in the first column, so the two electrode distances can be easily compared with each other.

As already seen in burners with an electrode distance of 1.5 cm, the ionisation expands immediately towards the burner wall (2b). Since the inner wall radius of both burners is the same, the radially directed electric field is hardly affected by the increase of electrode distance. The time required for the ionisation to propagate towards the wall is therefore in good approximation independent of the electrode distance: approximately 25 nsec for both burners (1b and 2b). After the wall contact an axial directed streamer is formed (2c). Since the electrode distance is increased and the applied voltage is the same, the axial component of the electric field in the gap is decreased. This explains the lower axial streamer velocities (2c-2g). The breakdown time increases for larger electrode distances, due to a lower axial streamer velocity and a larger distance that has to be crossed by the streamers.

The streamers show more branching than the ones in the shorter burners. Since they travel further, they have more time to branch. But this is not the only reason. The streamers also have an increased tendency to branch for higher electrode distances. This is a similar effect as seen when the pressure is increased (figure 5.1): in both cases the reduced axial electric field \( \left( \frac{E_x}{p} \right) \) decreases, which seems to result in lower streamer velocities and more branching. In this case a \( pd \) similarity seems to be valid. The grounded electrode ionisation starts at \( t = 130 \) nsec (2f), when the high voltage electrode ionisation has crossed...
approximately 40% of the gap. The breakdown time is approximately 220 nsec (2i). The breakdown mechanism is also for an electrode distance of 2.7 cm streamer.

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*Figure 5.2: Pictures of breakdown evolution in 300 mbar Argon burners. A +4 kV voltage is applied to the left electrode. In column 1 (left column) the electrode distance is 1.5 cm and in column 2 it is 2.7 cm. Under each picture the time t in nsec and the picture reference is shown. The time t = 0 is chosen to be the moment at which the first emission is visible.*
As described in paragraph 4.3, from a picture series an x-t plot can be created, in which the axial ionisation front position is plotted as function of time. Such x-t plots can also be created for high aspect ratio burners. In figure 5.3 the x-t plots of high aspect ratio burners filled with Argon are shown. The plots of \( d = 1.5 \) cm burners and \( d = 2.7 \) cm burners are included in the same figure. In figure 5.3a the 300 mbar results are shown and in 5.3b the 700 mbar results.

As can be seen in figure 5.3a, there seems to be a kink in the x-t plot of a short 300 mbar Argon burner at \( t \approx 25 \) nsec. During the first 25 nsec the ionisation expands mainly in the radial direction resulting in a smaller axial velocity of the ionisation front. The position of the kink in the plot corresponds to the moment the ionisation touches the wall. The x-position of the ionisation front is in good approximation linearly time-dependent. Though the external electric field in front of the streamers increases as the streamers come closer to the cathode (due to a only slightly decreasing potential difference over a smaller distance), the streamer velocity is not affected. The own electric field of the streamers is apparently more important than the external electric field. From the linear fit of the data points after the kink, a streamer velocity is determined: \( v = (1.87 \pm 0.09) \cdot 10^5 \) m/s.

In the x-t plot of a 300 mbar Argon burner with an electrode distance of 2.7 cm also a kink is present at the moment that the ionisation touches the wall (\( t \approx 25 \) nsec). In this case, the streamer velocity \( v = (1.57 \pm 0.06) \cdot 10^5 \) m/s.

In the x-t plot of a 700 mbar Argon burner the kink is present at the moment that the ionisation touches the wall (\( t \approx 40 \) nsec). In this case, the streamer velocities \( v = (1.30 \pm 0.08) \cdot 10^5 \) m/s and \( v = (1.11 \pm 0.05) \cdot 10^5 \) m/s respectively.

The x-t diagram of Xenon for an applied voltage of +4 kV is shown in figure 5.4. The time required for the ionisation region to make contact with the wall is much lower for Xenon.
Therefore the kink in the x-t plots is not so obvious. Linear fits of the data points have resulted in the streamer velocities shown in table 5.1.

**Figure 5.4:** The ionisation front position x in cm as function of time t in nsec in burners filled with 300 mbar (a) and 700 mbar Xenon (b). In each plot one burner with an electrode distance of 1.5 cm and one of 2.7 cm are shown.

**Table 5.1:** The influence of the electrode distance on the axial ionisation front velocities and their standard deviations in $10^5$ m/s.

