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Electric field measurements on streamers using electric field induced second-harmonic generation

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Electric field measurements on streamers using electric field induced second-harmonic generation.

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Abstract

Streamers are propagating ionization fronts that appear when a non-conducting medium is suddenly exposed to a high electric field. Moreover, they carry a self-sustained electric field enhancement at their tip themselves. To obtain a picture of all important parameters in a streamer, the electric field distribution needs to be known. As the driving force of a streamer, the electric field determines the trajectory of high energy charged particles and is, consequently, responsible for the gas temperature and the gains and losses in particle collisions that determine the chemical activity of the plasma. The method used to measure the electric field applied in this work is electric field induced second-harmonic generation (E-FISH). This method exploits the fact that a laser beam interacts non-linearly with an external electric field, resulting in a small portion of frequency doubled light. Because the intensity of this frequency doubled light scales quadratically with the external electric field, the latter can be determined and split into its vertical and its horizontal components.

In this work, the vertical and horizontal components of the electric field of a streamer, propagating from the top to the bottom electrode, is measured. The streamers are operated in 110 mbar air and are initiated with a 23 kV 180 ns high voltage pulse. To measure the electric field, the E-FISH setup developed by Anne Limburg is adapted to the low pressure streamer setup. As an exploratory measurement, the influence of the E-FISH laser on the streamer is investigated as the invasiveness of the laser has proven to alter the E-FISH results. Laser-streamer interaction was indeed observed under certain circumstances. However, it was found that within the measurement frame chosen for the final results, no interaction is observed. To obtain these particular conditions, the influence of the laser power, the presence of nitrogen and the pressure of the gas are investigated. Additionally, a calibration method for the E-FISH results is developed using COMSOL. In this application, the electric field of a tip-to-plate geometry is simulated and integrated over the interaction length in which second harmonic signal is generated. The resulting calibration factor is used to convert the relative values of the E-FISH signal to absolute values for the electric field distribution. The results of the vertical component of the temporal scan show a peak of two times the background electric field when the electric field is measured near the streamer head. A secondary smaller peak is observed after the streamer has crossed the gap which stays below the level of the background electric field. Additionally, the horizontal component was found to be close to a factor twenty lower than the vertical component of the electric field. The radial scans of the electric field show the contour of the streamer head and additionally reveal a large asymmetry in the measured signal of both components. This was not caused by the alignment or by the position of the lens in front of the electrodes and will likely be due to the asymmetry in the surrounding vessel. Remarkable is that the effect seems to be larger for the horizontal component. Aside from the asymmetry, the radial scans show that the method is highly reproducible and provide proof of a radially outwards directed electric field with its main component pointing down. The final result, the 2D map of the electric field of the streamers once again displays the field amplification at the streamer head and also shows the contours of the conductive channel. Hence, it can be concluded that the method of E-FISH is suitable for measuring the electric field distribution of low pressure streamers in this setup. With some improvements, the results can be very useful for comparison with simulations and provide information of an additional plasma parameter to complement the measurement techniques of ICCD imaging and Raman and Thomson spectroscopy.
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Chapter 1

Introduction

In plasma physics, streamers are known as propagating ionization fronts and more generally familiar as a precursor to sparks and lightning. Streamers are cold atmospheric plasma discharges, where cold indicates that the ions and molecules are merely at room temperature, whereas the electrons are very hot. These cold discharges, containing high electron energies, have the ability to start high-temperature chemical reactions in a room temperature environment; convenient for practical reasons. Therefore, streamers occur in various industrial applications such as plasma medicine [1], combustion [2] and air cleaning [3]. In addition, a proper understanding of streamers also benefits applications like lightning protection and high voltage switchgear. To improve the knowledge about the natural phenomena as well as to apply that knowledge in daily life, streamers are widely investigated. Important parameters in this puzzle are the ion, molecule and electron temperature and density, the gas composition and the electric field of which some are shown in figure 1.1.

Figure 1.1: A simulation executed in a axisymmetric fluid model [4] of a streamer in atmospheric air in a gap of 16 mm with an applied voltage of 32 kV [5].

A widely used method to measure the electron density and temperature is Thomson spectroscopy in which light is scattered on free electrons. Consequently, the half width at half maximum (HWHM) of the spectral distribution of the scattering signal is proportional to the square-root of the electron temperature and the integrated area under the curve of the spectral distribution is a measure for the density of free electrons. In addition, Raman spectroscopy can be used to measure the rotational temperature of the molecules from scattering light. As a result, the relative intensities of the individual rotational lines in the obtained Raman spectrum give the molecular temperature [6].

Recently, electric field induced second harmonic generation (E-FISH) found its application in plasma physics. E-FISH is a method to measure the amplitude as well as the direction of an electric field by means of a laser. A very useful method, since more knowledge about the electric field of
a plasma could help find a link between the electric field and the plasma parameters mentioned before. The general idea is that the laser beam interacts non-linearly with the to-be-measured electric field, resulting in frequency-doubled light. As the intensity of this frequency-doubled light scales with the square of the electric field, the latter can be obtained using inversion techniques. The advantage of E-FISH over conventional methods is that the method is highly sensitive and is claimed to be non-intrusive, the setup is relatively simple and, also important for plasma applications, the method is applicable to both atomic and molecular species.

In this work the method of E-FISH is applied to a low pressure streamer setup. The streamers are in initiated in 50-250 mbar air and cross a gap of about 10 centimeters, resulting in 1 centimeter wide ionization fronts that travel at a speed of \( \approx 1 \text{ mm/ns} \). This is a novel application of the E-FISH method which counts zero publications on streamers of this size to this day. The simple optical setup needed for these E-FISH measurements was altered to fit next to the high voltage circuit and the streamer equipment was on its turn adjusted to provide a clean laser beam path. After successful implementation of the method, some preliminary tests were executed testing both the laser-plasma interaction as well as a calibration method to obtain absolute values for the electric field. The exploratory laser-plasma interaction measurements raised several questions regarding the the non-intrusiveness claim of the method. Finally, after optimizations, a temporal and radial scan of the electric field of a streamer was made.

1.1 Previous research on E-FISH

In 2017, Dogariu et al. showed the plasma community a non-resonant technique using an ultra fast source to perform Femtosecond Localized Electric Field Measurements (FLEMs) [7], also known as E-FISH. The idea of this technique was based on older work performed in the 1970’s in which second harmonic generation was used to acquire the nonlinear susceptibility of a gas using a known electric field [8]. Dogariu et al. inverted this idea and successfully measured the electric field in a variety of gases including air, Ar, H\(_2\), N\(_2\), CH\(_4\) and CO\(_2\) as shown in figure 1.2. A focused 800 nm fs laser was sent through a uniform electric field, sustained between two parallel plate electrodes. The induced 400 nm second harmonic signal was separated from the fundamental 800 nm beam using a dispersion prism and its intensity was measured by a photomultiplier tool.

![Normalized calibration curves for several different gases. The second harmonic signal (indicated as the FLEM response) is related to the square of the electric field [7].](image)

Figure 1.2: Normalized calibration curves for several different gasses. The second harmonic signal (indicated as the FLEM response) is related to the square of the electric field [7].

One year later, Goldberg et al. present an extension of this technique favorable for plasma measurements by replacing the fs laser by a ps laser [9]. The ps laser has pulses with a narrower spectral bandwidth compared to femtosecond lasers, allowing for better separation of the desired second harmonic signal from the background plasma induced emission. However, using a laser with a longer pulse decreases the temporal resolution; when the plasma is measured with the ps laser, the electric field is known over a time domain which is \( 10^3 \) times bigger. That is comparable to
only knowing what happens every twenty minutes in stead of being able to keep track of changes in the electric field every second. Additionally, as ps lasers emit pulses with a lower intensity, the amount of second harmonic signal created will be lower as the signal scales with the square of the intensity of the incoming beam. A trade-off between good spectral resolution and a high signal with a good time resolution must be made.

After this kick-start, several papers were published on the topic, mostly using ps or fs pulsed lasers. One particular topic of interest when studying the electric field is the propagation of ionization waves, earlier referred to as streamers. Chng et al. enlarged the distance between the electrodes by several centimeters compared to the setup of Goldberg et al. such that the development and propagation of the ionization wave in nitrogen could be investigated in more detail [10]. They showed that the method is applicable in low-pressure discharges (20-100 mbar), when the detection of the second harmonic signal is challenging due to a relatively low second harmonic signal created by the discharge compared to the signal created by the external electric field. Later, they also use the same setup to prove the feasibility of E-FISH measurements for atmospheric pressure discharges, showing a more pronounced ionization wave front due to operation at higher pressure [11].

Mid 2019, Goldberg et al. present for the first time a dynamic, time evolving one dimensional electric field profile measurement with sub-nanosecond resolution using E-FISH [12]. They extended the fs laser setup used in earlier research with a cylindrical lens for focusing into a laser sheet, enabling 1D measurements. The advantage of using a laser sheet is that the laser can be operated at full power due to less intense focusing. Prior to this research, when focussing the laser to a small dot, the laser beam must always be attenuated to prevent breakdown or exploding dust particles near the focus. In this case, the output signal is lower due to a lower laser beam energy which limits the measurements.

Furthermore, the E-FISH diagnostic was used to measure the electric field distribution in a nanosecond pulsed dielectric barrier discharge (DBD) plasma actuator for different pulse trains [13]. A dielectric barrier discharge is, as the name suggests, a discharge between two electrodes that are separated by a dielectric material. For the application of a DBD plasma actuator they are mounted asymmetrically and supplied by AC voltage, a ns pulse train in this case. When a sufficiently high voltage is applied, a discharge occurs at the outer parts of the electrodes that do not touch the dielectric. The result is an electrodynamic force that manipulates the air boundary layer, enabling control of the airflow [14]. The measurements using E-FISH give a quantitative look into the electric field distribution of such actuators in order to learn more about its dynamics and to optimize its applications.

Also, Yong Tang et al. used the method to demonstrate the feasibility of enhanced flame control [15]. Like Semini et al., they use a nanosecond pulsed dielectric barrier discharge. The DBD is used to induce oscillations of a counterflow atmospheric pressure diffusion flame. The electric field during the pulses and the electric field of the afterglow is measured using E-FISH. Several parameters are varied to observe the behavior of the flames to deduce optimal conditions.

Furthermore, Yingzhe Cui et al. measured the electric field distribution in DC corona discharges between coaxial cylindrical electrodes in ambient air. The goal was to investigate Kaptzov’s assumption in the ion flow model which is widely used for solving the electric field distribution in corona discharges. The assumption states that the electric field at the surface of the conductor remains at the onset value. From the results of the E-FISH measurements it was found that Kaptzov’s assumption is valid only when the discharge current approaches zero [16].

Last year, using both a ps laser sheet and a focused ps laser to complement each other, the electric field of positive and negative polarity quasi-two-dimensional helium plasma jets at atmospheric pressure impinging on liquid water was measured by Orr et al., revealing a non-uniform electric field across the jet. Also, propagating surface ionization waves and differences in charge accumulation for the different polarities were observed [17]. Ionization waves were investigated in more detail using the same setup on a plate to plate geometry filled with nitrogen [18].

Although widely available, ns lasers were used for a limited number of E-FISH experiments. This is due to the fact that they have a relatively low temporal resolution as the temporal resolution of E-FISH measurements is physically limited only by the laser pulse duration. This certainly restrains the observation of fast characteristic processes like plasma self-shielding and the earlier
mentioned ionization waves. Another problem arises from the fact that, to obtain an E-FISH signal comparable in strength to those produced by picosecond and femtosecond lasers, nanosecond lasers need very high laser pulse intensities. Because at higher intensities the limiting process of laser-induced breakdown becomes more abundant, nanosecond lasers are less suitable for all previously mentioned experiments. However, some solutions are recently presented to solve this problem.

Chng et al. worked their way around this problem by slicing a conventional Nd:YAG laser with a pulse duration of 20 ns down to three ns pulses using a Pockels-cell-based slicing scheme. These sliced pulses in turn are used to execute the E-FISH measurements on a pulsed electrostatic field at five bar [19] as well as in ambient conditions [20]. Successful implementation should make sub-nanosecond resolution available on a larger scale and could even promise picosecond resolution with standard nanosecond lasers after more optimization of the slicing scheme. No results indicating the temporal or spatial resolution were given for the high pressure, but the ambient conditions experiments resulted in a temporal resolution of about three ns.

Adamovich et al. suggested a different approach and were able to obtain a high temporal resolution by resolving the temporal variation of the electric field over the duration of the ns laser pulse. In this way the temporal resolution is limited only by the time response of the detector and oscilloscope. The experiment was done on a pin-to-pin nanosecond pulse discharge in ambient air at one and two bar with a very promising temporal resolution of potentially 0.56 ns [21].

To conclude, although the principle behind E-FISH measurements has been around for a while, this particular implementation to plasmas has been investigated for only a few years. Hence, there is much more fundamental research yet to be done and many applications yet to be investigated. Large scale low pressure streamers being one of them. How I aimed to fill in this gap will be discussed below.

1.2 Aim of this work

The aim of this thesis is to be able to experimentally obtain an overview of all important plasma parameters for one and the same plasma. The electric field distribution is added to the list which already contains the electron temperature and density, the rotational temperature of the molecules and the optical emission. This is achieved by adding the measurement technique of E-FISH to a low pressure streamer setup that already has the following diagnostics in operation: ICCD imaging, Thomson Spectroscopy and Raman Spectroscopy. These are novel experiments and valuable for a few different reasons.

First of foremost, adding a method to measure the electric field puts us one step closer to describing the full physics of the streamer. In this way, the electric field, the optical emission, the electron density and temperature as well as the rotational temperature of the molecules can be measured for the same plasma. This is something that is modelled before [5], but comparable experimental results are still absent. This work aims to produce experimental results that can be compared to simulations like the onesh owed in figure 1.1. This one-on-one comparison conceivably leads to improvements of the simulations, which in turn results in improvements of the streamer related applications mentioned before.

