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Characterization of a floating DBD at atmospheric pressure

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Abstract

Electrical and optical characterization of dielectric barrier discharges (DBD) is essential in understanding and controlling plasmas for biomedical applications. Previous research that proved DBD treatment can successfully treat a lot of wounds. An example of the applications in medicine is the sterilization of wounds. Despite this success, relatively little is known about the electrical circuit of the plasma. Results in this report offer a model of the electrical circuit describing the high voltage source and the plasma. With this model current and voltage output can be predicted for different parameters. This offers insight in the electrical scheme and how to control the plasma. Measurements in this report show that by varying the distance between electrode and dielectric and by using different materials as dielectric the characteristics of the plasma is changing. Results show that the plasma is filamentary for frequencies in the range of 50 – 2500 Hz and for all different distances between electrode and dielectric. Also an emission spectrum of the plasma is measured. This spectrum was dominated by transitions of the second positive system of N_2 C→ B. With a high resolution emission spectrum, the filament temperature is determined to be 330K +/- 20K. The average gas temperature is lower. The results provide a general characterization of the plasma and can be used as inspiration for future research.

Contents

Introduction

In today's world plasmas are used in a wide variety of applications. It is used for surface treatments such as etching, cleaning and thin film depositions on a lot of different materials [2]. Also in the medical world plasmas are already used to clean and treat all different kinds of wounds and sterilize medical instruments. In addition to a lot of industrial plasmas, medical applied plasmas require some more specific parameters to ensure safe treatment. In order to apply plasmas on human skin, the plasma should work under atmospheric pressure, production of reactive species in the gas or at human skin has to be in safe limits, the gas temperature should not become too high and the current through the body as a result of the discharge should not be too high [12]. Earlier research of Fridman already showed that the use of a cold non-equilibrium dielectric barrier discharge (DBD) plasma fulfills a lot of these conditions in order to safely treat human tissue [2]. But primarily, they showed successful results in sterilization of wounds and blood coagulation for treatment times of a few seconds. However, there is not a lot of research performed on power and current output of the discharge. Despite the fact that with high voltage input low current is essential for safe treat of patients. Therefore models of the electrical scheme are very useful in understanding the output and with that, important characteristics of the plasma.

When high voltage is applied between an electrode and a dielectric a plasma is created between these two materials. When using human skin as a dielectric, a plasma between the first electrode and skin can be created and treatment of human tissue is possible [2]. As mentioned before, parameters influencing the discharge should be controlled very accurately. Therefore it is worth investigating what parameters influence the current and voltage of the plasma and in what way they do.

DBD's have in general two different modes, a homogeneous mode and a filamentary mode. The filamentary mode consists of a lot of micro discharges of which the positions are statistically distributed, in time and space [6]. In order to create a homogeneous treatment of tissue, this mode is less suited than the homogeneous glow mode [6]. This mode is better for homogeneous surface treatment. The characteristics of those atmospheric pressure air plasmas, including the kind of mode of the plasma, depend mostly on the distance between the electrodes, which shall be called interelectrode distance from now on, the applied voltage, the materials used as electrode and the dielectric, the frequency of the pulse and the pulse width [3]. These parameters are controlled by the power input and therefore very dependent on the power setup used. In order to understand the plasma those parameters will be varied and characteristics will be described.

This will be done by performing voltage and current measurements as a function of frequency, interelectrode distance and by using different materials as dielectric. Gaining insight in how all these parameters influence the voltage and power is the main goal of this research. Next to this, an attempt will be made to look for conditions for homogeneous treatment of surfaces. At last time and space averaged measurements of the emission spectrum will be obtained in order to briefly look into the chemical processes and species present in the plasma gas. By looking in more detail to the emission spectrum of the nitrogen molecule an average gas temperature can be determined in order to see if the plasma is suited for treatment.

Experimental design

Setup

In order to measure voltage and frequency the electrode was put into a holder at a fixed height. Both quartz and aluminum were used as a dielectric for the discharge. In the quartz case, a cylindrical shaped piece of quartz with height 4 mm and a diameter of 45 mm was used. The specifications of the aluminum were 62 mm by 136 mm and 1 mm thick. A metal mesh was placed underneath it to conduct the charge to the ground. The mesh was made of aluminum and the metal – gap ratio was about 1:4. This mesh was placed on a surface and grounded. In the aluminum case, the aluminum was simply grounded directly.

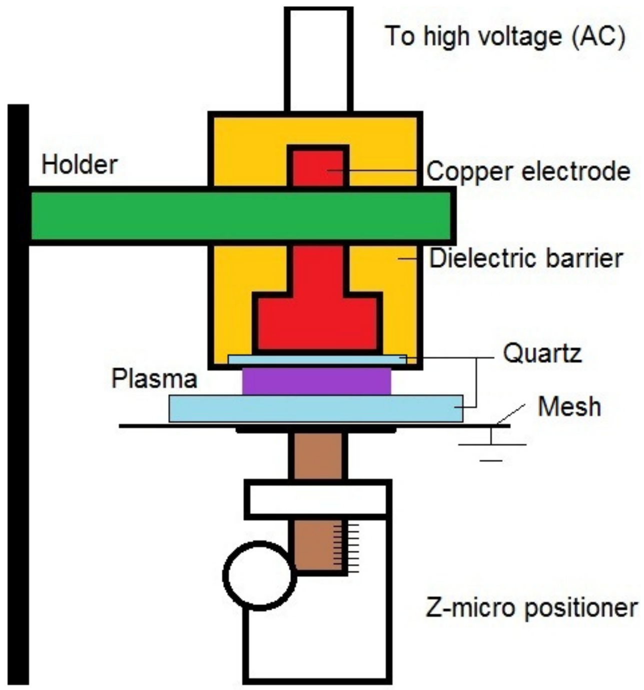

Figure 1: Schematic view of the setup of the DBD.

The surface with either the aluminum or the mesh and the quartz, was adjustable in height with an accuracy of +/- 0.05 mm (Fig. 1). The copper electrode was covered by a dielectric barrier. For this dielectric barrier Teflon was used [A1].The dielectric barrier was in contact with a piece of quartz For measuring the voltage a Tektronix Voltage probe was used, for measuring the current a Rogowski coil was used (Fig. 2).