<table>
<thead>
<tr>
<th>Axial ionization front velocity / ($10^5$ m/s)</th>
<th>d = 1.5 cm</th>
<th>d = 2.7 cm</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 mbar Argon</td>
<td>1.87 ± 0.09</td>
<td>1.57 ± 0.06</td>
<td>1.19 ± 0.11</td>
</tr>
<tr>
<td>700 mbar Argon</td>
<td>1.30 ± 0.08</td>
<td>1.11 ± 0.05</td>
<td>1.17 ± 0.09</td>
</tr>
<tr>
<td>300 mbar Xenon</td>
<td>1.67 ± 0.08</td>
<td>1.36 ± 0.04</td>
<td>1.23 ± 0.09</td>
</tr>
<tr>
<td>700 mbar Xenon</td>
<td>1.16 ± 0.05</td>
<td>0.99 ± 0.04</td>
<td>1.17 ± 0.06</td>
</tr>
</tbody>
</table>

Comparing the streamer velocities of the short burners (d = 1.5 cm) with the long burners (d = 2.7 cm), the velocities in the short burners are in all four cases approximately 1.2 times as high. The velocity ratios are consistent with each other. The axial external electric field ratio of the two burners is equal to 1.8. The external electric field apparently only has a slight influence on the streamer velocities. In table 5.2 and 5.3 the velocity ratios of Argon versus Xenon and 300 mbar versus 700 mbar are calculated. It is based on the same data as in table 5.1, but arranged in a different way to make it more convenient to study the influence of the different parameters.
Table 5.2: The axial ionisation front velocities and their standard deviations in $10^5$ m/s for the various burners. Argon versus Xenon.

<table>
<thead>
<tr>
<th>Axial ionization front velocity / ($10^5$ m/s)</th>
<th>Argon</th>
<th>Xenon</th>
<th>ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 mbar, $d = 1.5$ cm:</td>
<td>1.87 ± 0.09</td>
<td>1.67 ± 0.08</td>
<td>1.12 ± 0.12</td>
</tr>
<tr>
<td>300 mbar, $d = 2.7$ cm:</td>
<td>1.57 ± 0.06</td>
<td>1.36 ± 0.04</td>
<td>1.15 ± 0.07</td>
</tr>
<tr>
<td>700 mbar, $d = 1.5$ cm:</td>
<td>1.30 ± 0.08</td>
<td>1.16 ± 0.05</td>
<td>1.13 ± 0.09</td>
</tr>
<tr>
<td>700 mbar, $d = 2.7$ cm:</td>
<td>1.11 ± 0.05</td>
<td>0.99 ± 0.04</td>
<td>1.12 ± 0.06</td>
</tr>
</tbody>
</table>

The Argon-Xenon-ratios are consistent with each other. The streamer velocity in Argon is between 12% and 15% higher than in Xenon. Since the short-long-ratios as well as the Argon-Xenon-ratios are all consistent, one can expect that the high-pressure-low-pressure-ratios also must be consistent, as is confirmed in table 5.3.

Table 5.3: The pressure influence on the axial ionisation front velocities and their standard deviations in $10^5$ m/s.

<table>
<thead>
<tr>
<th>Axial ionization front velocity / ($10^5$ m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>300 mbar</td>
</tr>
<tr>
<td>Argon, $d = 1.5$ cm:</td>
</tr>
<tr>
<td>Argon, $d = 2.7$ cm:</td>
</tr>
<tr>
<td>Xenon, $d = 1.5$ cm:</td>
</tr>
<tr>
<td>Xenon, $d = 2.7$ cm:</td>
</tr>
<tr>
<td>700 mbar</td>
</tr>
<tr>
<td>Argon, $d = 1.5$ cm:</td>
</tr>
<tr>
<td>Argon, $d = 2.7$ cm:</td>
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<tr>
<td>Xenon, $d = 1.5$ cm:</td>
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<tr>
<td>Xenon, $d = 2.7$ cm:</td>
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In discharge measurement often a $pd$ similarity is observed. This means that an increase of pressure with a factor $n$, has the same effect as an increase of the electrode distance with the same factor $n$. Let us determine in what extend this $pd$ similarity is valid for the measured ionisation front velocities. Therefore we compare the pressure ratio times the velocity ratio with the electrode distance ratio times the velocity ratio:

$$\frac{700}{300} \frac{v_{700}}{v_{300}} = 1.65 \quad \text{and} \quad \frac{2.7}{1.5} \frac{v_{2.7}}{v_{1.5}} = 1.51. \quad (5.1)$$

In which $v_{700}/v_{300}$ is the averaged velocity ratio in table 5.3 and $v_{2.7}/v_{1.5}$ is the averaged velocity ratio in table 5.1. The ratios in (5.1) are quite close. A wider range of values for $p$ and $d$ are needed to study the validity of a $pd$ similarity in this case. The increase of the electrode distance has relatively a slightly stronger effect than the increase of the pressure.

