The effect of electric pre-ionization on the laser-induced breakdown of helium

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Abstract

We investigate how electric pre-ionization (PI) of helium affects laser-induced breakdown. Plasma created with and without PI is compared while the effect of PI and the laser pulse energy are varied. An attempt is made to explain the differences using the theoretical model of laser-induced breakdown. We see PI lowers the energy needed for laser-induced breakdown and also results in better reproducibility. For some plasmas, the breakdown initially takes place in two isolated regions. The plasma expands and contracts over its 15 \( \mu s \) lifetime. The decay of plasma light intensity is first super-exponential but then becomes approximately exponential. Under our experimental conditions, plasma evolves into a stable torus shape. This structure may prove useful for creating plasma with a non-zero helicity.
Contents

1 Introduction 7

2 Pre-ionization and laser-induced breakdown in literature 9
   2.1 Laser-induced breakdown 9
   2.2 Cascade ionization 9
   2.3 Multi-photon processes 10
   2.4 Laser-induced breakdown after pre-ionization 10

3 Experimental Setup 13
   3.1 Optical setup 13
      3.1.1 The Nd:YAG laser 13
      3.1.2 The ICCD camera 15
   3.2 The plasma chamber 16
   3.3 The pre-ionization setup 16
   3.4 Timing 17

4 Long exposure time measurements with varying delay and laser intensity 21
   4.1 Analysing data 21
   4.2 Varying laser pulse energy 21
      4.2.1 Results 21
      4.2.2 Discussion 23
   4.3 Varying pre-ionization delay 24
      4.3.1 Results 24
      4.3.2 Discussion 25
   4.4 Dispersion of plasma intensities 26
      4.4.1 Results 26
      4.4.2 Discussion 27
   4.5 Separating the pre-ionization plasmas into two groups of different intensities 28

5 Time-resolved measurements: initial breakdown and long-term evolution of intensity 31
   5.1 Comparing pre-ionization with no pre-ionization plasma using data from the first nanoseconds after first breakdown 31

Version of July 2, 2015– Created July 2, 2015 - 18:07
5.1 Results 31
5.1 Discussion 32
5.2 Long term decay of intensity 33
5.2.1 Results 34
5.2.2 Discussion 35

6 Evolution of the shape of plasma for different conditions 37
6.1 Spatial intensity distribution as a function of time 37
6.1.1 Results 37
6.1.2 Discussion 37
6.2 Spatial intensity distribution in the plane perpendicular to the laser propagation 39
6.2.1 Results 39
6.2.2 Discussion 39

7 Conclusion 41

8 Appendix 43
8.1 Appendix I: A simple model for laser-induced breakdown through cascade ionization 43
8.2 Appendix II: Visualizing the Hopf fibration 46
8.2.1 Knots in plasma 46
8.2.2 The Hopf map 46
8.2.3 Visualizing the Hopf fibration 47
8.2.4 Visualizing knots 48
Introduction

Plasma is the term used to describe matter in the gas phase that is partially or fully ionized. It is commonly found in the world around us, in the form of, for example, fluorescent lamps, lightning and the sun. Hopefully, it will be found in fully functional fusion reactors, too, some day.

Fusion reactors are maybe the most important reason why studying plasma is interesting. Hydrogen fusion would provide a great and clean source of energy, but there are no functioning reactors yet. The main problem is that confining and heating plasma inside the reactor requires more energy than is generated by the fusion taking place.

Plasma is sometimes referred to as the fourth state of matter, but this does not completely hold. Whereas solids, fluids and gasses are described by the statistical physics of neutral atoms, the plasma consists of particles with an electric charge. For this reason, plasma is highly conductive. Electric current can exist, which means there can be magnetic fields. These fields can then again affect the current flow. This makes the dynamics of plasma very complex. The theory of magnetohydrodynamics (MHD) combines fluid flow theory (Navier-Stokes) with classical electrodynamics to describe plasma.

It has been shown that the helicity of a plasma, defined by $\int A \cdot B dx^3$, is conserved in time in ideal MHD[13]. Moffatt[5] has shown that helicity can be seen as linking of the magnetic field lines.

Smiet et al.[7] have recently conducted MHD simulations using plasmas with a non-zero helicity as initial condition. They showed that these initial conditions re-configured into self-confining, stable structures in which magnetic energy is localized. Initial conditions with higher initial helicity lost their magnetic energy at a slower rate. This structure can be described mathematically by an adaptation of the Hopf map. In appendix II, this map is discussed and visualized.

Now, our ambition is to create plasma with a non-zero helicity experimentally. We can use two techniques to create plasma. By focusing a strong laser beam into a small volume of gas, spontaneous formation of plasma can be achieved. This is referred to as laser-induced breakdown. By applying a large voltage across a gas, a partial ionization is also obtained.

In order to create a plasma with helicity, a combination of the two methods may
be required. Because in our experiments, the electric ionization precedes the laser ionization, we will refer to the former as pre-ionization. In this work, a description of plasma created using a combination of both techniques and of plasma created using only laser breakdown is given. Some differences are found which can be taken into consideration during further experiments. Also, we show evidence that the plasma we create reconfigures into a stable torus shape 6 $\mu$s after it is created. It does so without external influences. This is an unexpected, but potentially very useful result.
Pre-ionization and laser-induced breakdown in literature

2.1 Laser-induced breakdown

It is generally accepted that laser-induced breakdown has two main underlying processes: an electron cascade process and multi-photon ionization (MPI). The cascade requires the presence of free electrons, whereas multi-photon ionization creates free electrons through interaction of multiple photons with a helium atom. It is important to know that the density of free electrons naturally present in gas is far too low for a significant amount of free electrons to be in the laser focus volume. Without pre-ionization, therefore, there has to be some source of initial free electrons. Another option is the presence of tiny particles of pollution or dust, which is mentioned frequently [2, 6, 11]. Because tiny particles of any material present in the gas used for breakdown would be able to absorb light energy effectively and in that way cause ionization and heating locally, they would provide a foothold for breakdown in the gas. In cases where the laser intensity would not be enough to cause breakdown in a pure gas, contaminations of this kind might allow the formation of plasma to take place.

2.2 Cascade ionization

Ionization processes that use electrons to ionize gas are self-amplifying and cause exponential growth of ionization of a cascade-like nature. The electron cascade is thought to be at least partially caused by inverse bremsstrahlung absorption[6]. In this process, free electrons absorb energy from the laser light in the presence of an atom. When an electron has gained enough energy to ionize another atom, an additional free electron is produced and the process can repeat itself, causing the amount of ionization to increase exponentially. Other interactions between light and electrons are possible, too. Because of the nature of cascade ionization, it is more effective at higher pressures and longer laser pulse durations.
2.3 Multi-photon processes

The ionization of helium by photons has to be a multi-photon process, because the photon energy at 1064 nm is about 1.17 eV, while the first ionization energy of helium is about 24.6 eV. This means at least 21 photon energies will be needed in order to ionize helium. This may be possible through what are referred to as ‘virtual states’ [6]. Because of the time-energy uncertainty relation, single photon absorption not leading to an exited state could be allowed for a short time. Morgan [6] provides an estimation of ionization rate \( W \) in which

\[
W \propto F^k,
\]

where \( F \) is the photon flux density per time and \( k \) the amount of photon energies needed for ionization, 21 in the case of helium and 1064 nm light. Through another method, Keldysh [4], arrived at the same laser intensity-dependence.

Processes where excitation states of the gas atoms can be reached as a intermediate state, are called REMPI or Resonance-Enhanced MultiPhoton Ionization. The existence of a resonance level could increase multi-photon ionization rates by creating a somewhat stable platform (assuming exited state life time is greater than ‘lifetime’ of virtual states), allowing full ionization to take place in two leaps. The expected order of non-linearity, \( k \), normally the amount of photons needed for ionization would then become the amount of photons needed for the biggest multi-photon leap needed for ionization. Agostini et al. [1] showed experimentally that for helium, \( k = 18 \pm 0.3 \). The 2p state lies within a range of 0.12 eV from the energy of 18 photons. This state could be a resonance state. The MPI processes were isolated in this experiment by using a low pressure that would not allow for cascade to take place.