Secondly, during this project a second method of measuring the electric field was used by others in parallel: by means of relative intensity of spectral lines measured by a monochromator. This idea originates from a paper of Tomas Hoder et al [22] and can act as a complementary reference source for the results obtained with the method of E-FISH. Disadvantages of this method over the method of E-FISH are the facts that the measurement range is restricted to the light emitting area and that it does not (partly) resolve the direction of the electric field.

Lastly, by implementing a high power laser in the setup, previous research on laser-plasma interaction could be elaborated. Anne Limburg [23] questioned the non-intrusiveness of the the method of E-FISH in her master thesis and after further investigation Thijs Keur [24] indeed found proof of laser-induced plasma branching as shown in figure 1.3. However, these experiments were conducted on a small nitrogen jet. To see if the same is observed in a low density plasma (low pressure streamers are about ten times as wide) is of interest for the application of E-FISH in further research.
1.3 Research goals

In this master thesis, the aim is to answer the following research question:

Is the method of E-FISH suitable for measuring the electric field distribution of a low pressure streamer and if so, what is the radial and temporal electric field distribution?

To this end, several sub questions were addressed:

1. How can the method of E-FISH be implemented in the low pressure streamer setup such that Thomson and Raman scattering as well as ICCD imaging is possible at the same setup?
2. What is the effect of the E-FISH laser beam on the streamer and does this affect the E-FISH results?
3. Which calibration procedure can be used to determine the relation between the second harmonic signal and the electric field strength?
4. What is the temporal electric field distribution of the low pressure streamers measured using E-FISH?
5. What is the radial electric field distribution of the low pressure streamers measured using E-FISH?

1.4 Outline

The structure of this thesis is as follows: chapter 2 will give the needed theoretical background on which the experiments and corresponding results are based. This includes the plasma source, the laser diagnostics applied on it and some theory on the laser-plasma interaction.

Subsequently, chapter 3 describes the method used to conduct the experiments. First of all, the experimental setup that aims to answer the first sub-question is explained after which the method for executing the temporal and radial electric field scans is explained in the second section.

The results of the experiments answering research question 2 can be found in chapter 4 as well as the discussion. This part covers the laser-streamer interaction to see whether E-FISH is possible without disturbing the plasma. Chapter 5 covers questions 3 till 5. The chapter starts with a section that shows the time evolution of the electric field. To obtain absolute values for the electric field of the streamer, a calibration method is added. Finally, the temporal and radial electric field distributions of a streamer in 110 mbar air measured using the method of E-FISH are shown.

The thesis is finalized in chapter 6 which contains the summary and conclusions. Additional improvements on the setup and method and recommendations for further research are elaborated in chapter 7.

A side note on this thesis is that, due to Covid-19, there were only four months available for the build-up of the setup and actual experiments in the lab. As, at the end of the first measurement series some crucial equipment was damaged, there was little room for improvements. Hence, the
results presented in chapter 4 and 5 are merely preliminary results and may contain certain obvious errors and some suggested improvements may therefore seem quite straightforward. Luckily, the long preparation proved to be fruit full as the results, although unpolished, clearly show the potential of this work.
Chapter 2

Theory

In this chapter, the required theory to be able to follow and interpret the experiments later on in this thesis is described. First of all, the concept of plasma as well as the special case of low pressure streamers are discussed. In-depth theory on streamer initiation, propagation and the properties of streamers is included. Next, a section is devoted to the laser diagnostic with basics on Gaussian beams, non-linear optics and the method of E-FISH itself. The last section explains the interaction that occurs between the plasma and the laser beam as this proved to be very important for the interpretation of the results.

2.1 Plasma

Plasma can be seen as the fourth state of matter; just like solid, liquid and gas, plasma is just another form in which a substance can exist. A medium can transit from a gas into a plasma by increasing its temperature up to 4000 to 20000 Kelvin, creating an ionized gas. This is a gas in which electrons are not bound to an atom or molecule, but move freely throughout the gas leaving atoms and molecules positively charged. These free charges bring along some important properties: plasma’s are electrical conductive, internally active and respond strongly to electromagnetic fields [25]. The fractional ionization of a plasma equals

$$x_{\text{ionization}} = \frac{n_{\text{ions}}}{n_{\text{gas}} + n_{\text{ions}}}$$  \hspace{1cm} (2.1)

with $n_{\text{ions}}$ the positive ion density and $n_{\text{gas}}$ the neutral gas density. If $x_{\text{ionization}} \rightarrow 1$, the plasma is fully ionized.

An important parameter that describes the length scales in plasma’s is the Debye length

$$\lambda_{\text{Debye}} = \left( \frac{\epsilon_0 k_b T_e}{n_e e^2} \right)^\frac{1}{2}.$$  \hspace{1cm} (2.2)

In this equation $\epsilon_0$ is the permittivity of free space, $k_b$ the Boltzmann constant, $T_e$ the electron temperature, $n_e$ the electron density and $e$ is the charge of an electron [26]. The Debye length gives the distance over which a charged particle is shielded by its environment such that the net potential is zero.

When in equilibrium, a plasma is characterized by a particle density $n_{\text{electrons}} \approx n_{\text{ions}} \approx n$ and a common temperature $T_{\text{electrons}} = T_{\text{ions}} = T$. However, a great deal of plasmas, just like the one treated in this paper, are not in equilibrium. To this end, two important types of plasma discharges can be distinguished: high-pressure arc discharges and low-pressure discharges. High-pressure discharges, operated mostly around atmospheric pressure, have $n \approx 10^{14}$-$10^{19}$ cm$^{-3}$, $T_e \approx 0.1$-2 eV and $T_i \leq T_e$. These types of plasmas are often used to transfer heat to a surface. Low-pressure plasma discharges on the other hand, are characterized by $n \approx 10^8$-$10^{13}$ cm$^{-3}$, $T_e \approx 1$-10 eV and $T_i \ll T_e$ [26]. Why this is beneficial will be explained below.

2.1.1 Streamers

The plasma of interest in this thesis is a streamer. Streamers are fast-moving ionization fronts that belong to the group of cold atmospheric plasma discharges. The ions and neutral particles
are around room temperature, but the fast moving electrons on the contrary are very hot [27]. As
as result, these streamers are capable of starting high-temperature chemical reactions in a room
temperature environment. Another advantage compared to thermal plasmas is that the chemistry
evolves very efficiently as no energy is lost to gas heating [5]. How these useful streamers are
initiated and how they evolve in space and time will be addressed in the next few sections.

2.1.2 Starting a streamer

Streamers are driven by collisions between the hot, accelerated electrons and the neutral, cold gas
molecules. These collisions can be either (1) inelastic or cause (2) excitation, (3) ionization of the
gas molecule or (4) attachment of the electron to the molecule.

When the electrons and the gas molecules collide elastically, kinetic energy is conserved by
definition. As for the excitation, when a fast moving electron excites a gas molecule to a higher
energy level, the molecule can fall back to a lower energy level and emit a photon in the process.
These emitted photons can be used to observe the plasma with a camera. It must be noted that in
air only the tips, the actively growing regions of the streamer discharge, will be imaged like shown
in figure 1.1. In this region the electric fields are strong enough for the electrons to gain sufficient
energy to be able to excite molecules to high enough levels.

For the growth of the streamer, collision processes 3 and 4 are the most important. Let us start
with the ionization of the gas. For streamers in air the reactions are:

\[ \text{O}_2 + e \rightarrow \text{O}^+ + 2e; \tag{2.3} \]
\[ \text{N}_2 + e \rightarrow \text{N}^+_2 + 2e. \tag{2.4} \]

This results in an increase of ions and electrons in the gas. However, for the plasma to actually
grow, more electrons must be created than there are lost due to attachment: the ionization rate \( \alpha \)
must exceed the attachment rate \( \nu \). In other terms, the effective ionization coefficient, also known
as the Townsend ionization coefficient,

\[ \pi = \alpha - \nu, \tag{2.5} \]

should be larger than zero. When this is the case, a new electron is created which accelerates
and can ionize a molecule on its turn and so on. So, more electrons and positively charged gas
molecules are created: they form a so-called avalanche.

When growing, this avalanche drifts a distance

\[ d = \mu_e E t \tag{2.6} \]

with \( \mu_e \) the electron mobility and \( E \) the electric field. Furthermore, the number of electrons is
multiplied by a factor \( e^{\pi(E)d} \). When the newly created space charge of the avalanche induces an
electric field itself which is in strength comparable to the external electric field, the avalanche
transitions into a streamer. This transition is better qualified by the Meek criterion, which in air
equals \( \pi(E)d = 18 \). However, Montijn et al. found that a correction is needed when taking electron
diffusion into account, resulting in a longer transition time [28].

When a needle electrode is used to induce a streamer, the avalanche does not directly transits
into a streamer, but an intermediate stage arises known as the inception cloud. In this phase, light
is emitted from a semi-spherical body surrounding the tip electrode. The inception cloud expands
and forms a shell around the needle electrode. When the shell destabilizes, it forms one or multiple
streamers [29].

2.1.3 Streamer propagation

There are two types of streamers: positive streamers which propagate in the direction of the
electric field and negative streamers which propagate in the opposite direction [30] as shown in
figure 2.1. This works as follows: in figure 2.1a the external electric field is pointed downwards
which accelerates the electrons upwards. The electrons inside the streamer will move against the field direction and create a current following Ohm’s law

\[ j = \sigma E, \quad (2.7) \]

with the conductivity of the medium \( \sigma \). As electric charge is conserved, the charge density distribution \( \rho \) in the body changes as

\[ \delta \rho + \nabla \cdot j = 0. \quad (2.8) \]

This shift in charge distribution leaves a positive charge surplus at the streamer head. The separated charge carriers inside the streamer induce a change in electric field inside the streamer according to Gauss’s law:

\[ \nabla \cdot E = \frac{\rho}{\varepsilon_0} \quad (2.9) \]

in which \( \varepsilon_0 \) is the dielectric constant. This attracts more free electrons outside the streamer that ionize more gas molecules on their path and elongate the streamer. For the negative streamers displayed in figure 2.1b a reverse reasoning can be followed, resulting in a streamer moving in the opposite direction.

![Figure 2.1: (a) a positive streamer, (b) a negative streamer.](image)

The streamers considered for this paper are positive streamers. It has been previously observed that these streamers start more easily and propagate faster and further than negative streamers. This is because the charge layer at the tip exists of heavy ions that move hardly, maintaining the enhanced electric field better than freely moving electrons for negative streamers [5]. As the induced positive streamer is an elongated conducting body, the streamer will act as an extension of the needle on the upper electrode with a dense electric field near its tip. It is exactly this electric field enhancement that we want to study in this work.

### 2.1.4 Discharge criteria

For a positive streamer to propagate, two main criteria must be met: free electrons should be present and the electric field has to be sufficiently high.

An important source of free electrons for propagating streamers in air are the electrons created by photo-ionization. When a high energy electron moving in air collides with a nitrogen molecule and excites it, the nitrogen molecule can emit a particular photon with a wavelength of 98-102.5 nm. This photon in turn can ionize an oxygen molecule somewhere else, creating an extra electron [31]. The process of photo-ionization stabilizes the discharge front in both inception cloud phase and in the propagating streamer phase.

Besides due to photo-ionization, free electrons can also be present from previous discharges and electron detachment from negative ions. Also, external radiation like cosmic rays or bremsstrahlung photons from very fast runaway electrons can act as an electron source. The latter are created when electrons are accelerated to an energy above the so called “runaway threshold” at which the...
energy loss due to inelastic and ionizing collisions is over its maximum [5].

The external electric field in the setup used in this work is graphically shown in figure 2.2. It consists of two electrodes, where the upper one is connected to the high voltage circuit and has a needle attached to it and the bottom electrode is connected to ground. The needle concentrates the electric field locally to initiate the streamer at that tip whereas the electrodes provide a large uniform background electric field that guide the streamer. The color in figure 2.2 indicates the electric potential and the red arrows show the electric field distribution. The wider the arrow, the stronger the electric field. The boundary conditions in the simulation include a grounded \( (V = 0) \) surrounding vessel and bottom electrode and a initial value for the upper electrode \( V = V_0 \). Additionally, charge is conserved in the entire selection.

![Figure 2.2: A graphical overview of the electric field (arrows) using COMSOL. The upper brass electrode is connected to the high voltage supply and the lower copper electrode to ground, creating an electric field pointing downwards. A conducting tungsten needle is connected to the upper electrode, concentrating the supplied power.](image)

The electric field between two infinitely long parallel plate electrodes can be described as

\[
E = \frac{U}{d}.
\]

In this equation \( U \) is the potential which is applied and \( d \) the distance between the two plates. However, in this setup the plates are not infinitely long, which creates boundary effects near the edges of the electrodes. Additionally, with the presence of the electrode tip, the actual background electric field deviates from equation 2.10. Therefore, the application COMSOL multiphysics is used to compute the electric field distribution. This application uses the finite element method to calculate certain properties in a physics or user defined mesh grid.

2.1.5 Streamer properties

The free electron source and the external electric field have been discussed, but what parameters are responsible for which streamer properties?

First of all, the gas density \( N \) determines the particle mean free path \( l_{mfp} \propto 1/N \) as the number of particles determines the likeliness of collisions. Also, the time scale is influenced by the pressure in a same manner \( \propto 1/N \). Additionally, the electric field created by the streamer scales like \( \propto N \) and the ionization degree is proportional to \( N^2 \).

Moreover, the composition of the gas determines the transport and reaction rates as well as the strength and properties of photo-ionization [5].