The same transformer as used by Fridman et al [2] was used in order to produce high voltage signals in the order of kilo-Volts. Typical current values produced by the source were in order of mA. Surface powers were in the range 0.5 - 1 W/cm^2 according to Fridman [9]. The output of the power source could be controlled in order to adjust frequency, duty cycle and pulse width. This frequency was adjustable to values in a range of 50-3500 Hz in ten non-linear steps. The duty cycle could be varied in steps of 10%, from 0% to 100%. The pulse width was adjusted from 1 to 10 μs in linear steps of 1 μs. The pulse width is fixed at 10 μs.

The cable between the transformer and the copper electrode turned out to be very sensitive for discharges on other dielectrics. This results in an unknown power loss in the setup.

The cut off distance is the distance defined as follows. When increasing the distance between electrode and dielectric to the point where the plasma just disappears, that distance is defined as the cut off distance. This was necessary in order to rule out effects of possible hysteresis. By repeating this 5 times a good approximation of the cut-off distance could be found.
At different cut off distances, also the breakdown voltages could be determined. This is done by looking at the maximal voltage the breakdown voltage can be approximated.

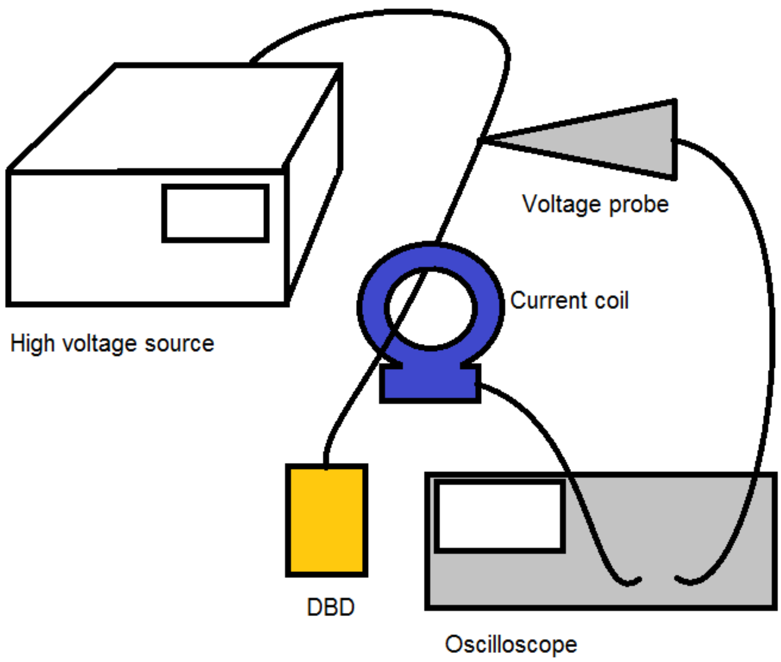

Figure 2: Schematic setup of the high voltage source, the voltage probe, the current coil and the oscilloscope.

Electrical scheme

In this section all components of the electrical scheme will be explained. The setup was taken apart in order to measure and determine the voltage and current through specific components. This was done by opening and shortening the windings. However, not all components could be determined and had to be estimated. Therefore some values are estimated with output of the model in the next section and measured output current and voltage. Measured output can be characterized as a strongly damped signal with strong ringing present, especially in the first 50 μs of one period (Fig. 3).

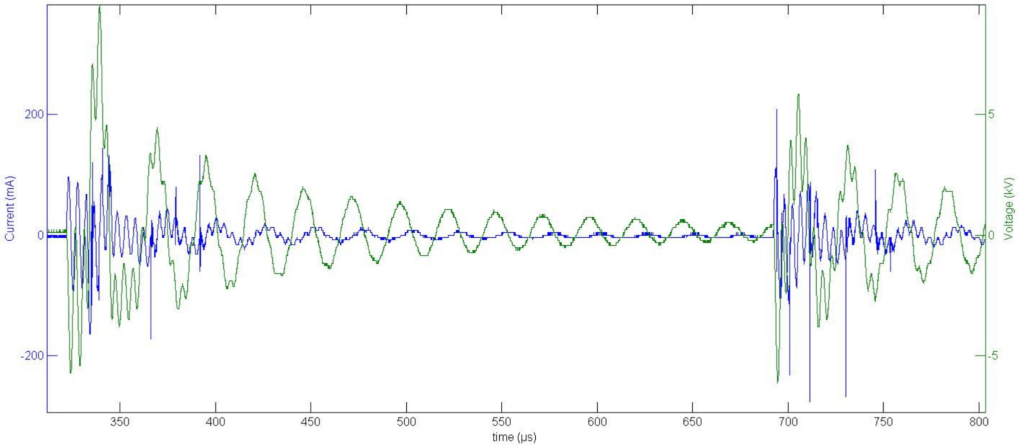

Figure 3: Measured voltage (green line) and current (blue line) as a function of time for 1500 Hz input, the duty cycle was 50%. As a dielectric the quartz is used. There is no plasma present, the interelectrode distance was 0.5 mm behind cut off distance. This distance is 4.86 mm +/- 0.05 mm.

The electric scheme is from Fridman, who used the same device (Fig. 4) [2]. The circuit can globally be divided in three parts. The first part produces a pulse with rise time t_{1r}, pulse width t_{1w} and frequency f_1. This is determined by analyzing the output voltage and the structure of the circuit. The values of these variables are unknown and fixed. The purpose of this part of the scheme is to charge the capacitors in the second part of the scheme. The left capacitor C_1 had a capacitance of 1.1 mF. The right capacitance C_2 was very small in order to protect the diode bridge, in the order of nF. The charge on the capacitors in the second part of the scheme build up in one period will discharge with frequency f_2. This frequency is determined by the diode bridge, which transforms the AC voltage to a pulsed DC voltage. This frequency f_2 is controllable, as mentioned in the section before and could be varied in a range of 50 Hz to 3500 Hz. The pulsed DC voltage is transformed by a transformer to a high voltage signal. The primary coil of this transformer has 12 windings with an unknown inductance. The secondary coil has an unknown amount of windings with an inductance of approximately 90.5 mH. Part 3 of the scheme consists mainly of the load and the oscilloscope and a voltage and current probe in order to measure the output. The load consists of a capacitance C_{gap} in accordance with the air gap between electrode and dielectric. When a plasma is present, an extra resistance R_{plasma} parallel to this load is added to the electrical scheme. An overview of all these variables, their values and position in the part of the scheme is given [A3].