In air at atmospheric pressure, using a 193 nm laser, evidence for the strong effect of REMPI was found, too [12]. REMPI could contribute significantly here, because the photon energy was high and multi-photon processes required only three photons or 2+1 in the case of REMPI.

2.4 Laser-induced breakdown after pre-ionization

The effect of ionizing a gas before causing laser breakdown has been studied several times. Recently, a study on the effect pre-ionization was conducted[14]. In this specific case the source of pre-ionization was a 266 nm laser pulse of about 10 ns duration, while the breakdown laser light was a 1064 nm 13 ns pulse, very comparable to the laser used during the experiments described here. The gas used by Yalin et al. was air at a pressure of 0.80 bar, while we use helium at atmospheric pressure. The delay used by this team was 10 ns between peak intensities, which they indicated gave the strongest effect of the pre-ionization. The effect of pre-ionization laser pulse energy on the intensity breakdown-threshold of the main laser pulse was studied. The result showed that pre-ionization resulted in a clear decrease of threshold intensity. As an example also used by the authors, a pre-ionization intensity of \( 7 \times 10^9 W/cm^2 \) lowered the 1064 nm breakdown threshold by about a factor of 2. This pre-ionization intensity was half the breakdown threshold intensity for the 266 nm pre-ionization pulse.

Brown and Smith[2] varied the time between electric ionization of the breakdown gas helium and measured the threshold intensity for breakdown. They report seeing
the breakdown threshold significantly reduced, up to a factor of 10 for certain focal volumes. They also report another effect of pre-ionization. For no pre-ionization, the breakdown was such that sometimes, under the same conditions, bright plasmas were observed, while at other times, no plasma was observed. When using a significant amount of pre-ionization, the transition between not observing plasma and observing plasma would be gradual when increasing pre-ionization. Also, the observed plasma was more consistent between measurements.
Chapter 3

Experimental Setup

In this chapter, a description of the setup is given.

3.1 Optical setup

An overview of the optical part of the setup is depicted in figure 3.1a. Intense laser light is produced by the laser, which is focussed in the centre of the plasma chamber by an air spaced doublet lens with a focal distance of 100 mm. The plasma is imaged by an ICCD camera through a window of the chamber. A mirror in the plasma chamber allows for images of the plasma from a different angle. When using the mirror, we view the plasma from a direction almost parallel to the laser axis.

In order to regulate the laser power, two half-wave plates and two polarizing beam splitters are combined. The beam splitters allow only vertically polarized light to pass, reflecting the horizontal polarization in the direction of the beam dumps. By changing the orientation of the half-wave plates, we can adjust the amount of light passing straight through the PBSs.

A flip mirror is able to direct the laser beam towards the power meter to measure pulse energy. When doing this, no light will enter the plasma chamber. A photo diode captures the diffuse reflection of light from the power meter surface. It can be used to make time-resolved measurements of the laser light intensity.

3.1.1 The Nd:YAG laser

The laser light is provided by a Q-switched Quanta-Ray GCR-3 1064 nm Nd:YAG laser. The laser beam profile does not have the Gaussian intensity distribution. The intensity distribution shows rings of higher and lower intensity. Using the power meter we record the energy of individual pulses and using the fast photo diode, we measure the evolution of the laser intensity through time for a single pulse.

The total power of the laser can be set by varying the energy per pulse that is used by the flash lamps. The laser is designed to function optimally at maximum energy, which the internal energy meter of the laser indicates to be 85 J. The minimum energy for which the laser will still operate is around 40 J. At 85 J, the pulse intensity has
Figure 3.1: The experimental setup. a) Provides an overview of the setup. The laser light is indicated by red lines, the light emitting from the plasma created in the chamber by blue lines. b) Shows an example of a picture taken with our camera. c) Shows the plasma chamber seen from the camera point of view. Here, the pre-ionization setup is visible.
a FWHM in time of about 8 ns. When using 40 J, the resulting pulse will be longer, with around 16 ns FWHM. We determine these values using the fast photo diode. The results of these measurements are presented in figure 3.2. Here we show photo diode signal as a function of time for three different flash lamp energy settings. Because the photo diode output responds linearly to intensity the FWHM determined using the photo diode output should be the same as the FWHM of light intensity in time.

The laser can create pulses with over 1 J of energy, but is usually operated in the region of 50-100 mJ. At these energies, the spread of pulse energies typically has a standard deviation of 0.3 mJ, or 0.6%, provided that the maximum lamp energy of 85 J is used. When using lower lamp energies, the spread of pulse energies is higher. When causing laser-induced breakdown using a longer pulse, different results are obtained. As will be discussed later, longer pulse durations have higher breakdown energy thresholds. Because of this, varying laser pulse energy during measurements is always done using the half-wave plate and PBS combination and never by varying the energy directed to the flash lamps. In most cases, the maximum flash lamp energy is used to ensure optimal laser performance.

![Graph showing photodiode signal in time for three different settings of the laser: 40 J, 65 J, and 85 J.](image)

**Figure 3.2**: The photodiode signal in time of a single laser pulse for three different settings of the laser: 40 J, 65 J, and 80 J. A Gaussian fit was made for all three of the pulses in order to obtain an indication of the FWHM. The resulting values are displayed in the figure’s legend.

### 3.1.2 The ICCD camera

We image the plasma through the light that it emits. Recombination of electrons and ions inside the plasma is one process underlying this emission, but there are also other mechanisms through which light is radiated. The camera that is used is a PI-MAX Camera from Roper Scientific. It is capable of strongly intensifying in-falling light. The amount of amplification, referred to as gain, can be regulated such that the CCD can be exposed to a sufficient amount of light when taking a long exposure, but also when taking short exposure pictures. By a lens outside the chamber the light is focused on the CCD (figure 3.1a,c). The camera is connected to a programmable timing generator (PTG), which can be controlled by a computer to set CCD exposure times and delay from external triggers. The minimal exposure time is 2 ns and the delay from external...
triggers can be set with 1 ns accuracy, where 50 ns is the minimal delay. The CCD is 512x512 in size and returns measured counts per pixel in 16 bits. It has no colour filters and can therefore not separate different wavelengths. It is sensitive for light in the region between 200 and 900 nm.

Two methods of imaging are used. For the first method, the CCD exposure is long, lasting from before the laser pulse arrives in the chamber until the plasma emits almost no light, about 10 $\mu$s. By using this method one captures an integration of the light emitted by a single plasma. For the second method a CCD exposure of less than the plasma lifetime is used. By varying the moment of exposure a time-resolved image of the plasma can be made. It is important to note that, because the CCD readout time is of the order of seconds, each exposure will have to be taken from a different instant of plasma creation. For short exposure time, even with maximum gain, the amount of light captured can be too little. In this case, the CCD will be exposed multiple times, with the same duration and at the same time after the external trigger. These exposures will be taken from different instances of plasma creation and the resulting image will be sum. Variation in the plasma from shot-to-shot can therefore distort the result.

An example of a picture taken of a single plasma during this experiment is given in figure 3.1b. Black indicates lowest intensity. The same numbering of pixels will be used when referring to specific locations in pictures. What is displayed here as x-axis will be referred to as such later on. The laser pulse propagates along the x-axis from right to left. This can also be seen in figure 3.1c, where a cross-section of the chamber is displayed from the camera point of view. The picture in b has the same orientation as the cross-section in c. The area that is images has a size of 3.8x3.8 mm.

### 3.2 The plasma chamber

Plasma is created inside an air-tight chamber filled with helium. When preparing the setup, the chamber is brought down to a pressure of $<5$ mbar and then filled with helium to atmospheric pressure. When the chamber was previously exposed to air, this process is repeated once, giving a impurity of 25 ppm, ideally. The quality of the helium used is, however, not well defined and is a limiting factor in this setup. The plasma is created at a rate of 10 Hz and in order to provide constant experimental conditions, new helium is constantly flowing through the chamber. The flow into the chamber runs through the glass tube surrounding the needle, displayed in figure 3.1c. Plasma is created just a few millimetres above the needle and therefore this flow makes sure the helium in the laser focal region is refreshed between laser pulses. Pressure is kept constant at 1 atmosphere.