Besides the gas composition and pressure, the streamer diameter and velocity also strongly depend on the applied voltage: the applied potential, the length of the voltage pulse as well as the voltage rise time and polarity of the voltage.
The streamer path is mainly determined by the external electric field lines because those field lines cause the electron drift that drives the streamer. However, deviations from these electric field lines do occur. Firstly, because the streamer tip itself enhances and deviates the external electric field lines. Furthermore, as explained before, positive streamers strongly depend on the available electron source in front of them. Hence, the position of this source might affect the path the streamer takes. Luckily, in air photo-ionization provides a big enough source of electrons such that this effect is minimal, but when using other gases this might be important to take into account. Additionally, the remnants of previous discharges may guide the new streamer. This is known as the “memory effect” [32, 33]. Finally, another important guiding mechanism occurs when using laser diagnostics on the streamer: the streamer is guided by pre-ionization created by the laser beam [34, 35, 36, 37]. This phenomenon is referred to as laser-streamer interaction and is discussed in more depth in section 2.3.

2.2 Laser diagnostics

A laser (Light Amplification by Stimulated Emission of Radiation [38]) is a device that produces an intense, monochromatic, highly collimated and nearly coherent beam of light [39]. These properties allow lasers to be very useful for various types of research and applications in medicine [40] as well as in industrial [41] and in communication [42] applications. A Nd:YAG laser is one of the main components used in the low pressure streamer setup. Therefore, this section will give some theoretical background on the beam properties of lasers as well as the specific diagnostics used for the experiments.

2.2.1 Beam properties

Most lasers emit Gaussian shaped beams. Therefore, it is useful to get a closer look at those specific beam properties. An overview of these properties is given schematically in figure 2.3.

![Figure 2.3: Focussed Gaussian beam with the width $w(z)$ of the beam in red. Also the waist size $w_0$, the Rayleigh Range $z_R$ and the confocal parameter $b$ and the half angle divergence $\theta$ are indicated.](image)

In figure 2.3 the width of the Gaussian beam is shown in red and reaches a minimum at the beam waist $w_0$. With $\lambda$ being the wavelength of the laser, the beam width follows the equation

\[ w(z) = w_0 \sqrt{1 + \left( \frac{\lambda z}{\pi w_0^2} \right)^2} \]  

(2.11)

along the $z$ axis. At some distance from the waist, at $z_R$ and $-z_R$, the beam width has increased by a factor $\sqrt{2}$ with respect to the beam waist. This is called the Rayleigh Range and gives information about the focus of the beam. By putting $w(z_R) = \sqrt{2}w_0$ in equation 2.11, the quantity can be calculated from

\[ z_R = \frac{\pi w_0^2}{\lambda} \]  

(2.12)

The smaller this number, the more focused the beam. As already shown in the figure, the complete span of the Rayleigh Range on both sides of the waist is given by the confocal parameter $b = 2z_R$. Also the half angle of divergence is indicated and shows how much the beam diverges. Far from the waist $z >> z_R$, the angle can be approximated by

\[ \theta = \frac{\lambda}{\pi w_0} = \frac{w_0}{b} \]  

(2.13)
2.2.2 Nonlinear optics

In the setup the laser travels through different media (air, windows, mirrors etc.), hence this section will elaborate on the resulting effects.

An optical material becomes nonlinear when a light beam passes through it with sufficient intensity, like a laser beam, such that it causes changes in the optical properties of the material [38]. It is called non-linear because the relation of the distorting electromagnetic field, the laser light, and the response of the material is non-linear. The actual degree of non-linearity can be found by considering the polarization \( P \) which is the charge displacement upon applying an external electric field \( E \). In the case of linear optics, these relate as

\[
P(t) = \epsilon_0 \chi^{(1)} E(t),
\]

where \( \epsilon_0 \) is the permittivity in free space and \( \chi^{(1)} \) is the linear susceptibility [43]. For non-linear optics, equation 2.14 can be expanded into a power series [43]

\[
P(t) = \epsilon_0 \left( \chi^{(1)} E^{(1)}(t) + \chi^{(2)} E^{(2)}(t) + \chi^{(3)} E^{(3)}(t) + \ldots \right).
\]

If the incident light is a harmonic wave, then the medium responds to the electric field as follows:

\[
P(t) = \epsilon_0 \left( \chi^{(1)} A(\omega) \cos(\omega t - k_\omega z) + \chi^{(2)} A(2\omega) \cos(2\omega t - k_{2\omega} z) \right).
\]

In this equation is \( \omega \) the frequency of the light, \( A(\omega) \) the amplitude of the field, \( k_\omega \) the wave vector and \( z \) the propagation direction of the light beam. In equation 2.16, the electric field was substituted in equation 2.15 and only the first two terms are considered. It shows that the second term is a wave with frequency \( 2\omega \), the second harmonic of the original wave, and has an amplitude proportional to the square of the electric field [44]

\[
E = A(2\omega) \cos(2\omega t - k_{2\omega} z),
\]

with the wave vector, which depends on the refractive index \( n(2\omega) \) and the speed of light \( c \) like

\[
k_{2\omega} = \frac{n(2\omega) 2\omega}{c}.
\]

This process is known as second harmonic generation and depends on the susceptibility tensor \( \chi^{(2)} \) and the phase mismatch \( \delta k \). The amount of second harmonic light generated is optimal for a maximal value of \( \chi^{(2)} \) and a minimal value for \( \delta k \), preferably

\[
\delta k = k_{2\omega} - 2k_\omega = 0.
\]

The process of second harmonic generation is graphically shown in figure 2.4a, in which two photons excite a molecule to a virtual state and a photon with doubled frequency is emitted. However, due to symmetry reasons, all even-orders of interaction cancel out in centro-symmetric media. Hence, second harmonic generation does not occur in gasses like air.

2.2.3 Electric field induced second harmonic generation

The method of E-FISH uses the fact that an electric field can break the symmetry in a gas and therefore enables an otherwise forbidden second harmonic generation. This leads to an output beam with \( 2\omega \) and an intensity proportional to the square of the electric field, as discussed above. For comparison, both second harmonic generation (SHG) and electric field induced second harmonic generation (E-FISH) are shown in figure 2.4.
By filling in the non-linear polarization relation 2.15 in the general wave equation, as was done in detail by Thijs Keur [24], the following relationship between the electric field $E$ and the second harmonic light $I_{2\omega}$ can be found:

$$\sqrt{\frac{I_{2\omega}}{I_{\omega}^2}} = C_{\text{cal}} \left| \int_{-L/2}^{L/2} E(z) \, dz \right|$$

(2.20)

which can be simplified to

$$E^* = \frac{1}{C_{\text{cal}}} \sqrt{\frac{I_{\text{EFISH}}}{I_{\text{input}}}}$$

(2.21)

with $E^*$ the line integrated electric field over the interaction length $L$. So, by measuring the amount of second harmonic generated light, $I_{\text{EFISH}}$, and the incoming laser beam, $I_{\text{input}}$, the line integrated electric field can be reconstructed with a calibration factor. This factor can be determined by applying a known electric field. To resolve the electric field along the laser path, an inversion technique like Abel inversion can be used [45].

Furthermore, the orientation of the electric field can be measured with E-FISH since the output second harmonic beam and the electric field in which it is created have the same orientation. This is due to the fact that the electric field can only induce polarization components parallel to the field. The polarization of the input beam does not affect the polarization of the second harmonic light, but does influence the efficiency of the conversion process. The process of second harmonic generation is nine times more efficient if the input beam and the electric field have the same orientation. This originates from the susceptibility coefficient $\chi$ mentioned before. This tensor is hidden in the calibration factor $C_{\text{cal}}$ in equation 2.21 following $C_{\text{cal}} \propto |\chi^{(3)}|^2$ and has two non-zero components: the components obtained when measured electric field is perpendicular or parallel to the incoming beam. The latter is three times stronger than the first [46]. With the square dependence of the calibration factor on the susceptibility coefficient, the measured second harmonic signal is a factor nine higher for parallel polarizations.

### 2.3 Laser-plasma interaction

Until now, theory about plasma and lasers have been discussed, but another important aspect arises when combining the two: the laser is able to affect the streamer. The laser can initiate processes that change the distribution of the available electron source surrounding the streamer. This electron source is an important parameter for the inception of streamers as discussed in section 2.1.4, but under some circumstances also influence the propagation direction of the streamer as shown in figure 2.5. In this section, several laser induced processes are discussed that relate to laser-streamer interaction effects.
Laser induced breakdown

In a high intensity laser beam, especially in the focus where the irradiance is very high, laser induced breakdown (LIB) can occur. The phenomenon arises when, at a very high field strength, a gas that is usually transparent to optical frequencies becomes highly ionized. There are two processes that can be held responsible for breakdown in an intense electromagnetic field: avalanche ionization and photo-ionization as earlier described in section 2.1 [47]. During the laser driven photo-ionization, photons directly ionize a molecule or atom and create a free electron. Although the photon energy is too low to overcome the ionization potential in a one-on-one process, multiple photons together do exceed this barrier and are able to ionize when absorbed simultaneously in a multiphoton ionization process.

The laser intensity needed for this breakdown process depends on the pulse duration, the pressure of the gas and the wavelength of the laser pulse. Wu et al. showed that within a single pulse duration of 100 ps breakdown did not occur easily. This is due to the fact that there is not enough time for multiple collisions, limiting the avalanche ionization processes. Also, at higher pressures low threshold values for the intensity are observed, which is due to increased collisional frequency leading to slightly increased avalanche ionization processes. Furthermore, laser induced breakdown occurs at lower threshold values for a 532 nm beam compared to a 1064 nm beam [48]. This can be attributed to the higher photon energy of shorter wavelengths.

Detachment

Another process which contributes to the laser-streamer effect is electron detachment. Section 2.1.2 already explained its counter process: attachment, in which an electron is attached to a molecule and forms a negative ion. Inversely, an electron is gained during the electron detachment from a negative ion. The corresponding reaction for oxygen is:

$$O_2^- + M \rightarrow O_2 + M + e^- \quad (2.22)$$

in which M presents a neutral gas molecule. Also, $O^-$ exhibits electron detachment when colliding with a nitrogen molecule [49]

$$O^- + N_2 \rightarrow N_2O^- \rightarrow N_2O + e^- . \quad (2.23)$$

When a photon collides with a negative ion, a similar process occurs. An electron is released from a negative ion by irradiating the ion with a photon with an energy higher than the detachment energy. Shibata et al. showed in their simulations that photodetachment in an $O_2$ discharge by

$$O^- + h\nu \rightarrow O + e^- \quad (2.24)$$

resulted in a decrease in the number of ions in the incident region by 30 percent. In those simulations a laser of 300 W with a wavelength of 530 nm was used to irradiate an oxygen glow discharge continuously [50]. Also, Cosby et al. show that photodetachment from an $O_2^-$ ion occurs at photon wavelengths ranging between 640-565 nm [51].
As the laser used in the current setup has a wavelength of 1064 nm and thus carries photons with an energy too low to photodetach electrons, it is expected that this process plays no role. However, as will be discussed later in this work, a significant amount of 532 nm light was present in the output laser beam that crosses the threshold for photodetachment.

Laser induced breakdown and electron photodetachment become important for the to-be measured plasma because the ionization paths created by the laser influence the development of the streamer. As explained in section 2.1, streamers propagate along the external electric field lines. But, when there is pre-ionization present, these paths can deviate [52]. As the threshold for electron photodetachment is only a few eV, this process is expected to contribute most to the laser-streamer interaction.
Chapter 3

Method

In this chapter, a detailed description of the experimental setup is given. Section 3.1 treats the equipment and triggering circuit for the streamer generation and E-FISH measurements and section 3.2 explains the measurement procedure for the final results in which the temporal and radial electric field of the streamers is measured.

3.1 Experimental Setup

Creating the experimental setup was an important part of this thesis as the first goal was to implement the E-FISH setup made by Anne Limburg [23] on an existing low pressure streamer setup. The streamer setup was already equipped with the diagnostics of ICCD imaging, Raman and Thomson Spectroscopy. Therefore, the setup is quite extensive and will be treated in this paragraph piece by piece. First, the setup needed for the generation of the plasma is explained, followed by the adapted E-FISH setup which covers the main part of this thesis. The diagnostics of Raman and Thomson spectroscopy are not used in this work and will not be treated in this chapter.

3.1.1 Plasma source

The setup used to create a repetitive low pressure streamer, as well as the triggering used to operate the system, is schematically shown in figure 3.3.

Let us start off from where the setup is driven: the Keysight 33600A series waveform generator. This function generator triggers both the Highland Technology digital delay generator as well as the high voltage circuit.

The delay generator in turn triggers the Quantel Q-smart 450 laser from channel B and C as well as the LaVision PicoStar HR12 ICCD camera from channel D. Changing the timing between them is used in the investigation of the laser-plasma interaction as will be discussed in chapter 4. An overview of the triggering of the laser is shown in figure 3.1 and works as follows: first, a trigger is sent to the flash-lamp, followed by a trigger to the Q-switch. About 40 ns after the Q-switch has received the external trigger, a laser output pulse of 7 ns is produced. The delay between the flash-lamp trigger and the Q-switch trigger determines the output power of the laser as is shown in figure 3.6. Optical fibers are used to reduce EMC issues in the large distance between the delay generator and the laser.

The function generator also triggers the high voltage circuit. Also here, the electrical trigger is converted to an optical signal, travels several meters and is converted back to an electrical signal when it enters the EMC box. In this box most of the high voltage equipment is contained and shielded from the surroundings when closed. When the electrical trigger reaches the BEHLKE 501-15-SiC fast high voltage push-pull switch, the switch opens up and allows the load on the capacitor to be discharged (yellow) in very short pulses (about 250 ns). The negative end (black) is connected to the ground through a 400 Ω resistor.

The capacitor is charged by the Wallis fuse 6807 High Voltage supply. A voltage up to 35 kV is connected to a resistor of 3 MΩ. The large resistor allows the high voltage to be unloaded fast without damaging the DC source. The high voltage is loaded on two ceramic capacitors in series.
having a combined resistance of 1000 pF. The high voltage is connected to the positive side of the switch (red) through another resistor to limit the current.