The electron drift velocity in 300 mbar Argon, $d = 1.5$ cm, $V = +4$ kV ($E/p = 12$ Vcm$^{-1}$Torr$^{-1}$) is $0.04 \cdot 10^5$ m/s$^{16,17}$, which is much smaller than the ionisation front velocities. The ionisation mechanism therefore is definitely not Townsend for any of the measured burners.
5.2 Negative voltages

So far the high aspect ratio burners are only measured for positive voltages. Now we want to study the breakdown phenomenology for negative voltages. In figure 5.5 column 2 the breakdown evolution in a 300 mbar short burner \((d = 1.5 \text{ cm})\) is shown, when a negative voltage \((-4 \text{ kV})\) is applied to the left electrode. In column 1 the positive voltage results are presented, which are the same as in column 1 of figure 5.2.

<table>
<thead>
<tr>
<th>Positive voltage</th>
<th>Negative voltage</th>
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</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
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<tr>
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<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
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<tr>
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</tr>
<tr>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image17.png" alt="Image" /></td>
<td><img src="image18.png" alt="Image" /></td>
</tr>
<tr>
<td><img src="image19.png" alt="Image" /></td>
<td><img src="image20.png" alt="Image" /></td>
</tr>
</tbody>
</table>

**Figure 5.5:** Pictures of breakdown evolution in a 300 mbar Argon burner with an electrode distance of 1.5 cm. The +4 kV results are presented in column 1 (left column) and in column 2 are the -4 kV results. Under each picture the time \(t\) in nsec and the picture reference is shown. The time \(t = 0\) is chosen to be the moment at which the first emission is visible.
Initially the high voltage ionisation expands in a kind of spherical way (2b). The ionisation region forms a sphere that is stretched in the direction of the wall. Once the ionisation region touches the wall, it just keeps expanding as it did before, nothing special happens in contrast to positive voltages. The influence of the wall in case of negative voltages apparently is much smaller than for positive voltages. Initially the emission around the high voltage electrode is relatively intensive (2b, 2c), but as the ionisation region spreads out further (2d) the emission close to the high voltage electrode seems to fade out. A large part of the excited atoms and ions have fallen back to their ground state and no longer emit light. Meanwhile at the grounded electrode some emission becomes visible. The high voltage ionisation has crossed approximately 55% of the gap, when the grounded electrode ionisation forms some channels that expand in the direction of the high voltage electrode (2e). The two ionisation regions make contact with each other (2f), after which the light intensity quickly increases (2g). The ionisation is the most intense at the middle of the gap and two new ionisation fronts are raised. One ionisation front travels from the middle of the gap towards the high voltage electrode and the other towards the grounded electrode.

It is obvious that a negative voltage breakdown looks very different from a positive one. This points to a different breakdown mechanism. In the positive voltage pictures we saw beautiful streamers whilst the negative voltage breakdown is a very diffuse process. The negative voltage breakdown is an example of a fast ionisation wave in this burner. The pictures show some similarities with a Townsend breakdown mechanism. The main difference with Townsend is the velocity of the ionisation front, which is much higher than the electron drift velocity. The whole burner gets filled with charged particles (bulk discharge).

Similar as for earlier measurements we can create an x-t plot from the picture series. Since we have two ionisation fronts (a high voltage electrode ionisation front and a grounded electrode ionisation front), two plots are shown in figure 5.6.

![Figure 5.6: Plots of the axial ionisation front position versus time. The front of the high voltage ionisation (anode-directed) in black and the grounded electrode ionisation (cathode-directed) in red. Both plots are linearly fitted.](image-url)
The x-position seems to depend linearly on the time, indicating that the ionisation front velocity is constant, i.e. it does not depend on its x-position. Both velocities are approximately $1.0 \cdot 10^5$ m/s, which is significantly lower than the streamer velocity for positive voltages (+4.0 kV) in the same burner ($1.9 \cdot 10^5$ m/s). The fact that the velocities of both ionisation fronts are equal is probably just a coincidence, as we will see in other negative voltage results.

To study the influence of gas pressure and kind of gas for negative voltages, series of 40 measurement are done for different kind of burners. In figure 5.7 a representative selection is shown for 300 mbar Argon (same pictures as in column 2 of figure 5.5), 700 mbar Argon and 300 mbar Xenon.