### 3.3 The pre-ionization setup

A voltage of +4.36 kV is applied periodically to the needle in the centre of the chamber, that is displayed in figure 3.1c. The walls of the chamber are grounded. The voltage is produced using a pulse generator which is supplied by a high voltage generator and controlled by an arbitrary waveform generator. The pulse generator produces an
output with the same amplitude as supplied by the high voltage generator and has the waveform supplied by the waveform generator in lower voltage.

This pre-ionization results in a weak ionization visible to the eye as a purple glow of the gas close to the needle. This plasma can also be captured using our camera. In figure 3.3 a sequence of images is displayed that is taken just after high voltage was applied to the needle. Image exposure was 6 ns and time increment between images was also 6 ns. Several exposures were accumulated on the CCD. The images show a wave of ionization. When the voltage on the needle is removed, another wave is visible, also moving in the same direction. The time shown is the time after trigger, while the trigger is the output of the waveform generator. The glass tube surrounding the needle is indirectly visible in the first two images. There, it causes confinement in x-direction of the ionization in the lower part of the picture.

![Image](image.jpg)

**Figure 3.3:** A sequence of images taken just after the high voltage was applied to the needle. A wave of ionization is visible as it travels through the gas, away from the needle, which is in the bottom of the images.

### 3.4 Timing

In order to precisely control the time differences between the pre-ionization, the laser induced-breakdown and the CCD exposure, the following timing scheme is implemented. An overview of signals that are involved is displayed in figure 3.4. The errors given in the figure are an upper limit on variation, determined visually using an oscilloscope.

The laser is driven by a 10 Hz signal from the waveform generator, which can be seen in row 3 of the figure. About 800 ns before the laser produces a light pulse, which is a few milliseconds after it has received the waveform generator signal, the laser gives an electrical output (referred to as variable output), displayed in the first row of the figure. This signal triggers two processes: the triggered output of the waveform generator, which controls the PI, and the exposure of the CCD. The timing of the photo detector signal of the light pulse is displayed in row 4. An example of a CCD exposure is depicted in row 5. From 50 ns after the laser variable output, the CCD is exposed for 10 µs.

The PI control signal is a sequence of 303 repetitions of a waveform which consists of 500 ns wide square pulses with a 330 µs interval. This signal is depicted in row 2 of the figure. The total length of the PI control pulse train is such that the last pulse finishes just before the next laser variable output and the next laser pulse, 0.1s later.
Figure 3.4: An overview of the signals involved in the timing. The 10 Hz signal from the waveform generator triggers the laser, which gives a signal on its variable output some time later. The actual laser pulse is detected by the photodiode, which measures a diffuse reflection, around 826 ns later. The variable output triggers the new output from the waveform generator and also triggers the CCD exposure. The variations on these times are given as maximum observed deviations, if relevant.
We wish to make clear that the pre-ionization pulse train that ends just before the laser pulse causes breakdown was thus actually triggered by the laser variable output of the previous laser pulse. Due to this, there is a $0.5\,\mu s$ variation in the time between the pre-ionization and the arrival of the light pulse.

The PI control signal can be given an initial phase. For example, if we start the PI control signal with a phase of $1^\circ$ instead of $0^\circ$, the PI will last $\frac{1}{360}$ of $330\,\mu s$ less, which is $0.92\,\mu s$. The result is that the time between the last PI pulse of the PI control signal and the laser pulse will be increased with $0.92\,\mu s$. We will refer to the time between the final PI pulse and the laser pulse as the delay time. This delay time is equal to the time added by PI initial phase plus $1.8\,\mu s$ and has an error up to $0.5\,\mu s$ between measurements.
Long exposure time measurements with varying delay and laser intensity

4.1 Analysing data

The data from the pictures consists of 512x512 arrays of 16-bit integers indicating captured light intensity. There are different ways analyze the images. A measure of intensity can be calculated by summing the value of all pixels in an image. We also determine the ratio of pictures in which plasma is formed to the total amount of pictures.

The difference between an image which captured a plasma and an image which did not is clear in almost all cases. A plasma causes high pixel values in a region of the CCD, while the other pixels remain at a base level. We determine the standard deviation of pixel values within one image. If it exceeds a certain limit, the image is considered to contain a plasma. This criterium is found to be very efficient by manually inspecting pictures.

4.2 Varying laser pulse energy

In order to determine the influence of light intensity on breakdown, we image the plasma for different laser pulse energies. We do this with and without pre-ionization, to determine what effect PI has on the intensity dependence.

4.2.1 Results

The laser pulse energy was varied. For each pulse energy, 101 images were taken for both 9.17 µs delay and for no pre-ionization.

In both figure 4.1 and 4.2 the ratio of plasma images to total images was plotted as a function of laser pulse energy. In figure 4.1 this is done for three different delay times from pre-ionization for the 85 J setting of the laser flash lamps. In figure 4.2 this is done for two different delay times, but for the 85 J setting and the 40 J setting of the laser. The blue and red results in figure 4.2 and 4.1 are from the same data.
Figure 4.1: The ratio of plasma images to total images found while varying the laser pulse energy. For this data, the laser was set to use 85 J flash lamp energy. The PI clearly changes the ratio-intensity dependence.

Figure 4.2: The ratio of plasma occurrence as a function of laser pulse energy for different delays and different lamp energies. Because different lamp energies cause different pulse width, a difference between 40 J and 85 J was expected. The red and blue data are the same as in the previous figure.

For all conditions, increasing laser pulse energy eventually results in plasma being made with every laser pulse. For the same energy per pulse and the same pre-ionization, the shorter pulse from the 85 J flash lamp setting produces plasma more frequently than the longer pulse from the 40 J setting.

In both figures, the error bar in the y-direction is introduced by the limited amount
of samples (100) per measurement. It was determined by assuming the ratio would converge in a large enough dataset and then calculating the expected distribution of measured ratio using a Poisson distribution. The error in the x-direction is the standard deviation of the pulse energy average and is <0.1 mJ. It is too small to be separated from the markers.

4.2.2 Discussion

We can conclude that, even with a delay of over 10 μs, the effect of the pre-ionization is still present in the gas and aids the breakdown of the gas by the laser.

First, we will discuss the significance of using the ratio of plasma to no plasma to describe this system. The probabilistic behavior has been recorded before [?][2]. Because the plasma created is a macroscopic system, you would intuitively expect the variations on atomic scale, governed by probability, between different gas breakdowns to average out and the macroscopic parameters such as intensity and shape to be constant over measurements. The expected result would be a sharp threshold of laser intensity: using a laser intensity above this threshold would always result in plasma and below this, never. A ratio that is not either one or zero could then be explained by a variation in laser power that fluctuates around the threshold value.

Standard deviation of individual laser pulse energy around the average value is typically smaller than 0.5 mJ. The data taken without pre-ionization in figure 4.1 shows a non-zero probability of producing plasma at 42 mJ, while having a probability that is not one at 60 mJ. The deviation of laser power is not big enough to bridge this gap. It is not possible to set a threshold of laser power that fluctuates around the threshold value could be explained by a variation in laser power that fluctuates around the threshold value.

We argue the probabilistic behaviour is intrinsic to the plasma. Because the creation is based on a cascade effect, which starts on the single atom level, it is not surprising to see the probability at this small scale expressed on the large scale.

This would also explain why pre-ionization makes the transition of ratio from 0 to 1 quicker. Because the gas contains many more free electrons after pre-ionization, it makes the influence that probability has smaller. The interaction between light and a large amount of electrons will result in more constant outcomes. The production of the first free electrons and the interaction of these few with light are in this case what causes varying results.

We can be sure that MPI plays an import role in the breakdown without pre-ionization, since without it there can not be enough feed electrons for the cascade breakdown. However, it does not show the strong \( I^{18} \) behaviour previously reported for MPI[1]. This leads to believe it the cascade ionization may be the limiting factor in the breakdown. This has been suggested before for the same wavelength of the same pulse width in oxygen and nitrogen [9] and also for dry air [11]. In appendix I, a model is described that assumes cascade ionization and can be used to make predictions about the ratio when pre-ionization delay is varied. This will be discussed in the following section.