In order to determine a valid approximation of C_{gap} the driven electrode and the surface treatment are assumed to behave as a parallel plate capacitor (1). In this formula ε is the permittivity. This is defined as the product of the relative permittivity ε_r and the vacuum permittivity ε_0. A is the area of the driven electrode and d the distance between the plates. When taking an interelectrode distance d of 2 mm and calculating the surface of the electrode with a fixed diameter of 1.25 cm of the copper electrode, C_{gap} could be estimated. This was 2.2 pF for the given values. When varying the interelectrode distances between 0 and 4 mm capacitances of 43 pF and 1.1 pF were calculated, respectively. When taking a distance d of 1 mm, just as Fridman, the same value for C_{gap}, 4 pF is calculated.

$$C_{gap} = \frac{\varepsilon A}{d} = \frac{8.85 * 10^{-12} * 1 * \pi * (1.25 * 10^{-2})^2}{2 * 10^{-3}} = 2.2\,pF \quad (1)$$

Due to the ringing of the voltage and current signals, R_{plasma} could not be determined by integrating the product of current and voltage. Therefore, R_{plasma} is approximated by a model, this model is described in the next paragraph. Fridman found values of 5 - 10 MΩ for R_{plasma} [2].

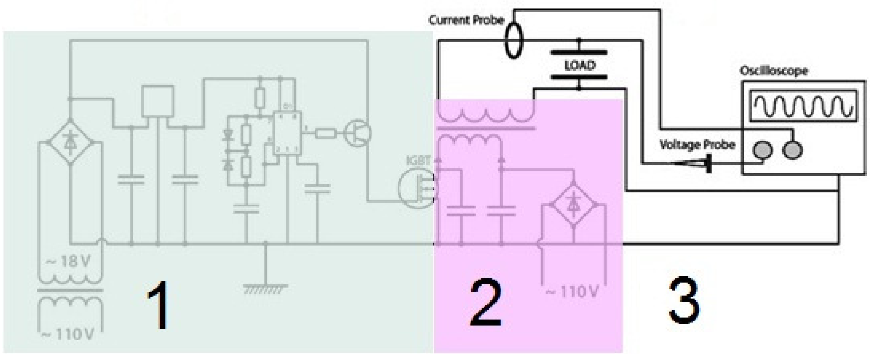

Figure 4: The electrical scheme of the DBD. Part 1 is marked green, part 2 is marked pink, part 3 is not marked. This is valid when no plasma is present.

Model

To gain more insight in the signal output of this setup a circuit was developed in collaboration with dr.ir. E.J.M. van Heesch of the faculty of Electrical Engineering at Eindhoven University of Technology (Fig. 5). This model is evaluated with the software Microcap [1]. The circuit can globally be divided in three parts. The first part consists of V_{in}, R_{in}, SW_{in} and V_{sw}. This part generates a pulse signal of about 100 V with a period of about 1 ms (Fig 6). For this output a pulse width of 1 µs is taken. The value of C_1 was determined to be 1.1 mF. This ensures a quick charge of the capacitor C_1, because a small RC time is achieved. This because product of R_{in} and C_1 gives the charge time t_{charge} which is in the order of µs, small enough to ensure a full charge of C_1 compared with f_2. The value of C_2 was estimated to be 1 nF. The purpose of the C_2 in the circuit was to protect the switch. Pulse width t_{2w} and frequency f_2 of SW_{main} can be regulated. The pulse width t_{2w} can be varied between 0 and 10 µs and the frequency f_2 between 50 and 3500 Hz, just as the power source described in the setup section. V_2 was taken to be 5 V, this suits the measured output the best. Transformer K_1 transforms the signal to a high voltage signal. For the coupling coefficient k a value of 0.99 was taken, for the inductance of the primary winding 15 mH. Again, these values were determined by analyzing the model output and the measured output signals. The model made clear adjusting the value of one inductance influences the frequency of f_3 and the damping. The third part of the electrical scheme consists of a small capacitance C_3 of 20 pF placed in parallel with C_{gap} and R_{plasma}. The small capacitance is again for protection of the other components and has negligible influence on the amplitude of the voltage and current. For $R_{plasma.}$ Values in a range from about 500kΩ up to about 1 MΩ suit the model best. The measured voltage then shows the same trend as the modeled voltage. When R_{plasma} is left out of the model, so only the capacitance C_{gap} is presence, the model does not give an output which corresponds to the measured values. For values of R_{plasma} in the order of Ω, there is hardly any damping in the system and the frequency f_3 is too high compared with measured values. Frequency f_4 is defined as the ringing frequency (Fig. 8).

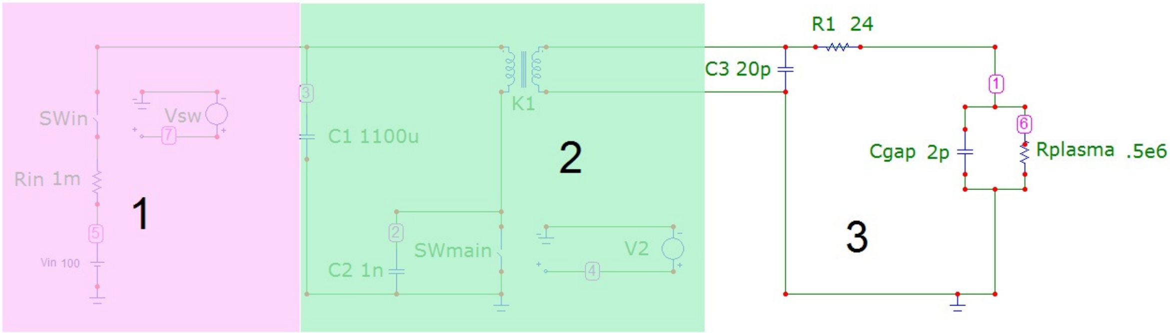

Figure 5: The model of the setup of the DBD. The components are shown in this model accompanied with their values. The numbers in the red box on the wires indicate nodes at which output signals could be evaluated.