If the switch is open, the high voltage pulse is transmitted through a coaxial cable to the upper electrode in the vessel. The shape of such a pulse is shown in figure 3.10 in red.

Figure 3.1: Schematic overview of the timing of the laser pulse for external triggering. Adjusted from Quantel Q-smart 450/850 User manual.

A tungsten needle is mounted on the upper electrode to concentrate the high voltage, enabling inception of a positive streamer at the needle tip shown in figure 3.2a. Figure 3.2b shows a picture of the needle tip, which is cone-shaped with an angle of 60 degrees. After the streamer is initiated at the tip, it travels towards the bottom electrode which is connected to ground. The generated current between the electrodes as well as the shape of the high voltage pulse is monitored on an additional oscilloscope. An example of the current during discharge is shown in purple in 3.10.

The vessel is connected to both a pump and a gas supply to regulate the gas flow and corresponding pressure. Also, it has several windows that provide optical access. These are used for the ICCD camera and the laser in- and output. Additionally, a large translation stage has been designed for the vessel to be able to translate the streamer with respect to the laser beam, which will be elaborated in section 3.2.2.

Figure 3.2: (a) Geometry: 12 mm needle and a 98 mm gap (b) The tungsten electrode tip under a microscope 41:1.
3.1.2 E-FISH setup

The optical setup used to measure the E-FISH signal of the plasma is shown in figure 3.5. This setup is based on the setup used by Anne and Thijs, but altered such that the E-FISH method can operate in the streamer setup. It was also kept in mind that changing to the other measurement methods of Raman and Thomson spectroscopy should remain relatively easy.

When the Q-switch and the flash-lamp of the laser have received their triggers, a 7 ns horizontally polarized laser pulse leaves the laser cap and is sent through a half-wave plate. For the half-wave plate, angles of 0 or 45 degrees are used to either keep the polarization horizontal or change it to fully vertical. For the measurements of the vertical component of the electric field, a vertical input polarization is used and for the measurement of the horizontal electric field, a horizontal input polarization is used.

After passing the half-wave plate, the light is directed to go straight through the vessel using two mirrors: a 1064 nm coated mirror and a second 1064 nm & 532 nm coated mirror. To reduce the amount of unwanted second harmonic light created inside the laser or by the optics, a 1064 nm laser line filter is placed in front of the vessel.

After being focussed by a 500 mm plano-convex lens, the infrared light enters the vessel through a coated window with transmits the 1064 nm light. Once inside the vessel, a small amount of 532 nm light is generated around the focus due to interaction with the electric field between the electrodes. This is the second harmonic signal that is eventually used for the E-FISH results.

When both beams leave the vessel through an uncoated window, the light is once again collimated by a second 500 mm plano-convex lens.

As the setup contains many reflecting objects (like the metal vessel and the EMC box), it was chosen to filter out 95% of infrared light immediately after the light leaves the vessel. This is achieved with a dichroic mirror that reflects the 532 nm light and 5% of the 1064 nm and transmits most of the 1064 nm light. The latter is dumped in a beam dump, whereas the reflected light is purified even more by a NS-F11 prism. Due to the difference in refractive index for the two

Figure 3.3: Schematic overview of the high voltage pulse source, triggering circuit, the vessel with the gas supply and pump, and the ICCD camera.
wavelengths, the 532 nm and the 1064 nm beams are separated by 2 cm after traveling for 30 cm after the prism.

The left-over infrared light is steered to a beam dump by a dichroic mirror. A Thorlabs DET08C/M infrared detector measures this infrared light indirectly by looking at this mirror. This signal is sent to the oscilloscope and is used as reference signal to account for small variations in laser power.

Another dichroic mirror directs the green beam towards the Triple Grating Spectrometer (TGS). The Triple Grating Spectrometer is described extensively by van de Sande [53]. As the name suggests, it contains three gratings. However, in this work only one grating is used to filter out the last possible remaining portion of infrared light. Before entering the TGS, the light passes two 532 nm line filters to further reduce the remaining infrared light. Then, a second half-wave plate and an image rotator change to polarization to vertical as the TGS works optimal for this polarization. The polarizations throughout the setup for the measurements of the vertical and the horizontal components are graphically shown in figure 3.4. For the measurement of the vertical component for example, the input laser beam is turned to a vertical polarization after passing the first half-wave plate such that it has the same orientation as the electric field to ensure maximum output signal. The filtered second harmonic signal created by the electric field enters the half-wave plate in front of the TGS, which turns the polarization to horizontal. The image rotator then turns the polarization back to vertical to optimize the filtering of the grating. The beam passes the grating and is captured by a Hamamatsu H6779-04 photo multiplier tube (PMT) and connected to an oscilloscope.

![Figure 3.4: The polarizations throughout the setup for the vertical and the horizontal measurements.](image)

The TGS was used for two reasons: to filter out any left-over infrared light, but most importantly to create distance between the high voltage circuit and the PMT. It was found that the high frequency pulsing of the high voltage creates a lot of EMC noise on the electrical cables. As the noise was in the order of magnitude of the wanted second harmonic signal, distance was crucial to find any signal at all.

Besides the high power 1064 nm laser, an additional alignment laser is used. This is an INNOSLAB Edgewave low power (4 mJ), 532 nm emitting laser used to align the setup. As the green E-FISH signal is very weak and not observable by eye, this laser beam is used to visualize the path of the green light and to enable correct placement of the PMT.

An important limitation of the current set up is the amount of unwanted second harmonic light that was found when no electric field was applied, so when no E-FISH signal was expected. The 1064 nm laser line filter in front of the vessel aims to filter out most of this unwanted second harmonic signal, but there is always a small fraction that is transmitted. Furthermore, it was found that the lenses, the windows at the in- and output of the vessel plus the dichroic mirror after the window create a background signal that covers 10 to 30 percent of the total measured signal. Because the largest amount of high power infrared signal is filtered out after that dichroic mirror, the remaining optics do not contribute to the background second harmonic noise. However, as the total amount of unwanted second harmonic signal is significant, it is crucial to subtract the background signal from the E-FISH measurements.
Figure 3.5: E-FISH setup

Laser source

The laser used for the experiments is the Q-smart 450 high power nanosecond YAG-laser from Quantel. Using the horizontally polarized output wavelength of 1064 nm, the pulse duration (at FWHM) is 7 ns. The laser is operated at a frequency of 20 Hz. The Rayleigh range after the laser beam passes the lens with a focal distance of 500 mm can be calculated using equation 2.12 and is found to be \( z_R \approx 12 \text{ mm} \) with a beam waist of \( w_0 \approx 100 \mu \text{m} \). This results in a confocal parameter \( b = 2z_R \approx 24 \text{ mm} \).

The power output can be varied by changing the delay between the flash-lamp and the Q-switch. An overview of the corresponding laser output for different delays with the half-wave plate at 45 degrees is given in figure 3.6. Maximum power, 400 mJ, is obtained with a delay of 290 \( \mu \text{s} \).

![Image](image_url)

Figure 3.6: Power output at 1064 nm as a function of the delay between the flash-lamp trigger and the Q-switch trigger with the half-wave plate at 45 degrees.

This way of changing the output power is not optimal. The laser is most stable at max power and will be more unstable at delays further from this optimal point. Ideally, an additional polarizer would be added after the half-wave plate. In this way, the power can be changed as a function of the angle of the half-wave plate. However, in the current setup, variance in power output is accounted for by capturing the infrared signal of every laser shot and correcting for it.
The laser beam was investigated and the burn pattern of the laser in figure 3.7 shows a nice round, evenly distributed beam with a beam diameter of about 6.5 mm.

![Figure 3.7: Burn pattern of the 1064 nm output of the Q-smart 450.](image)

The jitter in the infrared beam varies significantly over the days. Below, two sets of infrared signals as detected by the oscilloscope are shown. Image 3.8a is from measurement day 1, in which the vertical measurements were executed and image 3.8b is from the day after, on which the horizontal measurements were carried out. The signal on day 2 is obviously less stable and almost halved compared to the signal of day 1. A lower input infrared signal will result in a lower second harmonic signal. Although the variations in laser power are accounted for in the final results, this will result in a lower signal to noise ratio. Also, the resolution of the signal in figure 3.8b is larger than the resolution in figure 3.8a. It is possible that the lower infrared signal caused the infrared detector to be less oversaturated, resulting in a signal with a higher resolution.

![Figure 3.8: (a) Infrared signal squared day 1 for vertical measurements (b) Infrared signal squared day 2 for the horizontal measurements.](image)

### 3.1.3 Reproducibility of the streamer: trade-offs

The streamer setup as shown in paragraph 3.1.1 deviates from the version that was initially available in the lab. In order to have the extra optical measurement of E-FISH working coherently with Raman and Thomson emission spectroscopy as well as optical imaging, some concessions had to be made. An overview of the occupied degrees of freedom and the measurement methods used is shown in figure 3.9.
Figure 3.9: Technical sketch of the vessel, including the line of sight of the laser (red), the plasma (pink), Raman and Thomson emission spectroscopy (orange) as well as optical imaging (blue) and E-FISH (green).

Prior to this research, the vessel was situated in a horizontal position (figure 3.9 tilted by 90 degrees) such that the plasma travelled in the horizontal plane. An advantage of this orientation is that the upper electrode was connected directly to the output of the switch. There is no need for an extra coaxial cable that might disrupt the voltage pulse. The setup in its horizontal orientation also includes a microwave which preheats the gas. Besides studying the effect of elevated gas temperature on streamers, this hot gas channel is used to redirect and guide the streamers to create a highly reproducible streamer.

However, when using the horizontal orientation, optical access to one of the windows is lost; one that is needed for measuring the E-FISH signal. For this reason it was chosen to put the vessel in the vertical position and add a coax cable to connect the upper electrode to the high voltage switch. However, this extra meter of cable resulted in an increase of the rise time of the high voltage pulse. The voltage pulse in the horizontal orientation is shown in figure 3.10. Ideally, one would like to have a step function for the high voltage pulse. In this way, the streamer is initiated at exactly that moment when the high voltage is on and it is initiated at the exact voltage that was aimed for. For the voltage pulse shown below, with a rise time of 120 ns, it is unsure to say at what exact time and voltage the streamer starts. This causes a variance of the streamer in time. The jitter in the streamer limits the spatial resolution of the measurements.

When measuring the E-FISH signals, about 50 oscilloscope traces are averaged. To minimize the error in the results, the streamer should be as stable as possible in time and space. Due to the orientation of the vessel, the rise time of the voltage pulse is far from optimal. There are several other parameters in the setup that might be tuned to improve the stability of the streamer. However, some of those optimizations will go at the expense of the already weak second harmonic signal. The following parameters were varied to find the optimal conditions in which the experiments should be conducted:

**Gas type**

Because the streamers are initiated in a closed vessel, experimenting with different gasses is possible. However, it was found that in this particular configuration air provides the most stable streamers. This is the result of a very high electron density in front of the streamer due to photoionization. Streamers are more likely to branch in low electron concentrations as in that case the streamer path changes along with varying electron densities [5]. Both CO₂ and N₂ lead to more
branching and less well defined streamer heads. As for the second harmonic signal, air, Ar, CO$_2$ and N$_2$ all produce a detectable amount. In the current setup, especially measurements in argon resulted in a high second harmonic signal, up to three times the amount produced in air. The E-FISH signal produced in air, CO$_2$ and N$_2$ are all in the same order of magnitude.

![Figure 3.10: The typical shape of the HV pulse sent to the upper electrode (red) and the measured current (purple).](image)

**Pressure**

The pressure can be varied from 0 mbar to atmospheric pressure. In general, reducing the pressure will give rise to faster and thicker streamers which are more stable. Furthermore, higher pressures can easily lead to laser-induced breakdown in the vessel. Hence, reducing the pressure allows higher laser powers in the medium without breakdown. Unfortunately, a lower pressure also means less gas molecules to create second harmonic light, making E-FISH signals harder to detect. This trade-off between stable streamers, no optical breakdown and a detectable second harmonic signal is found to be very delicate. In the end, a pressure of around 100 mbar is used in this work.

**Geometry**

The gap between the two electrodes can be varied from about 50 mm to 120 mm. When using a smaller gap, the electric field will be higher for the same applied voltage. Consequently, streamers will be initiated at lower voltages in a small gap compared to streamers in larger gaps. However, when using a small gap, there is only a small distance for the streamer to propagate. In this short observation time frame, less time steps in the streamer evolution can be evaluated.

There are several needles available varying in length between 12 and 50 millimeters. A shorter electrode tip allows the use of a higher voltage and creates thicker streamers. For longer tips, the electric field is concentrated more and the streamer will start at a lower voltage. For the results a gap of 98 mm and an electrode tip of 12 mm is used. This combination results in a streamer with an observable width smaller that the scanning range for the E-FISH measurements and yields enough observable time steps, while the applied voltage is still within the range of the high voltage supply.

**Repetition rate**

At a higher repetition rate, with more high voltage pulses per second, more free electrons will be present from previous discharges. This source of free electrons allows for easier inception and results in less jitter of the streamer which improves the spatial resolution. To match the pulse frequency of the laser, the high voltage is operated at a repetition rate of 20 Hz. In this way, the laser and the high voltage circuit can be delayed with respect to each other, which is useful for the timing as will be explained in the next section.
3.2 Method

To get to the final result, a 2D map of the electric field of the streamers, a temporal scan and a radial scan of the electric field was made. The method used for the two scans is explained in the following sections.

3.2.1 Temporal scan

For scanning the electric field of the streamer in the temporal plane, the delay between the high voltage pulse and the laser pulse is varied. A graphical representation is shown in figure 3.11. The high voltage pulse of 180 ns initiating the streamer is started first. After a time $t$, the laser pulse of 7 ns is released by opening the Q-switch. The integrated signal created during this laser pulse is measured with the photo multiplier tube.