When you compare the data taken at 40 J lamp energy to that taken at 85 J lamp energy...
energy in figure 4.2, it is clear that pulse width has an influence on creating plasma. At a same energy, the longer pulse at 40 J will have a lower average intensity than the shorter pulse at 85 J. It appears that this intensity is more important than the total energy that is used.

4.3 Varying pre-ionization delay

4.3.1 Results

For a constant pulse energy, the delay between the ending of the pre-ionization and the laser pulse is varied. Just as before, 4.36 kV was used for the pre-ionization. Each data point is determined using a set of 100 pictures. Just as before, this causes an uncertainty in ratio. The y-error bars represent one standard deviation of this uncertainty.

![Graph showing the ratio of plasma occurrence as a function of delay between pre-ionization and exposure to laser pulse. The dotted lines represent the values of ratio found for no pre-ionization.](image)

**Figure 4.3:** The ratio of plasma occurrence as a function of delay between pre-ionization and exposure to laser pulse. The dotted lines represent the values of ratio found for no pre-ionization.
4.3.2 Discussion

Both figure 4.3 and 4.4 show the decrease of ratio with increasing delay time that was expected. The data shows pre-ionization can still aid breakdown after as much as 100 μs.

In appendix I, a classical model is constructed based on cascade ionization that produces a probability (therefore, a ratio) of breakdown given a certain initial electron density. The model shows the observed probabilistic behaviour might be explained by the probabilistic nature of the first interactions of the light and the gas.

What is surprising, is the strong decrease of speed at which the ratio drops from 1 to the no pre-ionization value when comparing >50 mJ measurements with ≤ 50 mJ measurements. For the first group of measurements, the ratio starts visibly decreasing with increasing delay at 10 or 20 μs and then continues until well beyond 100 μs. However, when the ratio decreases for the second group, it drops to a minimum within several μs.

The model has a dependence on time that is not influenced by laser intensity. In its current state, as described in the appendix, it cannot be fitted to both >50 mJ and ≤ 50 mJ data with the same time constant of the electron density decay. A possible explanation for this could be that the electron density we used, an exponential decay, does not accurately describe the density for later points in time. Possibly, the density...
can be approximated with an exponential decay for the first microseconds, but slows down strongly when electron densities become low. This would explain the decrease in the ratio decay slope. Fitting the model’s final equation (assuming a constant MPI) to the data gives an electron decay time of $1 \mu$s for the $\leq 50$ mJ measurements, while giving a decay time in the order of $100 \mu$s in the $10 \mu$s + delay time region of the $<50$ mJ measurements.

4.4 Dispersion of plasma intensities

Several measurements of 1000 photos have been conducted in order to determine a distribution of the intensities of plasma found. This has been done while varying pre-ionization delay as well as while varying laser pulse energy. Intensity was determined by calculating the average pixel value after subtracting a constant background. Only images that were considered to show a plasma by the standard deviation criterium were included in the histogram.

4.4.1 Results

In order to compare the pre-ionization and the no pre-ionization case, several parameters of the distributions in figure 4.5 and 4.6 are calculated. The Full Width at Half Maximum (FWHM) parameter describes the peak of the distribution, where the standard deviation and average are calculated in the standard way.
Figure 4.6: A histogram of plasma intensity found while varying the laser pulse energy without pre-ionization. The total amount of images is 1000. Measurements were also done for 51 and 53 mJ laser pulse energy; these showed the same distribution as 54.93 mJ, but had less total occurrence and had lower average counts.

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</tr>
<tr>
<td>54.9 mJ</td>
<td>34.1</td>
<td>34.0</td>
<td>41.2</td>
<td>0.80</td>
</tr>
<tr>
<td>57.9 mJ</td>
<td>40.5</td>
<td>46.8</td>
<td>119.5</td>
<td>0.96</td>
</tr>
<tr>
<td>61.8 mJ</td>
<td>43.6</td>
<td>73.5</td>
<td>129.7</td>
<td>1</td>
</tr>
<tr>
<td>68.1 mJ</td>
<td>75.1</td>
<td>181.3</td>
<td>160.8</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 4.7: Several parameters that describe the distribution of plasma intensities around the peak value. Averages, standard deviation and FWHM are all given in average counts/pixel. The absolute value of this unit is not meaningful.

4.4.2 Discussion

For conditions that result in a ratio lower than one, distributions have the lowest histogram bin as most likely value. When increasing the laser intensity or pre-ionization, the most likely value becomes higher and a peak is visible.

Several parameters of these peaks are shown in figure 4.7. Compare the intensity distributions of 1.8 μs delay and 4.6 μs delay at 50 mJ from figure 4.5 with those of 61.8 mJ and 57.9 mJ without pre-ionization from figure 4.6. The average intensity of the 1.8 μs delay measurement is comparable to that of the 61.8 mJ no PI measurement and the
same is true of the other two measurements. The used laser power is lower (50 mJ). This means that, because of pre-ionization, it is possible to obtain the same plasma intensity with less laser power.

The FWHM of the peaks in these distributions is clearly lower in the cases where pre-ionization is used, where the standard deviation of the distributions is actually comparable (PI 85.5, no PI 73.5). When using pre-ionization, a narrower distribution is obtained, as can also be seen by eye. The standard deviation is comparable, because the pre-ionization distributions show a non-zero occurrence of intensities far higher than the peak value. This can be seen on the right side of figure 4.5: between 100 and 120 counts per pixel, there are still plasmas measured for all circumstances, while the peak values are much lower. The values displayed in the last bar of this distribution indicate the amount of occurrences that have intensities beyond the reach of the x-axis. This will be addressed in the next section. In the distributions measured without pre-ionization, this can not be seen due to the broader distribution.

We conclude that using pre-ionization results in a different distribution, where the occurrence of plasmas is more sharply peaked. There are, however, a few (13%) outlier intensities that differ more greatly from the peak value than is seen for the distributions without pre-ionization.

4.5 Separating the pre-ionization plasmas into two groups of different intensities

Here, we will further discuss the appearance of plasmas with intensities much higher than the peak value in the pre-ionization measurements in figure 4.5. We’ve analyzed the higher intensity plasmas by separating the 1.8 µs delay data into two groups by intensities, using 110 counts/pixel as a threshold. A red, dotted line indicates this threshold in figure 4.5. From these two groups, the average images are determined and displayed in figure 4.9, top two pictures. For the 1000 picture 1.8 µs delay data set, 12.7% has an intensity over 110 average counts per pixel.

A measure of relative deviation, independent of absolute intensity, between pictures was created in order to display the differences between pictures of different plasmas taken under the same circumstances. To do this, intensity pictures were normalized by their total intensity. After this, a standard deviation of pixel values across the total set of pictures was calculated. This is displayed in figure 4.9. The colour maps of the two pictures use the same absolute scale. The individual plasmas of group 1 (below 110 counts/pixel) (left in figure) are consistent in shape much more than the plasmas of group 2 (right in figure) are. The average of group 1 does appear to be symmetric. When taking a look at individual plasmas, however, it becomes clear that these are almost all not symmetrical or regularly shaped. They display a variety of shapes, which appear not to be biased towards
one particular direction, because the average is regular and symmetrical.

We assume that these group 2 plasmas of higher intensity and irregular shape are caused by a different process than the regularly shaped, lower intensity plasmas of group 1. This will be discussed again using the time-resolved images in the next chapter.

We calculate a centre-of-intensity for these pictures as a measure of location of plasma in space. The definition is similar to that of the centre-of-gravity: the x position of the centre of gravity is the average x value when x is weighed by the intensity of the corresponding pixel. Using this definition, it is possible to show another difference between the two groups. In figure 4.8, a normalized histogram containing the x positions of the centre-of-intensity for both groups is displayed. The x axis is the horizontal axis of the pictures, along which the laser pulse travels. The y position is not discussed because it does not deviate more than a few pixels between different pictures. For the low intensity plasma pictures, the x position is distributed around one most likely value. For the high intensity plasmas the occurrence is distributed around the same most likely position, but more broadly. The amount of plasmas not within a few pixels of the most likely position is much bigger. The x value is more likely to be smaller than this most likely value than bigger. Because the laser pulse propagates to the left side, this means centre of intensity of more likely to be downstream.