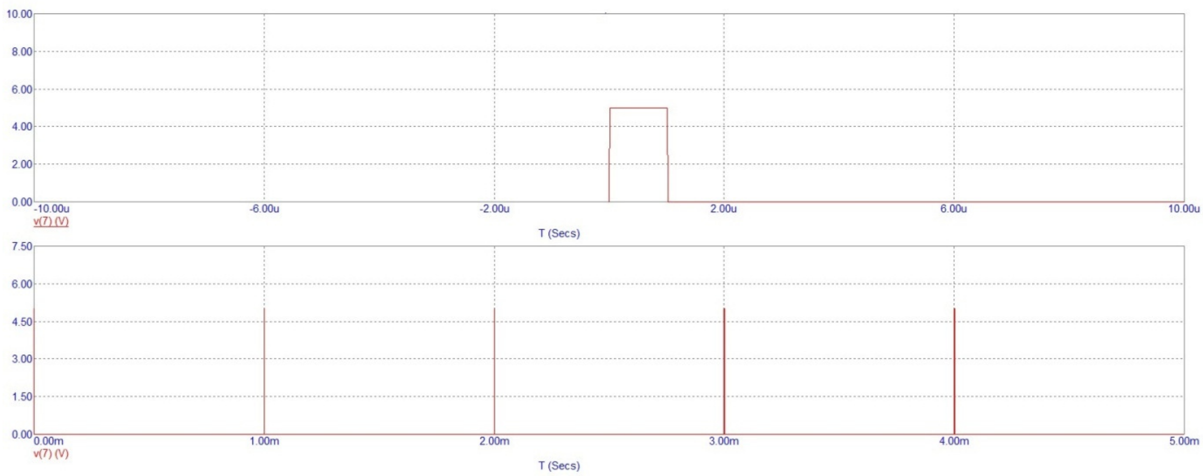

Figure 6: Output model at node 7 of Figure 5. The top figure shows the pulse with pulse width 1 µs. The bottom figure shows a frequency of 1000 Hz.

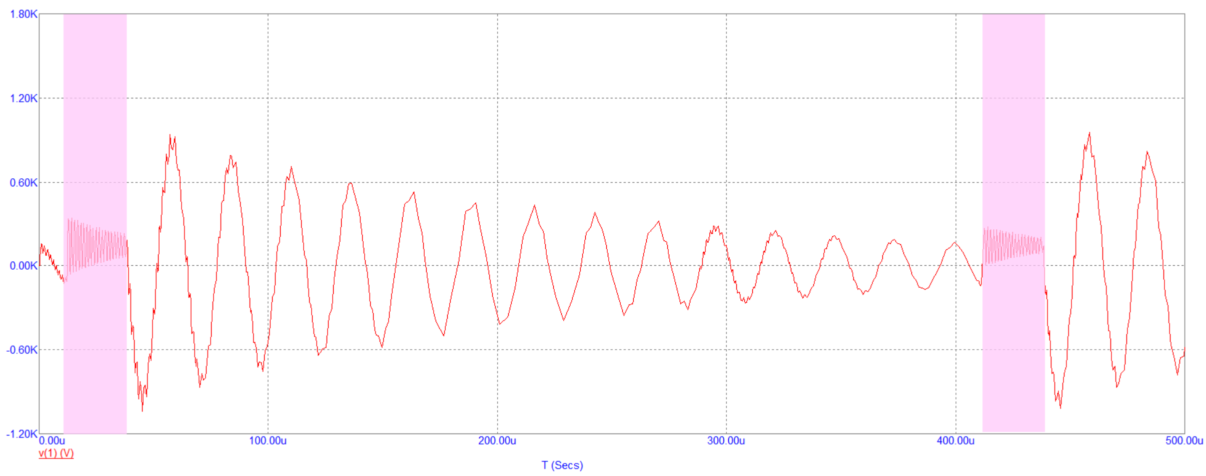

Figure 7: Model output at node 1 (Fig. 4) at 2500 Hz. The pink marked area indicates the first mode of the signal.

This model is used to understand the output voltage and current, described in the results section. The simulated voltage output, determined at node 1, has clearly two modes (Fig. 7). The first mode occurs in a very short time range, according to the model this is the quick oscillation that occurs in the first 30 µs (Fig. 8). In experiments this mode is hardly present. Therefore, this mode is not relevant to this research. According to the model the frequency f_3 of the signal in mode 1 is dependent of the coupling coefficient of the transformer. However, this adjustment causes also the frequency of the ringing of the voltage output in mode 2 to increase to frequencies higher than the measured ones. The amplitude of this mode is dependent of the value of C_3, decreasing C_3 leads to a smaller amplitude of the voltage in that mode. However, this causes the amplitude of the ringing of the voltage output in mode 2 to decrease to values lower than the measured ones. Measuring and determining these variables, by for example unraveling the high voltage power source further, should lead to a better model. The other mode differs from measured outputs in amplitude and slightly in ringing amplitude (Fig. 3). This can also be seen in the results section.

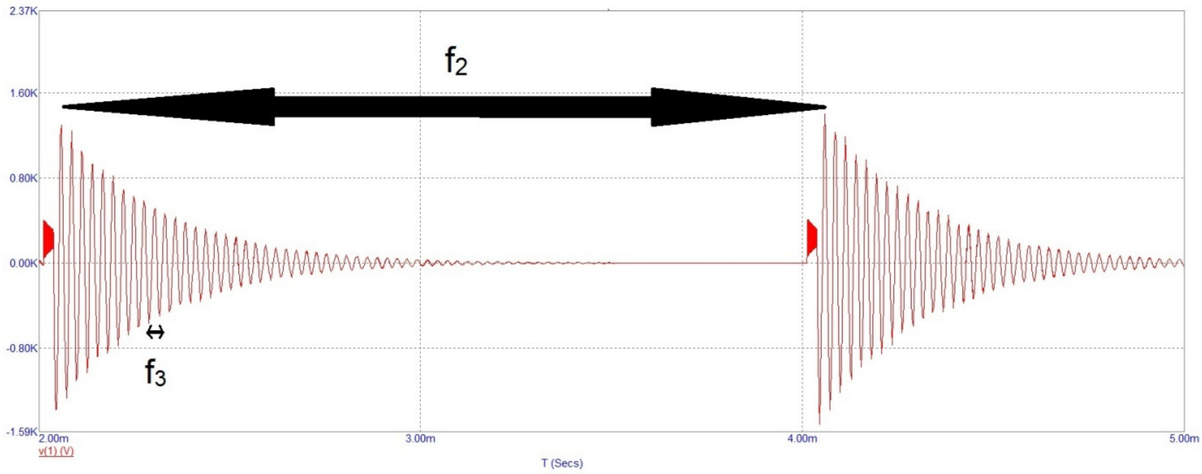

Figure 8: Model output at node 1 at ms time scale. Frequencies f_2 and f_3 are defined as indicated in the figure. The frequency f_4 is defined as the ringing frequency, better observed in the model output on a smaller time scale in figure 5 or in the setup output in figure 7.