![Graphical representation of high voltage pulse and laser pulse](image1)

Figure 3.11: The timing of the high voltage pulse and the laser pulse. The origin of time $t$ used in this thesis indicated.

What the streamer looks like for various timings $t$ is shown in figure 3.12. The red line indicates the line over which the second harmonic signal is integrated. As can be seen, for $t = 200$ ns to $t = 215$ ns, the electric field is measured ahead of the streamer, whereas at $t = 220$ ns and $t = 225$ ns the electric field in and around the streamer is mapped. A distinction between the vertical and the horizontal polarized fields is obtained by changing the half-wave plate and the polarizer in front of the TGS.

![Temporal scan images](image2)

Figure 3.12: The temporal scan of the electric field of the streamer. In red the laser path is indicated in which the second harmonic signal for the results is created. The timing is indicated in nanoseconds.

Two important remarks must be made on figure 3.12. First of all, the jitter in the streamer as explained in section 3.1.3, was found to be approximately 5 ns. This implies that the images shown may vary shot to shot. To account for deviations like this, the final result is averaged over 50 shots. Hence, after evaluating the E-FISH data, it was found that the head of the streamer was
measured at $t = 210\,\text{ns}$ rather than $t = 215\,\text{ns}$. A better representation could be made by layering multiple ICCD images on top of each other to see the mean and error in position. However, it should be kept in mind that from figure 3.1.3 only the optical emission can be observed, which does not necessarily include the full contour of the streamer.

Secondly, it should be noted that the pulse length of the laser is 7 ns and the time steps chosen here are 5 ns long. That means that during the laser pulse the streamer changes quite significantly. From ICCD images the speed of the streamer is found to be $\approx 1\,\text{mm/ns}$, which is in the expected order of magnitude [54]. Hence, the streamer propagates 7 millimeters forwards during the laser pulse. As a consequence, this deformation is included in the measured E-FISH signal. To improve the spatial resolution of these measurements, a laser pulse with a smaller pulse length like a picosecond laser should be used. Another possibility is to only use a limited time window from the PMT signal such that only the first part of the signal is included in the results.

### 3.2.2 Radial scan

The electric field of the streamer is also scanned in the radial direction. For this particular scan a translation stage for the vessel has been made. In this way, the streamer can be moved with respect to the laser beam path without having to move the laser itself. The windows that provide the entrance and the exit for the laser to the vessel have a diameter of 2 inch. Therefore, the translation in the radial direction is limited to this range. With steps of 1 mm, the streamer is translated 10 mm to the left and to the right of the middle by hand with a micrometer screw. The resulting measurement points are displayed in figure 3.13.

![Figure 3.13: The radial scan positions of the electric field of the streamer. In red the laser positions are indicated in which the second harmonic signal for the results are created. The steps between the red dots are 1 mm.](image)

To be able to see the contour of the streamer with E-FISH, the conditions are tuned such that the streamer as observed with the ICCD camera is around 5 mm wide.

The radial scan is executed two times in a row at $t = 210\,\text{ns}$ to determine the middle of the streamer. The first time from left to right, the second time the other way around. The average of two Gaussian fits of the vertical second harmonic signal on the oscilloscope is used to determine $d = 0$ as shown in figure 3.14. This point was found to be at a distance of 98.5 mm, which will serve as zero displacement from now on. This is an arbitrary point in space and has no physical value, it merely gives a reference point for the interpretation of the results. Figure 3.14 also shows that it makes little difference whether the vessel is translated from left to right or the other way around. Hence, for practical reasons, the scanning direction is alternated in the measurements.
Figure 3.14: The radial scan of the electric field of the streamer. In red the first full scan and in orange the second scan directly afterwards to determine the middle.
Chapter 4

Laser-streamer interaction: Results and discussion

In this chapter, the results of the laser-streamer interaction as observed with the ICCD camera will be shown and discussed. From previous research [34, 35] it became clear that laser beams can change the path and shape of a plasma, thereby challenging the non-intrusiveness claim of E-FISH. To test this claim, the interaction of the laser beam with the low pressure streamers is observed using an ICCD camera.

Figure 4.1 shows the result of a laser pulse of 280 mJ shot onto a passing streamer. Unfortunately, the exact timing of the laser pulse with respect to the streamer is lost while saving the data, but the streamer starts approximately 50 ns before the laser pulse crosses the gap. From figure 4.1, it is observable that laser-streamer interaction is indeed abundantly present. At the height where the laser crosses the streamer, from left to right in figure 4.1, a new streamer channel is observed on each side of the main streamer. These channels initially follow the laser path, but change their direction quickly afterwards to follow the electric field lines.

Figure 4.1: Laser-streamer interaction in 110 mbar air, 23 kV 180 ns high voltage pulse. The laser power is 280 mJ per pulse, the camera gate is open for 50 ns and the image shown is a 1 s accumulation at 20 Hz, so 20 frames are accumulated. The images are separated by approximately 30 ns.

For the E-FISH measurements these results seem disastrous. It is unclear what exactly is measured when E-FISH is used to determine the electric field of the streamer along the laser line. From these images one might conclude that the measured electric field also includes the field of those branches created by the laser, invalidating the field measurement of the streamer itself. The experiments of figure 4.1 were not conducted at maximum laser power. This raises the question whether it is possible to apply E-FISH to these streamers without disturbances but with enough signal. To see if this is the case, some additional measurements have been executed.

4.1 Influence of laser power

The first question that arose was: by how much should the laser power be reduced to avoid any observable laser-streamer interaction? To answer this question, a scan was made of ICCD images...
with decaying laser power from 220 mJ to 60 mJ per pulse. Some of these images are included in figure 4.2. It was found that the maximum laser power at which no observable branches were observed is 115 mJ. This is 29% of the maximum power of the laser. Since the second harmonic signal scales with the square of the input power of the laser, a lot of potential signal would be lost due to this restriction. Thijs Keur [24] found in his work that the E-FISH signal of his nitrogen jet was too low at laser powers were laser-plasma interaction vanished. Therefore, it is worthwhile to investigate whether other parameters can minimize the branching effects, such that the laser power does not have to be reduced substantially. To this end, the influence of the oxygen concentration in the air as well as the pressure of the gas and the timing of the interaction is investigated.

Figure 4.2: Laser-steamer interaction in 150 mbar air with a 7 kV high voltage pulse and laser powers of 220, 150 and 115 mJ. Each image shows 20 accumulations.

4.2 Influence of the oxygen concentration

Up to this point, we have focused exclusively on interaction in air as those streamers are the most stable in the current setup. To see if the oxygen concentration is an important factor, the laser-plasma interaction is investigated in pure nitrogen. The result of a similar measurement as shown in figure 4.1 for air, is shown in figure 4.3 for nitrogen. Contrary to figure 4.1, the streamer has already crossed the full length of the gap before the laser interacts with the streamer. Hence, all images show the streamer after the laser has passed. As explained in section 3.1.3, figure 4.3 indeed clearly shows that the streamer is less stable in nitrogen due to its reliance on free electrons. As a consequence, the interaction with the laser causes the path to be split in two. Therefore, it can be concluded that the effects caused by the interaction are more prominent in nitrogen than in air. This conclusion is in line with the work of Nijdam et al. [35]. Laser-streamer interaction was observed for oxygen concentrations of 0%, 0.1% and 1% and the results show that a higher oxygen concentration in nitrogen indeed leads to less laser-streamer interaction. A higher oxygen concentration results in higher contribution of photo-ionization, which locally increases the background ionization and hence attenuates the guiding mechanism.

Figure 4.3: Laser-steamer interaction in 150 mbar nitrogen with a 6 kV high voltage pulse and a laser power of 220 mJ. The image shows 20 accumulations. Starting from the left image, the images are separated by approximately 40 ns.

4.3 The influence of the pressure

Besides the gas composition, the gas density may also affect the laser-streamer interaction. When the pressure rises, there are more particles available near the laser path that can get involved in photo-ionization. Simulations of positive streamers show that the electron number density $n_e$
scales with the pressure $p$ like $n_e \propto p^2$ \cite{55, 56}. This provides more free electrons that guide the streamer in the direction of the electron source, so more laser-induced effects are expected. Figure 4.4 shows the streamer in air for two different pressures. The first row of images shows the propagation of a streamer in 100 mbar air after a voltage pulse of 4 kV is applied and the second row shows the streamer in 150 mbar air, initiated at a voltage of 7 kV. The time at which the ICCD frame is taken is indicated as well. The images are comparable in position of the streamer head rather than in time. This is because the streamer is initiated later in time and will have a different speed in a higher pressure as the time an length scales in the streamers depend on the pressure as $p^{-1}$ \cite{55}. As a reference, image 4.4a is set to $t = 0$ ns.

The first thing to notice is the fact that the second row of images is more bright. This has nothing to do with the laser beam, but is a result solely from the higher pressure and the higher voltage: more molecules are being excited to a higher energy level and send out visible light when falling back in energy, increasing the amount of detectable light.

As for the laser-induced interaction, when comparing image 4.4b and 4.4e, there is no significant change to be observed at higher pressure. The branches seem just as long and follow the same shape. However, from images 4.4c and 4.4f it becomes clear that at a higher pressure the interaction remains present for a longer part of the propagation. Whereas in image 4.4c at 100 mbar the branches are no longer visible, in image 4.4f at 150 mbar they appear even larger than when they were observed first. This might be caused by the larger electron source as suggested before. To exclude the fact that it could be a result of the difference in time steps between image 2 and 3 for both pressures, the duration of the laser induced branches in both pressures is checked. The branches are visible for 18 ns and 40 ns at 100 mbar and 150 mbar respectively, so the effects remain longer visible at higher pressure.

An even more interesting event is observed when the pressure is doubled to 300 mbar. Figure 4.5 shows a streamer in 300 mbar air, initiated at 14 kV.

Figure 4.4: Laser-steamer interaction in air for 100 mbar with a 4 kV high voltage pulse and 150 mbar at 7 kV and a laser power of 220 mJ. The images shown are not accumulated.
The image shows that the laser-induced branch joins the main streamer path again after some time. This event was not unique in its kind, since it was observed multiple times in 300 mbar and in 250 mbar as well. Nijdam [57] observed a similar event, in his paper referred to as ‘reconnection’. In his work, the reconnection was not a result of laser interaction but was caused by two tip electrodes and the results show that reconnection only occurs to streamer channels that have already crossed the gap, just as is the case in figure 4.5. It is suggested that the phenomenon is caused by electrostatic attraction of the, in this case, branched streamer to the main streamer that has already crossed the gap. When the main streamer crosses the gap and reaches the cathode, it changes its polarity from positive to negative. As a result, the positive streamer branch is attracted to the negative main streamer, causing the channels to reconnect.

Overall, from the measurements highlighted above it can be concluded that the laser induces less interaction effects at a lower laser output power, in a larger oxygen concentration and when operating in lower pressures.

4.4 Timing

In all the images shown above, the streamer head has passed when the laser hits the plasma. However, the most interesting part of the E-FISH measurements will be just ahead of the streamer due to the amplification of the electric field near the streamer head. Therefore, the same experiment has been executed in which the laser pulse has passed before the streamer passes the laser height. In this case, no laser-streamer interaction has been observed by the ICCD camera, even at maximum laser power. These images are included in figure 3.12.

Nonetheless, to obtain a full 2D map of the electric field of the streamer, the electric field should also be measured behind the streamer head, where branches were observed, and not just in front of it. To check whether the E-FISH signal is influenced by the branches seen in figure 4.1, experiments should be executed to get an idea of the time scale in which the branches are created. Is it an instant process, or is there a delay between laser impact and the creation of the branches?

Looking at the immediate impact of the laser on the streamer is rather tricky, because this means that the camera gate needs to be open when the high power laser pulse is in its line of sight. To avoid damage to the camera, an extra 1064 nm filter should be placed in front of it. This was not the case in the current setup, hence the interaction is observed only some time after the laser beam has passed. The timing of the laser pulse with respect to the streamer initiation and the camera gate was measured using an additional photo diode that looked indirectly at the vessel. The conclusion could be drawn that no immediate interaction is observed up to 10 ns after the laser pulse, which allows for the measurement of E-FISH within the streamer under the current conditions. However, for a clear time frame in which the interaction takes place, the timing between the laser en the streamer should be scanned with the 1064 nm filter in front of the camera as suggested.
Chapter 5

E-FISH: Results and discussion

In this chapter the results of the electric field distribution obtained with the method of E-FISH are shown and discussed. First, in section 5.1, the results obtained from the COMSOL simulation are considered to get an idea of what to expect from the electric field measurements. This section is followed by the E-FISH results. Section 5.2 contains the results of the temporal scan of the streamer with the contributions from both the vertical and the horizontal electric field. This section explains the evolution of the electric field distribution of the streamers over time and aims to retrieve absolute values for the electric field. Next, section 5.3 gives the results of the radial scans of the streamer and intents to explain the shape of the electric field distribution of the streamers. The last section shows the result of the combination of the temporal and radial scans in a contour plot. From this plot, the general shape of the streamer is discussed.

All measurements for these final results are executed in 110 mbar air, with a high voltage of 23 kV applied in pulses of 180 ns. The laser power is kept constant at a power output of 280 mJ per pulse. More information on the analysis of the data, including an overview of the used Matlab scripts, can be found in appendix A.

5.1 Simulation

As there are currently no other diagnostics that measure the electric field distribution of the streamers in this setup, a simulation was executed to obtain a rough understanding of what to expect from the E-FISH results. The simulation used for this purpose is explained in section 2.1.4 and was executed in COMSOL multiphysics. Because the streamer can be approached by a conducting rod, as explained in section 2.1.3, the streamer is modeled in a purely electrostatic way. The tip shown in figure 2.2 is elongated and widened to roughly match the dimensions of the streamers in 110 mbar air. The result of the simulation, for an applied potential of 23 kV, is shown in figure 5.1.