When the pressure is increased from 300 mbar to 700 mbar, the breakdown time increases significantly (becomes more than 4 times as high). The pictures 2a – 2d show the same processes as for lower pressure burners (1a-1d) only at a slower rate. Then the grounded electrode ionisation forms some small channels that look like streamers (2e). While the cathode ionisation front does not make much progress, the cathode-directed streamers quickly propagate in the direction of the high voltage electrode (2f). When a streamer enters the high voltage ionisation region, it just keeps propagating and its head becomes much bigger (2g, 2h). The streamers are more dominant than the high voltage ionisation when the two ionisation regions meet each other and the streamers therefore determine the ionisation front position after a unification of the two ionisation regions.

The breakdown time in 300 mbar Xenon is almost the same as in Argon (~90 nsec). The high voltage ionisation behaves the same as in Argon (3a-3f). The difference with Argon is the anode ionisation behaviour. In Xenon the channels are significantly smaller and look more like streamers than the ones in 300 mbar Argon. The grounded electrode ionisation behaviour of 300 mbar Xenon is similar to that of 700 mbar Argon.

The mechanism of the high voltage ionisation is FIW. It is very diffuse and fills the whole burner section with ionisation. The high voltage ionisation front velocities are quite low compared with streamers, especially in case of 700 mbar Argon ($v = 0.8 \cdot 10^5$ m/s), but are still higher than the electron drift velocity ($0.04 \cdot 10^5$ m/s). The ionisation front velocities are still too high for Townsend, but in case of 700 mbar Argon the mechanism is not so far away from a Townsend breakdown. The mechanism of the grounded electrode ionisation is streamer for 700 mbar Argon and 300 mbar Xenon. One or more small channels are clearly visible (2f, 3f), there are also signs of branching and the propagation velocity is much higher than the electron drift velocity. The mechanism of the grounded electrode ionisation of 300 mbar Argon is not clear (FIW or streamer).
Figure 5.7: Pictures of breakdown evolution of a -4 kV voltage applied to the left electrode. In column 1 300 mbar Ar, in column 2 700 mbar Ar and in column 3 300 mbar Xe. Under each picture the time $t$ in nsec and the picture reference is shown.
In figure 5.8 x-t plots are shown for 700 mbar Argon (figure 5.8a) and 300 mbar Xenon (figure 5.8b).

**Figure 5.8**: Plots of the axial ionisation front position versus time in 700 mbar Argon (a) and 300 mbar Xenon (b). The front of the cathode ionisation in black, the anode ionisation in red, the cathode directed streamer in green and once it enters the cathode ionisation it turns blue. All plots are linearly fitted.

In 700 mbar Argon the high voltage electrode ionisation expands at a constant axial velocity of \((0.24 \pm 0.04) \times 10^5\) m/s. In the plot of the grounded electrode ionisation (streamer) a kink is visible at \(t \approx 270\) nsec. This is the moment at which the two ionisation regions are very close to each other and begin to interact. They feel each other’s electric field. The cathode-directed streamers enter the high voltage ionisation region resulting in a higher velocity: \((1.9 \pm 0.1) \times 10^5\) m/s. In a region with preliminary ionisation, streamers can reach higher velocities, since the free electrons in front of the streamer, which normally have to be created by photo-ionisation, are already present in this case.

In the 300 mbar Xenon plot of the grounded electrode ionisation three phases can be identified. At \(t \approx 45\) nsec streamers are formed resulting in an increase of the axial ionisation front velocity. When a streamer enters the cathode ionisation \((t \approx 75\) ns) the velocity is increased further. Since the streamer is then surrounded by charged particles it can propagate more easily.
6 Discussion and Conclusions

In the introduction we summed up some objectives. We will discuss now which of them have been successfully fulfilled.

- We have succeeded in creating an experimental set-up capable of visualising the ignition processes that occur during tens of nsec with an accuracy of a few nsec.
- A large number of experiments have been carried out from which we gained more insight in the breakdown phenomena in HID burners. Those data consist mainly of pictures that were taken at different moments in time.

The pictures we obtained from our measurement are analysed in two different ways. First we used a qualitative approach. Conclusions were drawn by looking at the shape of the ionisations areas: small channels versus diffuse regions of ionisation, branching, at which electrode, tendency to propagate along the wall. Next to that a more quantitative approach was used. We determined the positions of the ionisation front in a series of pictures. By plotting the axial ionisation front position \( x \) as a function of time \( t \), the ionisation front velocity can be determined.