Spectrum analysis

With the Avantes AvaSpec-USB2 Fiber Optic Spectrometer the emission spectrum of the plasma in the range 200 to 900 nm was measured. This is done by using quartz-glass as a dielectric and by putting the sensor beneath the quartz and the mesh to collect the light (Fig. 1). The interelectrode distance was 3.40 mm +/- 0.05 mm, for this distance there was a strong plasma present. Due to possible corona discharges in the holder and power loss in the cable, which was not isolated well enough, power loss was inevitable. The spectra of two different frequencies were measured; 1 kHz and 2.5 kHz. The duty cycle of the plasma was 100% and the pulse width t_{1w} was 10 µs.

The temperature is a very useful parameter to know whether the plasma can be used on human tissue, as already mentioned in the introduction. In order to determine this a high resolution spectrum of N_2 (C – B) at 337 nm was measured, which is a good method for determining the rotational temperature of the nitrogen molecules. A Jobin Yvon Monochromator is used for this measurement. With an optical fiber the signal is transferred to the monochromator. The sensor was positioned on the side of the plasma. This is put there to be sure enough light was collected. Due to the mesh and quartz, not enough light could be collected when positioning the sensor beneath the mesh. The power source configuration was the same as with the Avantes Spectrometer measurements, only the frequency used was 1.5 kHz instead of 2.5 kHz. During 360 seconds the emission of the plasma was collected. The obtained rotational spectrum was processed and compared with a simulated spectrum using the software Specair [7]. By calculating and comparing the measurement with higher and lower simulated rotational temperature spectra an uncertainty in the temperature is determined.

Results and Discussion

Frequency dependency

For quartz the frequency f_2 of the high voltage are altered between 50 and 2500 Hz. This was at an interelectrode distance of 4.58 mm +/- 0.05 mm, while the cut off distance is 4.08 mm +/- 0.05 mm for 50 Hz. For 2500 Hz, the distance was 4.99 mm +/- 0.05 mm while the cut off distance is 4.49 mm +/- 0.05 mm (Fig. 9). There was no plasma present, the distance was 0.5 mm behind the cut off distances. A figure for 500 Hz can be found in [A6]. There are two main effects of altering the frequency of the high voltage. The first and most obvious effect is the length of one period corresponding with f_2.The second effect is much more subtle, a change of frequency from 2500 Hz to 50 Hz corresponds to a slight decrease of frequency f_3. By applying a Fast Fourier transformation to create a periodogram these frequencies appeared to be very close to each other, 38.2 kHz and 38.9 kHz, respectively [A5]. The predicted output of the model shows the same trend (Fig. 10). When compared with the earlier predicted output at 2500 Hz also a similar frequency shift of f_2 occurs.

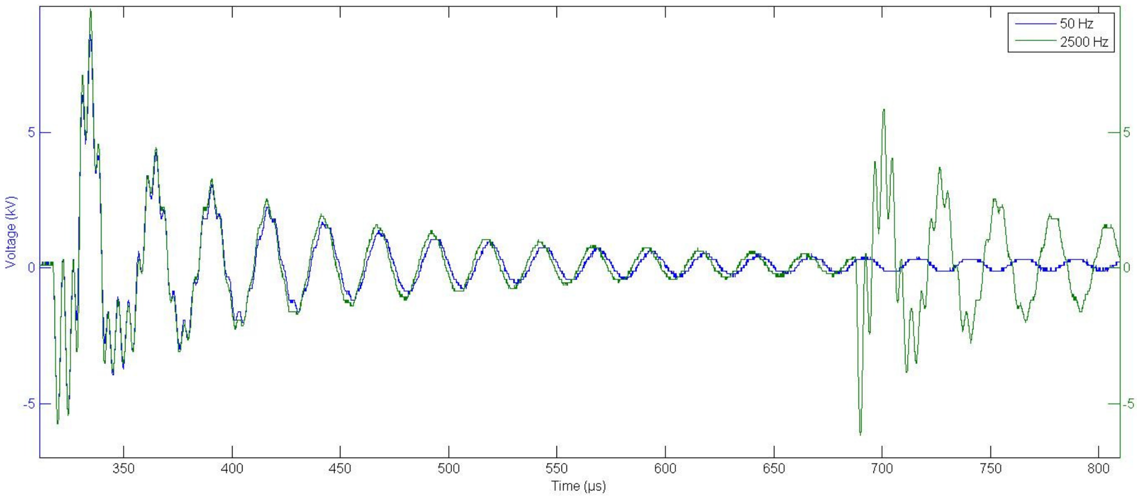

Figure 9: Measured voltage as a function of time for 2 different frequencies, 50 Hz and 2500 Hz, the duty cycle was 50%. Interelectrode distance was 50 mm behind cut off distance in order to validly compare both figures. There was no plasma present.