Concentrating on the area just in front of the tip of the conducting rod, it is observable that the electric field gets amplified near the head and is directed radially outwards. Further away from the tip, the horizontal component first increases after it decreases again with a lowering total electric field that matches the background electric field at a few centimeters outside the center. Moving one row upwards, the electric field is low at the sides of the electrode tip and has a large horizontal component. Further away from the rod, the electric field is mainly vertically orientated. Figure 5.1 is in line with streamer simulations, as shown in figure 1.1. Hence, the streamer is expected to have a large field amplification near the head of streamer which is mainly vertically orientated and the sides of the streamers are defined by a large horizontal electric field.
5.2 Temporal scan

The results of the temporal scan as explained in paragraph 3.2.1 are shown and discussed in this section. The relative values of the E-FISH signal are discussed to find the time evolution of the electric field distribution caused by the streamer. Furthermore, to be able to compare the E-FISH results of the temporal scans with simulations, the last section explains a method used to convert the relative values of the second harmonic signal into absolute field values. For the experiments, the translation stage is positioned such that the laser hits the streamer in the middle and the timing between the high voltage pulse and the laser pulse is prolonged with every measurement step \( t \). The mean background signal obtained from a measurement with an externally applied potential of 0 kV is subtracted from the measurements.

5.2.1 The vertical electric field

The result of the vertical electric field component over time is plotted in figure 5.2. The mean and standard deviation of the E-FISH signal, the third term in equation 2.21 calculated over 50 measurements, is shown in red. Also, the time evolution of the 180 ns externally applied potential pulse is included in blue. The time steps \( \Delta t \) used in the temporal scan vary: \( \Delta t = 50-100 \) ns ahead of the pulse and in the fall time of the voltage pulse and \( \Delta t = 2-10 \) ns in the region around 170-240 ns, where the streamer head is expected. Additionally, to support the E-FISH results, several ICCD images of crucial points in the figure are included in figure 5.3.

The temporal evolution of the E-FISH signal shown in figure 5.2 follows a characteristic curve. At \( t = 100 \) ns, when the voltage pulse starts, the vertical electric field starts to rise and follows the external voltage curve. At the end of the rise time of the voltage pulse, around \( t = 200 \) ns, the vertical electric field stops following the external electric field and shows a steep curve. This peak keeps growing as the streamer propagates downwards. A maximum is reached for \( t = 210 \) ns. Figure 5.3a indeed shows that in this time step the electric field in front of the streamer is measured. Hence, the hypothesis from the previous section, that the electric field rises sharply near the streamer head, is confirmed. Notable are the large error bars in the region around the peak. The largest contribution to the standard deviation is the variance is the second harmonic signal as the infrared input signal is very stable, shown in the previous chapter in figure 3.8. Because of the 5 ns jitter in the streamers, as explained in section 3.2.1, the exact measurement point with respect to the streamer head may vary a little for each measurement. Therefore, the second harmonic signal
around the streamer head increases and decreases very fast, causing a large standard deviation in that area.

Figure 5.2: The temporal scan of the relative vertical electric field of the streamer in red and the applied potential in blue.

After this peak, a sudden drop in electric field is measured when the streamer head has passed the laser beam. The lowest point is found at $t = 270\,\text{ns}$, when the streamer reaches the bottom electrode as visible in figure 5.3b. This sudden drop in electric field is measured in other E-FISH research as well [10, 18, 58]. An explanation of this drop in the electric field is that the E-FISH signal is measured inside the screened channel of the plasma. Although the signal is measured in the conductive channel, the signal remains higher than zero. In a paper of Chng et al. this was ascribed to the fact that the electric field here must remains higher than zero such that electrons created near the streamer head can be transported towards the anode [10].

A second peak is observed around $t = 290\,\text{ns}$. As this is just after the primary streamer has reached the bottom electrode, this second peak could be a result of the suddenly evenly distributed potential in the channel from top to bottom electrode. This is, once again, in line with the results of Chng et al. [10]. After this second peak, the E-FISH signal drops to below the detection limit as the externally applied electric field decreases again.

Figure 5.3: ICCD images of the streamer at (a) $t = 210\,\text{ns}$, (b) $t = 270\,\text{ns}$ and (c) $t = 290\,\text{ns}$. The red dot indicates the position of the laser.
5.2.2 The horizontal electric field

Figure 5.4 shows the horizontal component of the electric field. It is immediately visible that the horizontal electric field created by the streamer is a factor 20 lower than the vertical electric field. This is most likely because both the external background electric field and the propagation direction of the streamer are vertically orientated such that a higher contribution for the vertical polarization is expected as became apparent in the simulations shown in figure 5.1.

![Figure 5.4: The temporal scan of the relative horizontal electric field of the streamer in red and the applied potential in blue.](image)

A curve similar to the vertically orientated electric field can be observed for the horizontal electric field albeit with much lower intensity. A peak is observed at $t = 210$ ns after which the signal drops and rises for a second peak around $t = 280$ ns. However, one thing that is different in figure 5.4 is the signal that is measured ahead of the voltage pulse, before $t = 100$ ns. As there is no electric field present in that time range, no E-FISH signal should be measured. However, there is always a background signal present due to second harmonic signal that is emitted by the laser or created in the interaction with the optics in the path as highlighted in section 3.1.2. For the results in figure 5.2 and 5.4, the mean background signal is subtracted. But, as the E-FISH signal is very low for the horizontal electric field, the background signal is relatively large and fluctuations in the background field might cause errors like the one before $t = 100$ ns.

From the results of the temporal scans it can be concluded that an electric field amplification due to the streamer is observed and is orientated mainly vertical. The horizontally polarized contribution is a factor 20 lower, but follows the general shape of the vertically polarized electric field.

As now the general shape of the of the temporal evolution of the electric field of the streamer is known and a sharp increase is measured ahead of the streamer, the next step is to convert the E-FISH signals into absolute values for the electric field such that it is possible to compare them with simulations. Does the first peak measured in the vertical component indeed overshoot the background electric field as suggested in the simulations? And if so, does it reach a plausible value?

5.2.3 Absolute value for the electric field

To be able to compare the results of the previous sections to simulations and to use E-FISH as a quantitative measurement tool in the future, the absolute values for the electric field needs to be determined. The absolute values for the electric field can be obtained by means of equation 2.21 via the calibration factor $C_{cal}$. This calibration factor is obtained in two steps in which the signal collected from the oscilloscope is linked to a value for the electric field.
First of all, using the exact same geometry as in the final E-FISH results under the same conditions, the relative second harmonic signal from the oscilloscope $\sqrt{I_{SH}/I_{IR}}$ was monitored for different values of the applied voltage. Just like Lepdikhin et al. [58] pointed out, a 180 ns pulsed voltage allows for calibration at higher voltages without breakdown. The result of the calibration with a pulsed high voltage is shown in figure 5.6 in blue. In this graph, the signal obtained from the oscilloscope is linked to the applied voltage.

The next step is to determine the electric field that present along the laser beam path during the applied potential. For this step the COMSOL model as shown in paragraph 2.1.4 is used. An important factor in this calculation is the integration length over which the second harmonic signal is accumulated. As the incoming beam is focused by a lens, the intensity of the beam gets higher closer to the focus, generating more E-FISH signal. Hence, it can be expected that most E-FISH signal is generated near the focus, within the Rayleigh range, which is explained in section 2.2.1. However, the contribution of E-FISH signal might not be negligible outside the Rayleigh range as the beam area is larger further away from the focus and the electric field is sufficient to create E-FISH signal at these positions. To test this, two options for the integration range in the x-direction are investigated: the confocal parameter $b = 2z_R$ which ranges from -12 mm to 12 mm around the focal point (marked by the dotted line) and the upper electrode diameter $D$ which ranges from -50 mm and 50 mm around the focal point. Both parameters are indicated in figure 5.5. The integration step size in x- and y-direction is chosen to be 0.12 mm, which is the size of the beam waist.

![Figure 5.5: Graphical representation of the integration range for the electric field with the confocal parameter $b$ and the upper electrode diameter $D$.](image)

The table below compares the impact of the two choices. The corresponding calibration factor $C_{cal}$ is the slope of the linear fit through the calibration points, just like suggested in equation 2.21. This is plotted in figure 5.6 for the integration range $D$. To test the implications of the different integration ranges, the calibration factors are used to convert the E-FISH signal of a streamer measurement to absolute values for the vertical electric field in the next section. The maximum signal that was found in front of the streamer head is adopted as an indication of the validity of the integration range and this is expected to be 1-2 MV/m for a streamer in 110 mbar air, which is more than three times higher than the background electric field [30].

<table>
<thead>
<tr>
<th>Integration range</th>
<th>$C_{cal}$</th>
<th>Max field amplification due to discharge (MV/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confocal parameter $b$</td>
<td>0.2819</td>
<td>$\approx 0.1$</td>
</tr>
<tr>
<td>Upper electrode diameter $D$</td>
<td>0.0724</td>
<td>$\approx 0.5$</td>
</tr>
</tbody>
</table>

From the values in the left column of the table it becomes clear that the integration ranges result in calibration factors that differ by a factor 4, resulting in absolute values of the electric field which differ a factor 4. Also, both integration ranges do not lead up to the expected electric field of 1-2 MV/m. As the integration range of the upper electrode diameter results in values for the electric field that are only a factor 2 smaller than the expected electric field, it is this calibration factor that will be used to convert the final results. It is important to keep in mind that, because the calibration factor results in a lower field amplification than expected, the final results will likely underestimate the actual electric field as well.
The converted calibration results are shown in figure 5.6 in red together with applied potential in blue. Also the linear fit following equation 2.21 is plotted.

Figure 5.6: The measured second harmonic signal as a function of the applied potential (blue) and the integrated electric field as calculated in COMSOL (red). The integration rage is the upper electrode diameter $D$.

It can be concluded that the integration range has a large effect on the absolute field values of the final results. An improvement of this calibration method would be to account for both the varying spot size of the laser beam and hence the varying intensity of the laser beam at different distances from the focal point. For example, adding scaling factors for the different integration points could result in a more reliable calibration factor. A good approach which can be used for radially symmetric electric fields is to obtain spatially resolved electric fields by applying an Abel transformation to a set of lateral measurements. In such a mathematical transformation, the local data is reconstructed from the line-integrated signal [45]. The ingredients to perform an Abel transformation are a lateral scan of the electric field and a symmetric fit trough the results of this scan. Then, with the scripts from Chloe van den Heuvel [59], the spatially resolved contributions to the total field can be retrieved, discarding the problem of the integration length entirely. This method is not used in this work due to the large asymmetry that was found in the radial scan as will be elaborated in section 5.3. Consequently, a proper symmetric fit through the results was not possible. Another suggestion is to use a calibration geometry from which the electric field is known, like a plate-to-plate geometry of the electrodes. Then, step 2 can be skipped and the relation between the second harmonic signal and the electric field is found right away. However, this geometry differs from the one used to initiate the streamers, causing the calibration factor to be less reliable.

The converted results of the vertically polarized scan are shown in figure 5.7. Here, the calibration factor 0.07237, resulting from simulations with the upper electrode diameter $D$ as integration range, is used to obtain the absolute values of the electric field. Although the figure resembles figure 5.2, from figure 5.7 it can be concluded that the electric field induced by the streamer indeed overshoots the background electric field. The maximum vertical electric field is measured to be 0.52 MV/m, which is about 2 times the background electric field. This is lower than expected. Simulations by Luque et al. show field amplifications near the head of the streamer of about 4 times the background electric field [60]. The second peak, accounting for the crossed streamer, does not exceed the background electric field. The difference can be explained by the calibration method, which is currently not optimal. As discussed above, the calibration method will understate the measured values by at least a factor two.
To conclude, the electric field enhancement measured ahead of the streamer indeed overshoots the background electric field in the first peak. But only by a factor two, which is lower than the electric field values found in simulations. The second peak does not exceed the background electric field and results in lower values than expected as well. This underestimation can be ascribed to the calibration method. Hence, for future use of E-FISH in this setup, the calibration method should be improved, possibly with suggestions mentioned before.

5.3 Radial scan

Next, we treat the results of the radial scans. For these scans, a time \( t \) in the high voltage pulse is chosen for which the electric field is measured at displacement step \( d \) up to 10 mm to the left and 10 mm to the right of the middle of the streamer with a step size of 1 mm. From the temporal results it was concluded that the highest second harmonic signal was measured between \( t = 200 \text{ ns} \) and \( t = 225 \text{ ns} \). For this reason, the radial scans are executed within this time frame. The results of the vertical and horizontal electric field ahead of the streamer, at \( t = 205 \text{ ns} \), and after streamer head has passed, at \( t = 215 \text{ ns} \), for different displacements are shown in figure 5.8a to d. Just like in the temporal scan, the figures show the mean electric field and the standard deviation calculated from 50 iterations.

Figure 5.8a clearly shows the electric field enhancement due to the approaching streamer head. The electric field at \( d = 0 \text{ mm} \) is 36 percent higher than at \( d = -10 \text{ mm} \). This follows the shape predicted by simulations as shown in figures 2.5 and 5.1, where the electric field is maximum in the middle of the streamer head and gradually decreases when moving away from the center. In figure 5.8c, 10 ns later, the vertical electric field did not increase more, but now shows a dip in the middle of the curve. This is in line with the expectations as well. When taking a slice in figure 2.5 slightly above the streamer head, the electric field is maximal at the sides of the streamer. The middle, now inside the conducting channel, has a way lower electric field as was also measured in the temporal scan of section 5.2.1. A similar curve can be observed for the horizontal component of the electric field in figure 5.8d.