---

**Figure 4.8:** A normalized histogram of the horizontal positions of the center of gravity of plasmas. Blue represents the low group of 1.8 μs pre-ionization and red the group of higher intensities. The low group contains all plasma pictures of which the average pixel count is lower than 110. The high group contains the plasmas of which this value is above 110.
Figure 4.9: average pictures and pixel deviation pictures for data from figure 4.5. The distinction between two groups, one of high and one of lower intensity, has been made for the data gathered with 1.8 μs pre-ionization delay. The border between the group was set at 110 counts/pixel. Top left: average picture of low group. Top right: average picture of high group. Bottom left: pixel deviation picture of low group. Bottom right: pixel deviation picture of the high group.
Chapter 5

Time-resolved measurements: initial breakdown and long-term evolution of intensity

5.1 Comparing pre-ionization with no pre-ionization plasma using data from the first nanoseconds after first breakdown

To find more details about the effect of pre-ionization on breakdown we take pictures of the earliest phase of the plasma. We take 500 images with a 2 ns exposure time at 6 ns after plasma was first seen. This means we will take pictures at a 806 ns delay from trigger, while the first plasma is only seen when taking pictures at a 800 ns delay. For each image, the CCD was exposed just once.

When observing plasma at this early phase, two or more points of initial breakdown are visible for some plasmas. In these pictures, two disconnected regions of intensity are visible, spatially separated by a region of low intensity. From this we conclude that for some plasmas, the initial breakdown process takes place at two distinct points in the laser focus. When both of these breakdown points expand in size, they combine to produce a plasma which is irregularly shaped. In figure 5.1, an example is given of a picture showing two initial breakdown points.

5.1.1 Results

We look at the amount of initial breakdown points and the location of these points. To do this we determined the local maxima of the pictures. For this, our definition of a local maxima was a point which has a higher intensity value than all other points within a square with sides of 50 pixels surrounding this first point. Care was taken to avoid finding local maxima in the background noise by only taking into account pixel with an amount of counts significantly different from the background. When finding two local maxima in a picture, these were considered to be two separate breakdown points. The location of the local maxima was used as the location of the breakdown points. In
figure 5.2, the dispersion of the pixel values of initial breakdown points along the x-axis is displayed. For this graph, both plasmas with two or more initial breakdown points and those with just one are considered. In the figure, it is visible that for no pre-ionization, the peak value of occurrence is higher than for pre-ionization. The peak values for both are located that the same x-positions, although slightly shifted due to a mismatch of histogram bins. For the PI case, the breakdown distribution is more spread out. For PI, it is more likely to have a breakdown at an x-position lower than the most likely value than for higher x-values. The y-positions of all breakdowns are limited to a very small range of pixel values and are not displayed.

![Figure 5.1](image)

_Figure 5.1: Left: An example of two breakdown points. Right: One breakdown point. Image taken at 806 ns after trigger._

Of the pictures taken with pre-ionization that showed breakdown, 15 % featured two separate breakdown points. Without the pre-ionization this was seen in 12 % of the pictures.

5.1.2 Discussion

We assume that the most likely x-position in the histogram of figure 5.2 is the x-position of the laser focus. Because it is the point of highest light intensity, breakdown is most likely to take place here.

A contradiction arises from this result. From figure 5.2 could be concluded that with pre-ionization, the dependence of plasma ratio on intensity is less strong than without pre-ionization. This is because with pre-ionization, the local probability of breakdown drops less quickly when moving away from the most likely position (laser focus). Because the intensity drops when moving away from the focus, the probability thus drops less quickly when lowering the intensity for PI than for no PI. However, in figure 4.2, we have observed the opposite. There, with PI, the ratio depends more strongly on intensity. Here we have assumed the results of intensity-dependence in figure 4.2, measured for the entire focus, are applicable to small regions of the focus, too.

We also calculated the ratio of the amount of plasmas that had two breakdown points to the amount that had just one. From this data, it appears that pre-ionization does not greatly influence the chance of having two separate breakdown points.

These results may explain why some of the plasmas observed with pre-ionization had a deviating total intensity, as discussed in section 4.5. The plasmas of the group
Figure 5.2: A normalized histogram of position on the x-axis of the initial breakdown points of plasma for pre-ionization and no pre-ionization plasma. For the pre-ionization, the delay was 1. μs. For both the laser power was set at 65.7 ± 0.3 mJ and also 501 images were used for both conditions. The no pre-ionization case shows an x-position distribution that is more sharply centered around one value than in the no pre-ionization case. Both distributions have peak values at the same x-position.

with higher and more variable intensities could be those that had two or more initial breakdown points. Because two breakdown points occurred in 15% (PI) and 12% (no PI) of the breakdowns, this could match the 12.7% of plasmas of the high intensity group. When comparing the x-position histogram of the high intensities with the x-position histogram of the breakdown points, these provide further evidence. The distribution of breakdown points in figure 5.2 shows that, when two breakdown occur, the average will resemble the distribution of centre-of-intensities in figure 4.8. The averages will be spread out more broadly around the most likely position than with single breakdown and would also be more likely to be in lower x-positions than in higher x-positions, which matches with figure 4.8.

5.2 Long term decay of intensity

It is possible to make several sequences of photos that together cover the entire light-emitting lifespan of observed plasma. In this way, it is possible to study the decay of light emitted of the plasma over time.
5.2.1 Results

Multiple sequences with different camera gain settings are needed to cover the entire plasma lifetime. Each of these different measurements is depicted in a different colour. The samples are distributed over multiple measurements because exposure time and ICCD gain have to be increased when measuring the less bright plasma at several microseconds after the trigger. By changing the gain and exposure time, the absolute values of pixel counts are no longer comparable. To be able to compare them, different data sets are scaled to match. The first set of data (800-900 ns after trigger) is not altered. Every succeeding set has several pictures taken at times at which the previous set also has pictures. All of the measured values in the succeeding set are multiplied by a factor such that the average number of counts of the overlapping pictures matches this average of these pictures in the previous set.

In figure 5.3 the decay of intensity of plasma for a laser power of 49.9 ± 0.3 mJ and 1.8 ± 0.5 µs pre-ionization is plotted. The three different figures are representing the same data, but the time-axis range is varied to display different features of the decay. The y-axis is a logarithmic scale for intensity.

Note that at 800 ns, before plasma is created, the detector noise level is around $10^{-2}$ counts, whereas the noise baseline level at 10 µs is of the order of $10^{-4}$ counts. This is because the noise in all measurements has the same absolute value, but it is scaled down when the measurements are normalized to match at overlapping delay times.

![Figure 5.3: The average intensity per plasma as a function of time after laser variable out for plasma made with pre-ionization. A delay of 1.8 µs was used and laser power was set at 50 mJ. All three pictures display the same data, only the range of the time axis is changed to show different features of the intensity-time dependence.](image)

The same was done for 65.8 ± 0.3 mJ, with no PI and also with 1.8 ± 0.5 µs delay. The resulting graphs are comparable to those in figure 5.3. The decay consists of a quick rise in intensity, followed by steep super-exponential decay in the 800-850 ns interval, visible in figure 5.3c. After this, the decay shows decay that can be approximated by an exponential decay locally (e.g. red data, figure b), but has a changing time constant on longer time scales, visible as a changing slope in figure a.

In order to compare the decay for the three different experimental circumstances,
several time intervals of the decay were fitted with an exponential decay function. The corresponding time decay constants were determined and are displayed in figure 5.5. The time constants are in nanoseconds. In the left-most column, the laser power and PI are displayed, while the time intervals can be found in the top row. Also, the decay in the first 100 ns has been plotted in one graph for all three conditions in figure 5.4. The data has been normalized by peak intensity here.