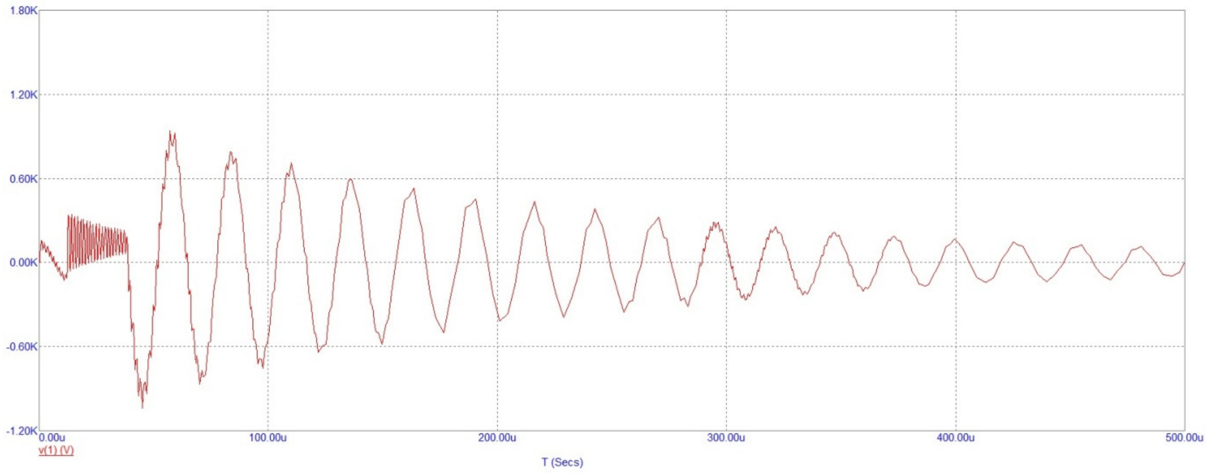

Figure 10: Output produced by microcap with frequency 50 Hz, the duty cycle was 50%.

Also the current is measured for 50 Hz and 2500 Hz, this was measured at the same distances as the voltage measurements (Fig. 11). Also here a small frequency shift is observed. This frequency shift of f_2 also shows here. All peaks present in the figure are probably indications of micro discharges or filaments. The positions in time of the micro discharges are the same for most of all filaments for both frequencies. There are a few shifts observable. Also the direction of the discharges is opposite sometimes. Because there was no plasma present, this indicates that there are some corona discharges in the holder and cable.
Although it seems the amplitude of the voltage decreases, this is not the case (Fig. 9). The amplitude of the voltage was subject to ringing and changed every period. This behavior is also predicted by the model by looking at different consecutive periods.

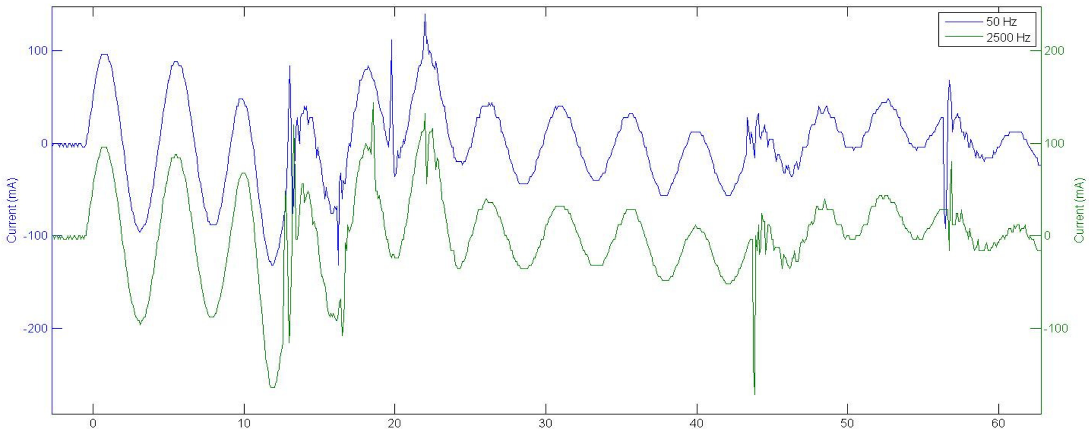

Figure 11: Measured current as a function of time for 2 different frequencies, 50 Hz and 2500 Hz, the duty cycle was 50%. Interelectrode distance was 50 mm behind cut off distance in order to validly compare both figures. There was no plasma present.

Interelectrode distance

The distance between electrode and the dielectric influences the output voltage and current. To measure the influence of the distance, fixed values for the frequency f_2, the duty cycle and the pulse width t_{1w} were used. The frequency f_2 was fixed at 2500 Hz, duty cycle fixed at 50% and pulse width t_{1w} was fixed at 10 µs (Fig. 12). The distances were varied from a touching situation and 4.99 mm +/- 0.05 mm, a distance were there was no plasma present.

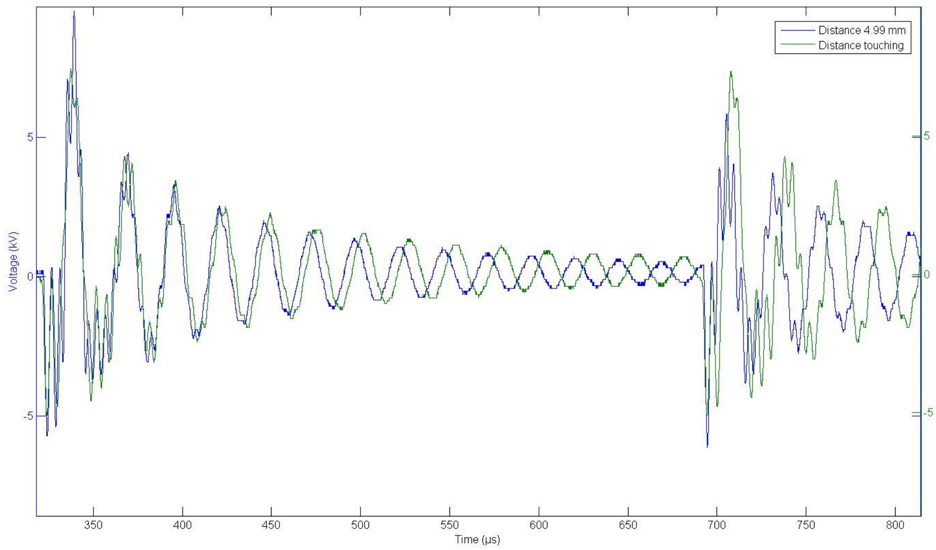

Figure 12: The output voltage as a function of time. The green line indicates the voltage when the electrode touches the quartz. The blue line indicates the voltage where the distance between electrode and the quartz is 4.99 mm +/- 0.05 m when there is no plasma. The frequency is 2500 Hz.