Notable is the difference between the vertical electric field at \( d = \pm 10 \text{ mm} \) in figure 5.8. The electric field drops less rapidly at the right side of the figure, around \( d = 10 \text{ mm} \), compared to the left side of the figure. The asymmetry for the horizontal electric field is even more pronounced and opposite: the horizontal electric field goes to zero for \( d > 0 \text{ mm} \) and rises for \( d < 0 \text{ mm} \), as shown in figure 5.8b. This is also observed for the radial measurements at \( t = 215 \text{ ns} \) in figures 5.8c and 5.8d.
Figure 5.8: The radial scan of the (a) the vertical electric field at $t = 205$ ns, (b) the horizontal electric field at $t = 205$ ns, (c) the vertical electric field at $t = 215$ ns and (d) the horizontal electric field at $t = 215$ ns.

To investigate the cause of this asymmetry, two hypotheses were tested. The first idea was that the alignment of the setup might influence the spatial results. To that end, the setup was realigned and the measurements repeated. This only resulted in an overall higher E-FISH signal, no changes in the radial shape of the electric field, as shown in figure 5.9a. The second hypothesis stated that the laser beam might be out of focus, as the focal length of the lens used to focus the laser beam is wavelength dependent. The lens was positioned at 500 mm from the electrode tip but from calculations it followed that the focal length for a wavelength of 1064 nm is 507.4 mm. For this reason, the lens in front of the vessel is put at different distances from the electrode tip. Once again, as shown in figure 5.9b, this only resulted in optimizing the total amount of signal, but cannot explain the asymmetry. Although figures 5.9a and b do not show a solution to the asymmetry problem, they do nicely show the reproducibility of the experiments. Even though the setup is realigned and a lens is moved, the E-FISH signal remains quite stable and shows the same curve.

Another explanation for the asymmetry could be the fact that the vessel assembly is asymmetric. With respect to the laser beam, it has one large quartz window on one side and two smaller windows on the other side as shown in figure 3.9. Just like illustrated in figure 3.9, the translation direction is perpendicular to the large window and when the vessel is translated in the positive direction, $d > 0$ mm, the laser beam is moved closer to the window. The vessel itself is grounded but it is a possibility that free charges accumulate at the windows, distorting the grounding function of the surroundings. Resulting in a slightly deviated streamer path. To test this theory in the current setup, all windows should be replaced by metal flanges, providing a more centro-symmetric surroundings for the measurements. An even better solution would be to replace the current vessel with a vessel with no windows save for the two small ones used for the laser beam. In this way, the grounded surroundings are as symmetric as possible.
From the ICCD images of the streamers no conclusions could be drawn on deviations of the streamer path in the direction of \( d \) as the images were taken perpendicular to the laser beam, in the same direction as the translation. Perhaps spatially resolved streamer paths from stereoscopic measurements of the streamer could provide a better feeling for the 3D effects of the asymmetry.

![Figure 5.9](image.png)

Figure 5.9: (a) The horizontal component of the second harmonic signal at \( t = 215 \) ns before and after realignment, (b) The horizontal component of the second harmonic signal at \( t = 215 \) ns for four different positions of the first lens with respect to the middle of the streamer.

Although the asymmetry question is not resolved, more information can be gathered from figure 5.8. The measurements at \( t = 215 \) ns (figure 5.8c and d) show a dip in the radial profile. The dip represents the conducting channel of the streamer where the electric field is almost zero, graphically illustrated in figure 5.10a in purple. Still, the electric field around \( d = 0 \) mm in figure 5.8c is way higher than zero. This can be explained by two different contributions: the vertical electric field amplification of the streamer head surrounding the conductive channel and the vertically orientated background electric field. These contributions are both included in the integrated signal. This is graphically represented in figure 5.10b, in which a slice of the dotted line in figure 5.10a is shown. Here, a top view of the conductive channel with the surrounding field amplification due to the streamer head is shown and the red lines indicate the laser beam paths for different displacements \( d \). The horizontal component of the electric field on the other hand does go to zero at \( d = 0 \) mm. As the background electric field is vertically orientated, it is expected not to give rise to any signal indeed. Since the horizontal contribution of the electric field amplification around the streamer head is also zero, two possible interpretations result in a zero horizontal electric field around \( d = 0 \) mm: either the electric field surrounding the streamer head in the middle is absent at \( t = 215 \) ns or the field amplification due to surrounding the conductive channel is mainly vertically polarized.

Assuming that the peaks on each side of the middle in figures 5.8c and d are due to the electric field that surrounds the conductive inner core of the streamer, the distance between those peaks can be used to determine the width of the streamer. From the results of the radial scan follows that the peak to peak value at \( t = 215 \) ns results in an electrodynamic width of \( w_{\text{elect}} = 10 \pm 0.5 \) mm and \( w_{\text{elect}} = 12.5 \pm 0.5 \) mm for the vertical and horizontal components respectively. As a comparison, the full width at half maximum from the light emitting part of the streamer in the ICCD images at \( t = 215 \) ns is found to be \( w_{\text{optical}} \approx 9 \) mm. From literature it is expected that the electrodynamical diameter of the streamer is about two times as large as the optical diameter [61]. Although the measured electrodynamical diameter is indeed larger than the optical diameter, the difference is small. Even more, the horizontal electric field seems to stretch more to the sides than the vertical electric field. In combination with the fact that no horizontal field was measured in the middle of the streamer it is suggested that the electric field surrounding the streamer gets a horizontal component in the direction of \( d \) only at the edges of the streamer (d close to \(-10 \) mm) as illustrated in figure 5.10c. This can be explained by an electric field that is directed radially outwards from the core of the streamer head as illustrated in figure 5.10a.
To conclude, both vertical and horizontal components of the electric field show asymmetry around the middle of the streamer. It has been shown that this asymmetry is not caused by the alignment or by the position of the first lens, but could be due to the asymmetry of the vessel itself. Additionally, the combination of the vertical and horizontal measurements reveals an electric field that is directed radially outwards and has a large component in the propagation direction of the streamer, as expected.

5.4 2D map

For the 2D map, the radial scan was executed for a set of timings between \( t = 200 \) and \( t = 225 \, \text{ns} \) in steps of 5 ns. The results of the two polarizations are collected in a contour plot shown in figure 5.11. In this figure the radial scans for the different timings are shown, where the color indicates the electric field strength. It is important to note that this is not an \( x,y \)-image of the electric field of the streamer, but rather the time evolution of the radial scan at \( y = 55 \, \text{mm} \) above the upper electrode.

Figure 5.11: A 2D contour plot of the (a) vertical component and (b) the horizontal component of the electric field with the displacement on the x-axis and the time on the y-axis. The color indicates the magnitude of the electric field. As \( t = 210 \, \text{ns} \) is missing in the vertical component, the data is extrapolated using the surrounding data.
Figure 5.11a nicely shows the electric field amplification ahead of the streamer tip as was expected. Closer to the streamer head, the electric field gets higher and quickly drops after the streamer head has passed. Just as figures 5.8a-d, figure 5.11 shows the asymmetry discussed in the previous section with slightly higher signals on the right side of the image. More surprising is the fact that the highest vertical electric field is measured at the sides of the streamers around \( d = \pm 5 \) and not at the center ahead of the streamer. This is a result of the missing radial scan at \( t = 210 \text{ ns} \) due to data storage problems during the measurement. When the same image is plotted as a function of the second harmonic signal that was monitored manually and which includes \( t = 210 \text{ ns} \), the largest field amplification is indeed found at \( d = 0 \text{ mm} \) at \( t = 210 \text{ ns} \). This result is shown in figure 5.12.

The total electric field is found when combining figures 5.11a and b. The result is shown in figure 5.13. This figure shows the sum of the vertical component and the horizontal component of the electric field as a contour plot and the deduced vector components in red. The direction of the orientation of the electric field can not be determined using E-FISH. Hence, for the calculation of these vectors it was assumed that the measured vertical polarization points strictly downwards and the horizontal polarization is always directed outwards from the center, \( d = 0 \text{ mm} \). In this way, the total electric field is aimed away from the streamer head. The figure nicely shows that the electric field decreases after \( t = 215 \text{ ns} \), that the asymmetries of both polarizations mostly cancel out in the total electric field, that the electric field indeed has its largest component downwards and that the vertical component gets higher further away from the center, later in time.

An explanation for the measured asymmetry in the separate components, but the symmetric total electric field could be that either the streamer moves slightly to the left, towards \( d < 0 \), or the radial measurement is slightly tilted. To check whether the propagation path of the streamer is shifted to either side of the center, the ICCD images were checked to see if the streamer moves out of focus, as these were taken perpendicular to the E-FISH measurements. This was not the case. At least, from the images it was not observable by eye. As suggested before, 3D images obtained with stereoscopic imaging could give a more conclusive insight on the exact path of the streamer.

The other possibility, which suggests that the radial measurements are executed under an angle due to uneven weight distribution on the translation stage, can be checked with a spirit level. As the vessel was tilted back to its original horizontal position after the measurements, this could not be tested. However, any weight related imbalance due to the translation stage is unlikely as the...
mass of all separate components were taken into account when it was assembled.

Figure 5.13: A 2D contour plot of the total electric field including the direction of the electric field in red.

Unfortunately, no papers were found on simulations in similar circumstances, as most simulations are executed for atmospheric pressure [4, 62, 63]. However, the results of the total electric field in this work, as shown in figure 5.13, are in line with the images of the total electric field in the simulations shown in figures 1.1 and 5.1. Therefore, an important conclusion can be drawn: the method of E-FISH is suitable for measuring the electric field around the streamer head. However, for retrieving absolute values of the electric field, improvements in the calibration need to be done. Also, the time resolution of images 5.11 and 5.13 could be improved by using a laser with a shorter pulse length, like a picosecond laser and by the stabilizing the streamer to a jitter of less than 5 ns. The latter can be achieved by reducing the rise time of the applied high voltage pulse. Additionally, as the electric field points radially outwards, it is desired to measure the radial component of the field. In the current work, the electric field is scanned over the Cartesian x-direction, not the Polar r-direction. Including an Abel inversion on the current work, as suggested in section 5.2.3, would introduce the possibility to convert the results to radial contributions.
Chapter 6

Summary and conclusion

In this chapter, the most important results will be summarized by answering the research questions stated in the introduction and some final conclusions will be drawn. The aim of this work was to see whether E-FISH could successfully be added to the low pressure streamer setup in addition to Thomson and Raman spectroscopy and ICCD imaging and, if so, what the temporal and radial electric field distributions of the streamer look like.

To answer the first sub-research question, the experimental setup used for the E-FISH measurements as well as the setup for creating the streamers in previous work were both adapted to fit together. The vessel was tilted by 90 degrees, some dichroic mirrors and a translation stage were added and the prism and the high voltage supply circuit were changed. In this way, it is feasible to conduct E-FISH measurements such that Thomson and Raman scattering as well as ICCD imaging are possible in the same setup.

The second sub-question considered the influence of the focused laser beam used in E-FISH measurements on the streamer, as previous research provided proof of the intrusiveness of the method to a related discharge. In the present work, it was found that the effects of laser-streamer interaction are observable and get more abundant for higher laser powers, for operation at higher pressures and in lower concentrations of oxygen. However, under the used circumstances, at least until 10 ns after the laser beam hits the streamer, no laser-streamer interaction was observed on ICCD images, allowing E-FISH measurements.

After it was established that the method of E-FISH is, under certain circumstances, a feasible method to measure the electric field distribution of the streamers, the electric field of the streamers was investigated. Additionally, to compare the E-FISH results to simulations, a calibration method was investigated. The values of the second harmonic signal were converted to absolute values for the electric field distribution by a calibration factor. This factor was determined from a linear fit of the second harmonic signal as a function of the applied electric field. To obtain this fit, first the second harmonic signal was measured as a function of the applied potential in the same tip-to-plate geometry used for the final results. Hereafter, the integrated electric field induced by the potential was determined by means of a COMSOL simulation. The integration range used in this last step is the upper electrode length as this yields a maximal electric field amplification closest to the expected value of about 5 times the background electric field.

With the calibration factor to calculate the absolute values for the electric field distribution, it was possible to interpret the temporal scan of the electric field of the streamer. Results for the vertical electric field show that the measured electric field initially follows the rising externally applied electric field, but is amplified to about two times the background electric field when measuring in front of the streamer head. After this first peak, which occurs ahead of the streamer, the electric field drops rapidly when measuring inside the conductive channel. After some time, a second peak is observed when the gap is bridged by the discharge. The results of the horizontal electric field show a similar curve but with absolute values which are about 20 times lower than the vertical electric field. Hence, it can be concluded that the electric field amplification created by the streamer is mainly vertically orientated. This was expected as this is the same direction of the background electric field and consequently the propagation direction of the streamer.

The radial scans of the electric field distribution of the streamer confirm this result and show a contour of the streamer head comparable to what has been observed on the ICCD images.
When combining the results of the vertical and horizontal electric field distributions, a radially outward electric field with a large component pointed downwards, in the propagation direction of the streamer, is found. The results of the radial scans also reveal a large asymmetry. This asymmetry is most abundant for the horizontal measurements and is not caused by misalignment or due to measuring out of focus, but could be a result of the asymmetry of the vessel in which the streamers are created.

When the temporal and radial measurements are combined in a 2D contour plot, the mapped electric field of the streamer resembles the shape suggested by simulations. Based on this result, a very important conclusion can be drawn: E-FISH is a suitable method for measuring the electric field distribution of the streamers in the current setup. Even more so, the results enable improvement of streamer simulations after comparison with the experimental results. As these simulations are an important foundation for many streamer applications, this research will eventually contribute to improvements for example in lightning protection, disinfection methods and high voltage switch gear.
Chapter 7

Outlook

The results presented in this work are very promising and give opportunities for follow up research, but also require various improvements. However, as the main part of this project was covered by implementing the setup, relatively little time could be spent on improving the results. To that end, in this chapter improvements and suggestions for further research are discussed based on the experience obtained from this project.