Figure 5.4: Intensity as function of time for the three different conditions from 800 to 900 ns after trigger. Intensities are normalized by peak value.

<table>
<thead>
<tr>
<th></th>
<th>876-1220 ns</th>
<th>1220-1550 ns</th>
<th>1550-2080 ns</th>
<th>2080-3750 ns</th>
<th>3750 - 16050 ns</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mJ, 1.8 μs</td>
<td>541</td>
<td>645</td>
<td>869</td>
<td>1205</td>
<td>1404</td>
</tr>
<tr>
<td>66 mJ, no PI</td>
<td>650</td>
<td>880</td>
<td>1052</td>
<td>1395</td>
<td>1874</td>
</tr>
<tr>
<td>66 mJ, 1.8 μs</td>
<td>578</td>
<td>653</td>
<td>930</td>
<td>1541</td>
<td>1775</td>
</tr>
</tbody>
</table>

Figure 5.5: A table containing time constants of the intensity decay data as presented in figure 5.3. Time constants were determined by fitting the data.

5.2.2 Discussion

Figure 5.3 shows us that the intensity decay does not follow a simple exponential decay. The first 40 ns after maximum intensity is reached, show a super-exponential decay of intensity. Gregorčič et al. ?? have determined expansion velocities for plasma in air using laser light, at a slightly shorter pulse width of 4 ns FWHM. At a time of 34 ns after breakdown, they measure an decrease in the decay of velocity. They argue that, before this transition, high-temperature plasma drives the shock wave. This could be the reason for the super-exponential decay of intensity we measure in this time interval. During the first phase, energy would be transferred to the shock wave and would therefore decay faster. After this the shock wave has a constant energy, as suggested by Gregorčič et al..
After this initial decay phase, the intensity decays in a close to exponential fashion. The time constant of the exponential decay that best fits the decay decreases when moving further in time, that is, the decay slows down. Apparently, the degree of ionization influences the speed at which intensity is lost. We think the reasons for intensity decay are a decrease in ionization degree and a decrease in plasma temperature.

From figures 5.3 to 5.5, no significant difference can be seen between the decay with PI and no PI or higher and lower laser power. The absence of a difference between PI and no PI is not surprising, since PI should in principle only affect the processes of plasma generation. What is surprising, however, is that although different ionization and laser powers result in different intensity plasmas, the decay of these different plasmas are comparable. As we can see in figure 5.5, the time constants of the decay are similar for all three circumstances, although the intensities of the plasmas are quite different. Peak intensity for the 66 mJ PI plasma is almost twice that of the no PI plasma, which is at least 1.5 that of the 50 mJ PI plasma (figure 4.7). When normalized, however, the intensity of the three cases agrees well in the 800-900 ns region in figure 5.4. From this we conclude that the decay pattern observed here applies to plasmas of different peak intensities. It also applies to PI plasmas as well as to no PI plasmas.
Evolution of the shape of plasma for different conditions

Using the same time-resolved imaging technique it is also possible to study the change in plasma shape in time. From this, we find details of the dynamics of plasma and we also find more effects of the use of pre-ionization.

6.1 Spatial intensity distribution as a function of time

6.1.1 Results

From the same data we used to determine the intensity decay we made the time cross-section images in figure 6.1. For several images in the sequence, cross-sections were made by averaging the images over either columns or row to turn the two dimensional image into two one-dimensional plots that show a distribution of intensity over the x- or y-axis. The plots were normalized by peak intensity.

In 6.1, the same 6 time cross-sections were made for both the x-axis (left column) and the y-axis (right column). This was done for the 50 mJ PI (top row), 66 mJ no PI (middle row) and 66 mJ PI (bottom row). The y-axis distributions show an expansion and are comparable for the different cases for all points in time. The x-axis distributions show an expansion up to about 1850 or 6050 ns, followed by a contraction. The size and shape of the expansion do differ. The no PI plasma appears to contract earlier than the PI plasma and for 66 mJ and using PI results in a larger expansion in x-direction.

6.1.2 Discussion

Because the plasma is hot and energetic, expansion of plasma is expected. In the y-direction, expansion is relatively constant through time. It eventually leads to two peaks of intensity, as can be seen in all graphs in the right column of figure 6.1. The expansion is of the order of 1 mm in 11 μs time, which gives an average speed of 91 ms⁻¹. For the expansion along the x-direction, we can find a much higher average
Figure 6.1: Cross-sections of pictures made by either removing the x or y axis by averaging it out, leaving only the other axis. The result is a 1d picture that has information about the spread of intensity over the x or y axis. This is done for 50 mJ and 65 mJ laser pulse energy, where for 65 mJ the measurement was performed with 1.8 µs delay from pre-ionization and no pre-ionization. The 50 mJ was only done for pre-ionization at 1.8 µs delay.
speed. The expansion between 810 ns and 900 ns is about 1 mm in both directions. This results in an average speed of 9520 ms\(^{-1}\).

In the x-direction, the expansion is followed by contraction. It is, however, important to note that we cannot be sure the plasma itself is contracting. It is possible that the intensity of plasma on the far left and right of the distribution is dropping faster than in the middle, giving the impression of a contraction.

The average plasma intensity is comparable for 50 mJ with PI and 66 mJ without PI. When you compare the cross-sections, you see that the dynamics are relatively comparable for the two. The use of PI does not result in different dynamics. One exception may be the shift of intensity to a lower x-position for 66 mJ no PI at later times (6050, 11050 ns), that is not visible for both PI measurements. We have no explanation for this yet and it would be a good idea to see if it is reproducible first.

### 6.2 Spatial intensity distribution in the plane perpendicular to the laser propagation

#### 6.2.1 Results

All data present thus far is collected using the camera point of view that is depicted in figure 3.1a, c. In this frame it is clear that there is no symmetry along the x-axis: the laser beam originates from only one side. For the y-axis this symmetry does exist, when you assume the density of electrons resulting from pre-ionization does not have a strong gradient. That is, if you assume the pre-ionization of gas is evenly distributed around the laser focus. Figure 6.1 shows both the asymmetry along x-axis and symmetry along y-axis. For the y-axis, this holds for both pre-ionization and no pre-ionization, indicating that the high voltage needle just below the plasma does not break the symmetry.

In order to further investigate this, pictures were made from a different angle. By imaging via the mirror in the chamber as in figure 3.1a, we can look at the plasma from a point of view close to the laser axis. We can see the dynamics of the plasma in the plane perpendicular to the laser beam. The results are visible in the top row of figure 6.2. The images of plasma are made with 20 exposures. The exposure time varies with the plasma intensity and the colour scale of the pictures have been normalized. In the bottom row you can see the same pictures, but then taken from the previously used point of view. These particular examples were collected with 66 mJ of laser power and 1.8 \(\mu\)s PI delay.

#### 6.2.2 Discussion

These results in the top row of figure 6.2 show that the plasma is symmetric in the laser axis. The images at 100 ns and 2 \(\mu\)s are not symmetric, because our point of view is not exactly that of the laser axis, but only close to. Structures that are elongated along the laser axis then become slightly elongated in this frame too.

The finding of a naturally forming torus shape of plasma is a surprising result. The torus is first visible after 5 \(\mu\)s. It remains visible until no intensity can be seen
any more. During this time, the ring slightly expands, but never obtains a radius bigger than twice the radius it has when it is first seen. The ring is visible for all three conditions we used, both with and without pre-ionization. There are also some quick measurements done with air instead of helium that seem to indicate the ring does not form in air. Rather, the plasma has the disk shape visible at 5 μs in figure 6.2 at later times.

From the measurements of dynamics from both this and the previously used point of view, several questions arise. Because of the conductivity of plasma, it can also contain current flow, resulting magnetic fields and also charge separation. Next to this, it also possesses fluid dynamics for sufficiently dense plasmas. It is not yet clear whether the plasma expansion and contraction we have observed are governed by fluid dynamics or that electric current is involved.