When the distance of the electrode and the dielectric increases the amount of micro discharges of the plasma reduces until it disappears after a certain distance. When this happens R_{plasma} will reduce and C_{gap} will increase. C_{gap} is varied from 1 pF to 50 pF, as calculated by the parallel plate assumption in the electrical scheme section. R_{plasma} was varied from 500 kΩ to 1.1 MΩ, these values were determined in the model section and turned out to give a representative output voltage. This increase of C_{gap} causes a small phase shift, which can be estimated as a decrease of 1/30th of a period of frequency f_3. This can be seen better in the periodogram, defined as the fast Fourier transform of the voltage signals of both measured voltages at touching distance and 4.99 mm +/- 0.05 mm (Fig. 13 and 14). The decrease in f_2 is too small to notice in both periodograms. Increasing the distance between the electrode and dielectric, meaning increasing the capacitance C_{gap}, results in a more broad collection of peaks around 40 kHz. This relatively small shift indicates that the repetition frequency f_2 is responsible for the behavior of the plasma. When the distance between electrode and the dielectric decreases, the highest frequency component f_4, the ringing, decreases from 235 kHz to 200 kHz.

In the micro-cap model also a periodogram could be calculated, there also peaks around 40 kHz were visible. This was done for a value of R_{plasma} of 500 kΩ and C_{gap} is 50 pF and a value for R_{plasma} of 1.1 MΩ and a value for C_{gap} is 1 pF. These combinations represent the situation with no plasma and the touching situation, respectively. When decreasing C_{gap} even more, the model was not representative anymore. It can also be seen that the amplitude of the ringing with frequency f_4 increases when increasing C_{gap} to 50 pF and decreasing R_{plasma} to 500 kΩ and also the ringing damps out slower than in the other limit [A7]. When comparing this with the measured figure this can be confirmed (Fig. 12). The model also predicts a slight decrease in the high frequency component f_4 visible in the periodogram, when adjusting the values for C_{gap} and R_{plasma}, just as observed (Fig. 12). The accuracy of the periodogram of the model was too low to produce a comparable figure, but the same trend was visible. As a result of this, predicted absolute values of the shift of frequency f_2 could not be determined with the model, this shift was too small to notice due to low accuracy.

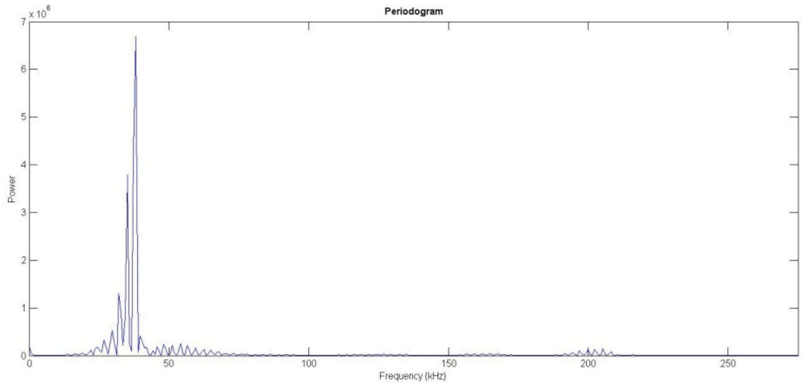

Figure 13: Periodogram of the plasma at 2500 Hz, when touching the plasma. This is calculated with a Fast Fourier Transform.

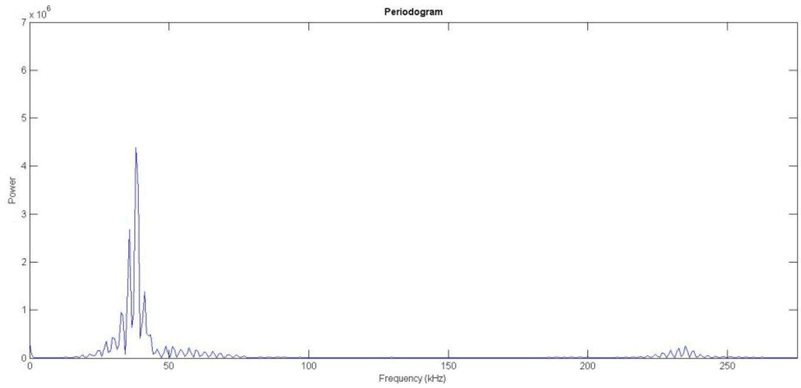

Figure 14: Periodogram of the plasma at 2500 Hz, at a distance of 4.99 mm +/- 0.05 mm, which was 0.5 mm behind cut off distance. This is calculated with a Fast Fourier Transform.

Cut-off distance as a function of frequency

For both aluminum and glass the cut off distance as a function of the frequency was determined (Fig. 15). The cut off distances of both aluminum and glass increase as a function of frequency until about 1 kHz. At a certain frequency around 1 kHz a saturation frequency is reached for glass. This means that when the frequency becomes higher than the saturation frequency the cut off distance stays constant. For aluminum the cut off distance at 1,5 kHz decreases, for glass the cut off distance remains about the same (Fig. 16). Due to the high uncertainty of the cut off distances for aluminum the same behavior as glass is possible. The RC time of capacitor C_1 was small enough to ensure a full charge of the capacitor.

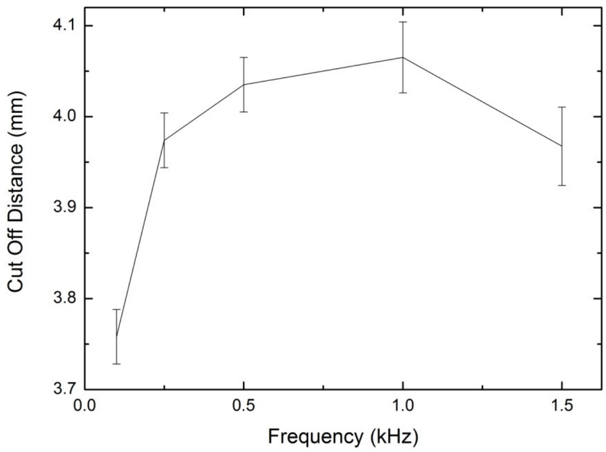

Figure 15: Cut off distance as a function of frequency by a discharge on aluminum.