From the data analyses a large number of conclusions are drawn. The most important conclusion is about the breakdown mechanism. In the theory three different mechanisms are discussed: Townsend, fast ionisation wave and streamer. From experiments it seems that for all burners that are studied, the breakdown mechanism is never a Townsend breakdown for the voltage pulses we applied. For this conclusion we provide the following arguments:

- The most important argument is that the ionisation front velocities are much higher than the electron drift velocities for the applied voltages according to literature.
- No signs of avalanche multiplication have been found.
- Cathode-directed breakdown is already observed before the ionisation front from the cathode has reached the anode.
- Small channels and branching occur under certain conditions, especially for positive voltages.

So the breakdown mechanism seems to be fast ionisation wave, streamer or a combination of these two. This depends on the applied voltage, the amplitude but also the polarity, the pressure, the kind of gas that is used, the electrode separation and burner aspect ratio. Now we will discuss the influence of all those parameters.

- Voltage polarity: In case of a positive voltage pulse of 4 kV the ionisation is a small channel and branching can occur, which implies a streamer mechanism. When a negative voltage pulse of the same amplitude is applied the high voltage electrode ionisation is much more diffuse, which is an indication for a fast ionisation wave mechanism.
- Voltage amplitude: The influence of the voltage amplitude is only studied for the low aspect ratio burners. When the voltage amplitude is increased the breakdown mechanism shifts in the direction of the streamer mechanism. The ionisation front velocities increase significantly and the ionisation is less diffuse.

- Pressure: An increase of pressure from 300 mbar to 700 mbar results in more branching and a decrease of the axial ionisation front velocity with approximately 40%.

- Electrode separation: An increase of the electrode distance has a similar effect as an increase of the pressure \((pd\) similarity). An increase of the electrode distance from 1.5 cm to 2.7 cm results in a 20% lower ionisation front velocity.

- Kind of gas (Argon or Xenon): The streamer velocities are approximately the same (the velocity is 10% higher in Argon). In Xenon more branching occurs.

- Burner aspect ratio: In the high aspect ratio burners the wall is relatively closer to the electrodes. As a consequence the electric field is much more radially directed and the ionisation regions expand in the direction of the wall. For high aspect ratio burners the wall has a much more important influence on the breakdown processes. In case of positive voltages for instance, streamers always propagate along the wall in high aspect ratio burners and always through the gas in low aspect ratio burners.

About the FIW mechanism versus the streamer mechanism we have the following remarks:

- In case of positive voltages \((+2.5 \text{ kV} \text{ or } +4.0 \text{ kV})\) the mechanism is always streamer. This is true for both low and high aspect ratio burners and for all pressures and electrode distances that have been measured.

- For low aspect ratio burners and negative voltages the mechanism is streamer for \(-4.0 \text{ kV}\) and FIW for \(-3.0 \text{ kV}\) and \(-2.5 \text{ kV}\).

- In case of high aspect ratio burners and an applied voltage of \(-4.0 \text{ kV}\) the high voltage ionisation mechanism is always FIW. The grounded electrode ionisation mechanism is streamer, with the exception of 300 mbar Argon in which the grounded electrode ionisation mechanism is not clear.

We have to conclude that the breakdown processes we studied are very complex. Even in ideal situations (point-to-plate configurations, no wall influence) streamers are still not understood completely and in literature there is still some discord about it. In the burners we studied the situation is even more complex mainly due to the wall influence. From experiments it seemed that the burner wall has a huge influence on the breakdown processes. For our convenience the burners we studied were filled with pure gases (Argon or Xenon). In real burners also salts (metal halides) are present which probably complicate things further. As a result of all those differences between the burners used in lamps and the ideal set-ups used for fundamental streamer research, one cannot just assume that all knowledge gathered from fundamental research is also applicable in lamp burners.
6.1 Recommendations

We gained a large amount of data about the breakdown phenomena in burners. Some open questions remain however. Further research is necessary. The following objects are interesting for further research:

- **2 bar Xenon**: We only studied 300 mbar and 700 mbar burners. 2 bar Xenon burners are also available for research. This increase of pressure would probably result in a transition of the breakdown mechanism from an ionisation wave to a streamer.

- **Influence of the wall**: how does the wall influence the initial electric field, and what is the influence of wall attachment? And investigate the influence of the kind of wall material that is used.

- **A real lamp burner with salts and mercury included.**

- **Resonant ignition**: when an ac-voltage is applied to the electrodes it is possible to reduce the breakdown voltage significantly. The theory behind this decrease of the breakdown voltage is still a mystery. A visualisation of the ionisation during a resonant ignition using the ICCD could help to gain more insight.

- **Numerical simulations**: these are extremely difficult for these non-idealistic circumstances however.

- **Investigate the influence of integrated antennas in high pressure lamps on the breakdown mechanism.**
7 References

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