Magnetic fields in plasma have been reported to reach over 100 T [8] when plasma was created by a laser focused onto an aluminium plate. A 100 ps laser pulse of 1064 nm light was used with an intensity of about 2 J. It is possible these strong fields are present, too, in our experiment, where plasma is created in a gas and without interaction with a solid. There is still much to be investigated about the dynamics of plasma and the occurrence of self-forming plasma rings.

Figure 6.2: Time evolution of plasma. Time indicated is time since plasma is first seen. The top row shows pictures from the laser axis point of view and the bottom row shows images taken from the side view.
Several conclusions can be drawn from the results presented in this thesis. First, we see that PI aids the breakdown of gas. The ratio of plasma increases from 0 to 1 more quickly with increasing laser pulse energy when the gas is pre-ionized. A model was constructed that can describe some aspects of the way ratio depends on PI delay. The model could not explain the slower change of ratio with time that is seen for 50+ mJ with respect to the change of ratio seen at 50 mJ and lower. One possible reason is that our assumption of ionization decay is too simplistic.

Next to this, PI changes the distribution of plasma intensities. Using PI with a certain laser power results in brighter plasma than when only the laser was used at that particular power. But when comparing plasmas of equal intensity, plasma produced with PI has a narrower distribution around the most likely intensity than plasma produced without PI. For both PI and no PI, a part (about 12%) of all plasmas showed more than one point of initial breakdown. We believe these can explain the group of higher intensity plasmas seen with PI, because both occur at the same rate and have deviating position. Multiple breakdown could also explain deviating intensity. It is not clear why the multiple breakdown plasmas would not reach such high intensities when no PI was used.

The decay of plasma intensity is similar for PI and no PI. When normalized, it shows the same trend for plasmas of different peak intensity. A 50 ns super-exponential decay is seen just after peak intensity is reached. After this, the intensity decays approximately exponential, with a time constant that becomes bigger when plasma intensity becomes lower.

Using picture sequences, we have been able to describe the dynamics of the laser-induced plasma in all three spatial directions. Plasma expands rapidly after formation, especially along the laser axis. Along this same axis, it also contracts after a few microseconds, while expansion in other directions continues. When using pre-ionization at a given laser energy, the resulting plasma will expand more strongly.

Observing the naturally occurring plasma torus has been a fortunate discovery, since a plasma ring might be of use in creating structures with non-zero helicity in plasma. It is relatively stable: it expands only slightly and is present for a time of at least 5 μs. These properties make it suited for creating plasma structures.

To be able to use the plasma ring, it is also important to have an understanding of
the driving forces behind the dynamics of our plasma. It is not yet clear whether these are governed by the electrodynamic aspect of MHD or only by the fluid dynamical aspect. In the experiment by Stamper et al.[8] Faraday rotation was used to determine magnetic field strength in plasma. This technique may be applied to this experiment too, but it only works for high magnetic fields. By exposing our plasma to an external magnetic field, possible current flows and internal magnetic fields could be distorted. By then looking at changes in dynamics, the amount of influence of magnetic fields in the structure can be determined.

Before these results are used in further experiments, however, they should be put on a stronger foundation. On several occasions, we have assumed that plasma should be located at every point from which we see light being emitted. This does not have to be the case. Since we are observing in the 200-900 nm region, we could also be seeing transitions within the neutral helium atom. There are several transitions in the region visible to our camera[10]. It is important to determine what is emitting the light we are detecting to be able to support our results. Similarly, it is also possible that there is more plasma structure that is emitting light at different wavelengths and that we currently can not observe.
Appendix

8.1 Appendix I: A simple model for laser-induced breakdown through cascade ionization

We can construct a simple model of breakdown probability or ratio as a function of PI delay. First, we model how the amount of free electrons evolves in time after pre-ionization stops at t=0. We assume the decay of electrons has the following time-dependency: \( N_e = N_0 e^{-ct} \). Here \( N_e \) is the amount of free electrons in a certain volume, \( N_0 \) the amount on \( t = 0 \) and \( c \) is the time constant of the decay. Next, when we assume that the pre-ionization leaves behind an electron density of \( \rho_0 \). We then also know \( \rho_e = \rho_0 e^{-ct} \).

What is the chance of finding \( n \) electrons in a given volume, such as the focal volume? First, the chance of finding no electrons in a volume \( V_1 \) when the density is \( \rho_e \). For this, take a second, much larger volume \( V_2 \), containing \( V_1 \) which is big enough to say that the amount of electrons inside is \( N_e \approx V_2 \rho_e \). Now the probability of finding no electrons inside is:

\[
P_0 = \left( 1 - \frac{V_1}{V_2} \right)^{V_2 \rho_e}
\]

It is simply the product of the probabilities for placing the electrons outside of the smaller volume. Now, the probability for finding one electron:

\[
P_1 = \left( 1 - \frac{V_1}{V_2} \right)^{V_2 \rho_e - 1} \left( \frac{V_1}{V_2} \right) \binom{V_2 \rho_e}{1} = \left( 1 - \frac{V_1}{V_2} \right)^{V_2 \rho_e - 1} \left( \frac{V_1}{V_2} \right) \frac{(V_2 \rho_e)!}{1!(V_2 \rho_e - 1)!}
\]

In general:

\[
P_a = P_{a-1} \frac{\frac{V_1}{V_2} (V_2 \rho_e - a + 1)}{a \left( 1 - \frac{V_1}{V_2} \right)}
\]

Taking the limit of \( V_2 \to \infty \) of both \( P_0 \) and the general case, we find:
\[ P_0 = e^{-V_1 \rho e}, \quad P_a = \frac{V_1 \rho e}{a} P_{a-1} \]

If we assume that any non-zero amount of electrons in the focal volume \( V_1 \) would result in a cascade breakdown, we find the expression for breakdown probability:

\[ P_{bd} = 1 - e^{-V_1 \rho_0 e^{-ct}} \]

This expression does not take the laser intensity into account. The intensity of the laser pulse affects the probability by changing the amount of photons available for the interaction between the electrons and the light that is at the basis of the cascade effect. We include the probability of causing a cascade with one free electron at a certain intensity \( I \), which we call \( P_1^c(1) \). The probability for causing a cascade with \( n \) free electrons is:

\[ P_n^c = 1 - (1 - P_1^c)^n \]

To find the breakdown probability \( P_{bd} \), we combine \( P_n^c \) and \( P_n \) found before.

\[
e^{-V_1 \rho e} \left( \sum_{n=1}^{\infty} \frac{(1 - (1 - P_1^c)^n)}{n!} \right) = e^{-V_1 \rho e} \left( \sum_{n=0}^{\infty} \frac{(V_1 \rho e)^n}{n!} - 1 - \sum_{n=0}^{\infty} \frac{(V_1 \rho e (1 - P_1^c))^n}{n!} + 1 \right) = e^{-V_1 \rho e} \left( e^{V_1 \rho e} - e^{V_2 \rho e (1 - P_1^c)} \right) = 1 - e^{-V_1 \rho e P_1^c} \]

We are allowed to split the initial alternating power series into two separate series because it is absolutely convergent. When we make the electron density a function of time, we get:

\[ P_{bd} = 1 - e^{-V_1 \rho_0 e^{-ct}} \]

Last, we can find the total probability over a volume of changing intensity, like a laser focus.

\[ P_{bd} = 1 - e^{-P_c \rho_0 e^{-ct}}, \quad P_c = \int P_1^c(I(r)) d\mathbf{r}^3 \]

The influence of laser intensity in this model would be restricted to the first exponent. Changing laser power and thus changing \( P_c \) would not change the maximum slope angle. In figure 8.1, this prediction of ratio versus delay time is plotted for several parameters values. The product \( P_c \rho_0 \) changes the location of the initiation of the drop from 1 to 0 ratio, while the time constant \( c \), a measure of decay of the density of free electrons, determines the maximum slope reached. The model is plotted for several parameter values in figure 8.1.
Finally, we can also assume a baseline electron density, which is produced by MPI. We would then insert $\rho_e = \rho_0 e^{-ct} + C_0$. Several examples of the resulting distribution are plotted in figure 8.2.