7.1 Suggested improvements

The suggested improvements are elaborated below and are divided in three different sections: the improvements of the optical setup used for the method of E-FISH, the improvements in the high voltage circuit and other changes that could upgrade the setup or the results. The suggestions follow the setup explained in section 3.1.

**Improvements of the optical setup:**

- Use a picosecond pulsed laser instead of a nanosecond laser to improve the spatial resolution. Measuring a streamer that travels 1 mm/ns with a 7 ns pulsed laser is not optimal as the field distribution changes significantly during the laser pulse. A laser with a shorter pulse length like a picosecond laser would improve the E-FISH results. Another idea is to slice the nanosecond laser pulse using a Pockels-cell-based slicing scheme to improve spatial resolution as shown by Chng et al. [19].

- Add a 1064 nm polarizer after the half-wave plate to control the laser power instead of using the delay between the Q-switch and the flash-lamp. In this way, the laser itself can operate at maximum output power, which gives the most stable output, but the input power for the E-FISH measurements can be varied nonetheless.

- Find a replacement for the 1064 nm line filter. The 1064 nm line filter of Thorlabs (FLH1064-10) used to filter out unwanted second harmonic signal created in the laser and by the optics was very easily damaged, probably due to higher order modes in the laser beam containing a lot of energy. An alternative with a higher damage threshold would improve the usability of the setup at high laser powers. Several other ideas have been tested. The laser beam path length between the laser output and the 1064 nm filter was elongated, with the intention that the higher order modes could diverge. This did not work as well as hoped. Also, the filter was swapped for a prism. In this way, the unwanted 532 nm beam was filtered out in the same way the laser and signal beams are separated in the second part of the setup. However, it turned out that this complicated the setup too much as two extra mirrors were needed to align the prism to fit perfectly in the beam path. A third idea was to swap the filter for a dichroic mirror that reflects the 532 nm beam and transmits the 1064 nm beam as the mirrors proved to have a larger damage threshold. However, this swap was not ideal for the same reason: the alignment became too difficult.

- Add more distance between the focal point and the second window to minimize damage. In the current setup, the windows are clamped to tubes that are connected to the vessel. The tube connecting the backside window is quite small due to the EMC box. Therefore, the
window has to be put very close to the focal point. To reduce the risk of damaging the window (which has happened), the gap in the plate at the front of the EMC box could be enlarged such that a larger tube, which places the window further out of focus, will fit.

- Reduce reflections inside the prism to minimize losses of 532 nm signal. The used NS-F11 prism originally had one rough side. To avoid dispersed reflections to all sides, this side was manually polished. Because the newly polished side caused unwanted, more directed reflections as well, the prism was taped with black tape. However, the glue of the tape is no longer present on laser height after the experiments are conducted, so it is possible that there might still be a noticeable amount of internal reflections that are lost in the output signal. To improve this, the angle of the prism should be optimized.

- Place the second mirror in a flip mount to be able to switch easily between the 1064 nm laser and the alignment laser. In the current setup, the second mirror has to be rotated every time the green light beam needs to be aligned; ruining the infrared beam alignment. By replacing the mount of the mirror, both wavelengths can be aligned at the same time.

- Improve the spatial resolution of the measurement by using two input laser beams instead of one, as suggested by Chng et al [64]. When two crossing 1064 nm beams are used, the interaction length and hence the spatial resolution are determined by the intersection volume as shown in figure 7.1. This approach increases the flexibility of the measurement as for example the polarization and the intensity of both beams can be controlled separately. This configuration has not been tested yet and has several disadvantages which should be considered as well. Besides increasing the level of difficulty of the alignment, the amount of signal will drop due to a larger wave vector mismatch.

![Figure 7.1: Schematic illustration of the concept of crossing two laser beams, from [64].](image)

**Improvements in the high voltage circuit:**

- Make sure the EMC box can be closed to further reduce noise of the pulsed high voltage on cables connected to detection devices and consequently improve the signals from the infrared detector and the PMT. Because in the current setup the optical path of the E-FISH measurements crosses the box, it can not be closed when executing these measurements. This could be solved by drilling a small hole into the side of the box.

- Enlarge the cap on top of the vessel to reduce EMC noise from the pulsed high voltage. The protective cap that encloses the pulsed high voltage on top of vessel is too small such that it is not fully effective.

- Improve the shape of the high voltage pulse by reducing the rise and fall time in order to reduce the jitter of the streamers, explained in section 3.1.3. Smaller capacitors could be used to discharge the load faster. Another more cumbersome improvement would be to build the high voltage circuit on top of the vessel such that the coaxial cable is not needed. As explained in section 3.1.3, the shape of the pulse worsened after adding the coaxial cable in the setup. Removing this as a whole would guarantee improvement of the pulse.
Other improvements:

- Execute the complete measurement set on one day. The laser has proved to vary in stability over the days which impacts the standard deviation of the results. Comparing results obtained with the same laser conditions is more reliable.

- Automate saving the traces on the oscilloscope by linking the delay generator and the oscilloscope in one single program. In this project, data was saved manually by pressing the start and stop button of the trigger on the oscilloscope, which is not very reliable for a large measurement set. Additionally, names for the traces were given manually, so mistakes are made quite easily. Automating this with for example a Matlab script would increase the user friendliness and reliability of the setup.

- Increase the symmetry of the surroundings of the streamers. A large asymmetry was found in the radial measurements of the electric field of the streamers. A possible explanation that was given was the fact that the surrounding vessel is not very symmetric either. The symmetry of the vessel can be increased by replacing the windows which are not needed for the E-FISH measurements with blank flanges or put in a metal cylinder around the electrodes containing only two holes for the laser in- and output.

- Visualize the infrared laser pulse in the ICCD images. In this way, the timing between the laser pulse and the streamer can be calibrated with the inserted delays such that delays due to wiring can be excluded. This is also beneficial for the laser-streamer interaction measurements investigating the timing of the effects.

- Apply Abel inversion on the results of the radial scan. Chloe van den Heuvel [59] developed a Matlab script that Abel inverts a certain data set. For this script to work, a fit through the data points is needed. Due to the asymmetry in the results in this thesis, a proper fit was not found. So, by solving the asymmetry problem or by investigating a function that is able to describe asymmetric results, Abel inversion can be applied in the current setup. An Abel inverted result would be a nice addition as it gives the spatially resolved result. This provides more information on the interaction length which should be taken into account for the calibration measurements and enables the conversion of the data of the radial scan to actual radial contributions.

7.2 Further research

The research executed in this work could be further developed in a few different ways. Several interesting follow-up investigations are suggested:

- Investigate the laser-streamer interaction with another method next to ICCD imaging. To investigate the origin of the interaction, it would be useful to measure the amount of free electrons in the laser beam path. Thomson spectroscopy, for example, could be used as this diagnostic is present in the current setup.

- Investigate the time scale in which laser-streamer interaction develops. When a filter is used to protect the ICCD camera from the indirect light of the laser pulse, the origin of the interaction can be investigated further. This might result in a value for the delay between the impact of the laser beam and the creation of the branches.

- Use an additional laser perpendicular to the the laser beam in the current setup to induce streamer branches. If the additional laser is used to create observable laser-plasma interaction, the E-FISH laser can be used to measure the electric field distribution surrounding these branches. A graphical representation is given in figure 7.2.

- Measure the E-FISH signal as a function of the electrode length, to test the contribution to the signal outside the focal region. A comparable measurement was executed for a paper of Chng et al [64] and they found that the E-FISH signal is highly dependent on the electrode length. As a result, they found an oscillating response of the E-FISH signal as a function of the electrode length. When the length of the electrodes was increased even further, the E-FISH signal became independent. This was assumed to be the result of the fact that the
signal is created only in the focal region due to higher laser intensity remaining unaffected by the far field. They, therefore, press to account for the length and shape of the electric field profile in order to obtain correct absolute field values.

Figure 7.2: Schematic illustration of two laser beams to measure the electric field around laser-induced branches (top view).

- Minimize the laser-induced breakdown in the vessel. Even though all experiments were executed in a clean low-pressure environment, a lot of laser-induced optical breakdown was observed at higher laser power and in higher pressures. In order to be able to measure in higher pressures and to use maximum laser power to increase the E-FISH signal, this phenomenon should minimized. It was found that the time the laser is off in between the measurements plays an important role, but the origin of the breakdown should be investigated in more detail.

- Find an experimental relation between the amount of second harmonic signal and the pressure of the gas. When scanning the gasses at different pressures, a counter intuitive pressure dependence was found. This is not investigated in depth and therefore not included in this thesis. Further research could give more insight in the impact of different calibration setups and the integration length on the E-FISH signal.

- Measure the electric field distribution of streamers in different gasses. It was found that nitrogen, argon and CO\textsubscript{2} all produce a measurable amount of second harmonic signal. It would be interesting to see how the electric field amplification at the streamer head differs for streamers in different gasses.

- Apply E-FISH on branched streamers in, for example, nitrogen. When Abel inversion is integrated in the analyzing script, the spatially resolved results should be able to assign different branches and measure the electric field distribution surrounding them. This could be valuable for further research on the behaviour of branches.

- Measure the electric field distributions using E-FISH, electron temperature and density using Thomson spectroscopy and the rotational molecular temperature using Raman spectroscopy for one set of conditions to be able to compare a large set of plasma properties to simulations.

- Investigate the theoretical link between the electric field distribution, the electron temperature and density and the rotational molecular temperature in order to interpret the full set of results.
Chapter 8

Acknowledgements

The last year has been a year with a lot of ups and downs resulting in loads of lessons, just as a graduation project should be, I think. However, I can say that I enjoyed doing this research very much and I am proud of the results. They even increased my curiosity on this subject and made me want to resolve all the unanswered questions. But, as this thesis must come to an end, I wisely put those suggestions on paper and leave those to be explored by future students.

Now that we have come to the final pages of this thesis, I would like to express my gratitude towards everyone who helped me along the journey. I would like to thank Sander and Anne for guiding me through this engaging experimental project of which, unfortunately, 3 months were executed from home. Coming up with an experimental setup without being in the lab turned out to be quite the challenge. Fortunately, Sander and Anne provided me with second-hand practical experience in various online discussions. After several months, when I was allowed in the lab, Jeroen from the workshop but also Ab and Pieter were always there to help me assembly-wise. For this I am very grateful because moving the vulnerable lasers, transporting the 70 kg vessel and rebuilding the voltage circuit would have been tough jobs without them. I also would like to thank Thijs for allowing the inexperienced me to join him with his final E-FISH measurements, as well as patiently answering the firing squad of questions I had to get familiar with the method. Also Anne was never hesitant to find time to help me with the E-FISH setup or meet me for a spontaneous brainstorm session about the course of the project. For the actual measurements on the streamers during the last few months, Siebe supported me a lot. The streamer setup itself is considerably extensive and would really have been a puzzle without him. Together we found new ways to tune the E-FISH setup to fit our streamer; sometimes they turned out to be improvements but just as often not. Luckily, after having changed every component about one hundred times we were able to create some nice results. Someone else who always asked the right critical questions during these lab days was Lukas; thank you very much. Those questions regularly provided fresh insights. Additionally, I would like to thank Philemon for the help he provided while revising this thesis and lastly I would like to thank the committee for putting in effort to read this thesis and prepare challenging questions for my defense. I hope this thesis provides you, the reader, with the required insights and if not, still sparked your interest in the fascinating world of streamers.
Bibliography


Chapter 8


Appendix A

Matlab scripts

The Matlab scripts used in this thesis including their purpose are shown in the table below. All scripts can be found in the folder https://gitlab.tue.nl/s1346861/master-thesis-britt-broekman.git.

The data for the E-FISH measurements is manually collected from a LeCroy oscilloscope in binary files. One set of wave forms called 'C1' contains the second harmonic signal obtained from the photomultiplier tube and the other set 'C2' contains the infrared signal that is used as reference signal. These binary wave forms can be transformed into useful data by the Matlab script 'ReadLeCroyBinaryWaveform.m', which is provided by LeCroy. The data for the calibrations, the temporal and the radial scans is analyzed in the scripts 'EFISH_analyzer_Calibration.m', 'EFISH_analyzer_HVdelay.m' and 'EFISH_analyzer_Radscan.m'. The latter two are variations on the original script by Anne Limburg [23]. For these three analyzing scripts, the integration range of the wave forms from 'C1' and 'C2' needs to be manually determined. The integration ranges used for the results in this thesis are shown below in figures A.1 and A.2. To obtain a 2D map from the temporal and radial scans including the vectors for the electric field, the script 'EFISH_analyzer_2Dmap_vector.m' can be used.

<table>
<thead>
<tr>
<th>Script</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>ReadLeCroyBinaryWaveform.m</td>
<td>Read binary waveform created by a LeCroy oscilloscope</td>
</tr>
<tr>
<td>EFISH_analyzer_Calibration.m</td>
<td>Use the calibration data to obtain a value for C_{Cal}</td>
</tr>
<tr>
<td>EFISH_analyzer_HVdelay.m</td>
<td>Analyse the experiments of the temporal scan</td>
</tr>
<tr>
<td>EFISH_analyzer_Radscan.m</td>
<td>Analyse the experiments of the radial scan</td>
</tr>
<tr>
<td>EFISH_analyzer_2Dmap_vector.m</td>
<td>Combine the temporal and radial results in a 2D contour plot</td>
</tr>
</tbody>
</table>
Figure A.1: The integration range used in the calibrations and the vertically polarized measurements. For the IR$^2$ signal 2280-2380 $\times 10^{-8}$ s and for the SH signal 2330-2430 $\times 10^{-8}$ s

Figure A.2: The integration range used in the horizontally polarized measurements, for the IR$^2$ signal 2470-2570 $\times 10^{-8}$ s and for the SH signal 2500-2600 $\times 10^{-8}$ s