In conclusion, this model shows the same general trend as is found in the experimental results of ratio as a function of delay time. One clear difference between the model and data is that the slope of the ratio does not change in the model, while it does in the experimental results. In our model, the parameter controlling the property of the slope that changes is the time constant of the electron decay. One reason for the discrepancy may be that our assumption of the electron density as a function of time was not correct. In this case, the actual electron density decay would slow down when electron density becomes low.
8.2 Appendix II: Visualizing the Hopf fibration

8.2.1 Knots in plasma

As mentioned in the introduction, it is possible to mathematically produce a magnetic field that has a non-zero helicity and describes the quasi-stable states of plasma found in the simulations by Smiet et al.[7]. This is done by using the Hopf map and the inverse stereographic projection. The result of this method is a tiling of $\mathbb{R}^3$ with circles of which each represents a magnetic field line. From this, a magnetic vector field can be constructed that has zero divergence, as is required by Maxwell’s laws. We will not discuss this. Depicting the tiling of circles already shows of the direction of the magnetic field at every point. Visualizing the circles can be useful for developing an intuitive understanding of the Hopf map. In this section, we will show several images of this tiling produced using a Python code. The code can be found on the Data01 drive of Leiden University, in the folder Data01/qo/Burgwal.

8.2.2 The Hopf map

Heinz Hopf defined a map from $S^3$ to $S^2$, now commonly referred to as the Hopf map [3]. When describing $S^3$ using the standard $\mathbb{R}^4$ coordinates $x_1, x_2, x_3, x_4$ and describing $S^2$ using $\mathbb{R}^3$ coordinates $x, y, z$ it can be expressed as:

$$h : S^3 \to S^2 \quad h(x_1, x_2, x_3, x_4) = (2(x_1 x_4 + x_2 x_3), 2(x_2 x_4 - x_1 x_3), x_1^2 + x_2^2 - x_3^2 - x_4^2)$$

By identifying $\mathbb{R}^4$ with $\mathbb{C}^2$ in the following way:

$$z_1 = x_1 + x_2 i, \quad z_2 = x_3 + x_4 i$$

we can write the Hopf map as:

$$h(z_1, z_2) = (2\text{Im}(z_1 z_2), -2\text{Re}(z_1 z_2), |z_1|^2 - |z_2|^2)$$

For our purposes the fibers $h^{-1}(x)$ for $x \in S^2$ are important, where $h^{-1}(x) = \{ y \in S^3 : h(y) = x \}$. These are of the form $h^{-1}(x) = \{ ye^{i\phi} : 0 \leq \phi \leq 2\pi \}$, where $y$ can be any $y$ with $h(y) = x$.

Next, we introduce the stereographic projection $\pi$ of $S^3 \setminus p$ onto $\mathbb{R}^3$. We will not make this explicit, but we will describe the basic concept. The stereographic projection can easily be generalized to $S^n$. In figure 8.3, the procedure of the projection is depicted for the case $n=1$. The projection makes use of one point $p \in S^4$ to project from. This point is therefore not mapped onto $\mathbb{R}^3$. The projection of $x \in S^3$ is defined to be the intersection of the line through $x$ and $p$, $l = \{ r(x - p) : r \in \mathbb{R} \}$, and the plane $x_4 = 0$. We will identify this plane with $\mathbb{R}^3$ through the bijection that takes the first three coordinates of $S^4$ to be the $x, y$ and $z$ of the corresponding point in $\mathbb{R}^3$. These steps are illustrated in figure 8.3.

The stereographic projection is continuous and bijective. All of $S^3$ can be filled with fibers of the Hopf map, because each point in $S^3$ maps to a point in $S^2$. Finally, note that each of the fibers is disjunct from the other fibers. Because of these three facts, it is possible to tile $\mathbb{R}^3$ with the projections of the fibers of the Hopf map.
fiber which will not be mapped completely, which is the fiber containing the projection point. In $\mathbb{R}^3$, this becomes a line that stretches out to infinity. The other fibers, when mapped to real three-dimensional space, are all circles.

In conclusion, we can fill $\mathbb{R}^3$ by using the fibers from a composition map of the inverse stereographic projection and the Hopf map that maps $\mathbb{R}^3$ to $S^2$.

8.2.3 Visualizing the Hopf fibration

When picking a point on $S^2$, it is possible to calculate any number of points in the corresponding fiber in $S^3$. We calculate:

$$\|z_1\| = \sqrt{\frac{1}{2} - \frac{z_2}{2}}, \quad \|z_2\| = \sqrt{1 - \|z_1\|^2}$$

after which we pick the argument of $z_1$ to be 0. We have this freedom, because we know that every point in the fiber multiplied by $e^{i\phi}$, $0 \leq \phi \leq 2\pi$ is still in the fiber. At this point, we can determine the argument of $z_2$:

$$\text{Arg}(z_2) = \arctan^*(y, x)$$

with:

$$\arctan^*(y, x) = \begin{cases} \frac{\pi}{2} & \text{if } x = 0 \text{ and } y > 0 \\ \frac{3\pi}{2} & \text{if } x = 0 \text{ and } y < 0 \\ \arctan\left(\frac{y}{x}\right) & \text{if } x > 0 \\ -\arctan\left(\frac{y}{x}\right) + \pi & \text{if } x < 0 \end{cases}$$

We can turn this single fiber point into a arbitrary amount of samples from the fiber by multiplying it with the $e^{i\phi}$ for $\phi$ evenly distributed between 0 and $2\pi$.

After this, we apply the stereographic projection to each of these points. We determine the intersection of the line through the projection point and the point to be projected with the plane $\text{Im}(z_2) = 0$. We then determine the point in $\mathbb{R}^3$ by the firs three coordinates of this point: $(x, y, z) = (x_1, x_2, x_3)$.

Using this method, we have calculated sets of fibers for different sets of points on $S^2$. The results are depicted in figure 8.4. Here you can see the fibers of three different collections of points on $S^2$. For each of the three, the points on $S^2$ are presented on the
left and the resulting fibers on the right. The colors of the $S^2$ points match those of the resulting fibers on the right.

These visualizations show some of the key elements of the Hopf fibration. As you can see in the top row of figure 8.4, the north pole on $S^2$ maps to the z-axis in $\mathbb{R}^3$, while the south pole maps to a circle in the y-x-plane. Every circle on $S^2$ with constant $z$ is mapped to a torus surrounding the south pole circle. When rotating the selection of points in $S^2$, depicted in rows 2 and 3 of the figure, we see that both of these points now map to linked circles in $\mathbb{R}^3$. The blue circles on $S^2$ are again tori surrounding these circles, but now there is one torus surrounding each red circle.

### 8.2.4 Visualizing knots

It is also possible to introduce another map $f$ of $S^3$ to $S^3$ so that we have a map $\mathbb{R}^3 \to S^3 \to S^3 \to S^2$ with which we can also tile $\mathbb{R}^3$, given that the new map satisfies certain conditions. We produce pictures for the case where this new map is given by $f(z_1, z_2) = (z_1, \frac{z_2}{\|z_2\|})$. Where fibers of single points in $S^2$ are circles in $\mathbb{R}^3$ without the new map, with the new map they are $(2,1)$ torus knots. The results are depicted in figure 8.5. The fibers are shown from two angles (left and right column). The points on $S^2$ that are used, are those of the middle row in figure 8.4, except for the fact that one of the red points is now coloured green. In the first row of figure 8.5, we have shown the fibers of just these two points. In the second row, we show one point and one circle and in the third row we show two points and two circles. This method can be generalized to produce $(n,m)$ torus knots by using the map $f(z_1, z_2) = \left( \frac{z_1^n}{\|z_1\|^{n-1}}, \frac{z_2^m}{\|z_2\|^{m-1}} \right)$. 
Figure 8.4: The fibers in $\mathbb{R}^3$ (right) for certain points on $S^2$ (left). The blue points and blue fibers correspond, just as with red.
Figure 8.5: The fibers in $\mathbb{R}^3$, where we have introduced an additional map $f$ such that the fibers of single points on $S^2$ are now $(2,1)$ torus knots. Two single points are red and green and two circles are blue.
References