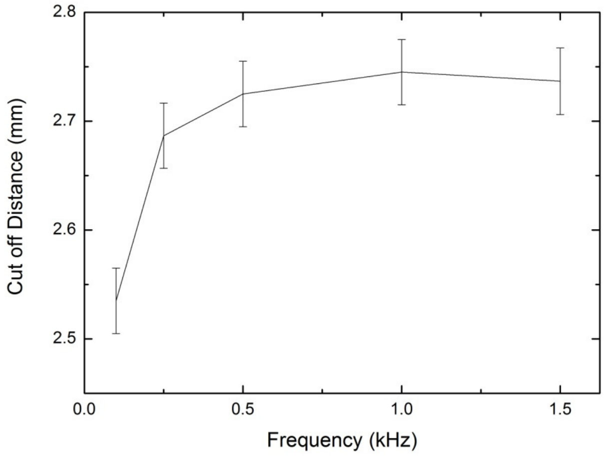

Figure 16: Cut off distance as a function of frequency by discharge on glass

By comparing the maximal voltage as a function of frequency for glass and aluminum the same trend as observed in the cut off distance as a function of frequency is observed (Fig. 17). Because of this the value of the maximum voltage is probably the main factor explaining the behavior of the cut off distance as a function of frequency. Earlier research by Nijdam also showed that at relatively low values of the repetition frequency, even in the order of Hz, the frequency influences the morphology of the plasma [10]. Therefore, also the frequency is still an important factor.

It can be seen the same saturation voltage is achieved for both aluminum and glass. Only for aluminum this is at a higher frequency compared with glass. An explanation could be the found in the difference in interelectrode distance. Because a higher interelectrode distance means a higher value of C_{gap}, a higher frequency is required to achieve the saturation maximal voltage. The difference in maximum voltage between 50 Hz and 1 kHz show at which position this maximum voltage is determined (Fig. 18).

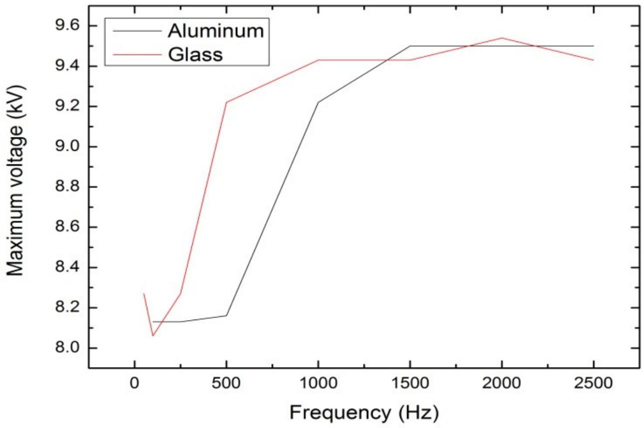

Figure 17: Maximum voltage as a function of frequency by a discharge on glass. Voltages are measured at cut off inter electrode distances, of which the values are plotted as a function of frequency in Fig. 16.

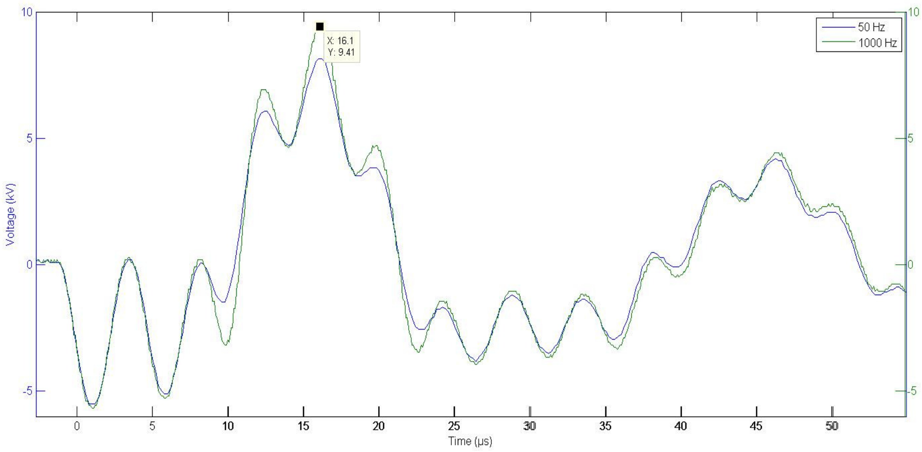

Figure 18: Voltage at cut – off distances for 50 Hz (blue line) and 1000 Hz (green line) for aluminum. The black dot indicates the position what value was taken for the maximum voltage.

Homogeneity

In order to achieve a homogeneous discharge, the discharge requires specific conditions. Kanazawa showed that in order to obtain a stable plasma a frequency f_2 of at least 1 kHz should be imposed [11]. Besides that, a homogeneous discharge should not have any filaments at all [8]. This is hard to determine by images, because a homogeneous looking plasma can exist of a lot of crowded filaments. By looking at the current signal, this can be determined better.

Two materials have been used to as a second electrode for the discharge; aluminum and quartz. The current output of the aluminum contains a lot of filaments. These filaments correspond with a breakdown in the gas gap. According to Kuchenbecker in every first quarter of a period one breakdown occurs [3]. The results show a somewhat different pattern, the breakdowns occur at more irregular moments during one period. However, this is difficult to observe because every filament is succeeded by strong ringing and noise (Fig. 19). Because the difference in distance is small, 1 mm, only a very small phase shift occurred. When performing the same measurement for quartz, but for a greater distance difference, this phase shift can be seen better [A4]. Also more filaments can be seen there when decreasing the distance between electrode and dielectric. To understand the homogeneity better, for two different distances the current output was measured. The first was 4.06 mm +/- 0.05 mm, the second 3.56 mm +/- 0.05 mm between electrode and aluminum. In general, more intense filaments occur at the closer distance. Massines observes micro discharges in the first couple of periods before a relatively stable and homogeneous current arises when applying a repetition frequency of 10 kHz [8]. They subscribe it to a memory effect. When looking at the results, this effect cannot be confirmed by the found results. In contrary, at the greater distance 4.06 mm, one big peak at about 18 µs can be noticed. This corresponds to a relatively big filament. These measurements show that the plasma still is filamentary no matter the distance, also when the electrode touches the dielectric [A4].

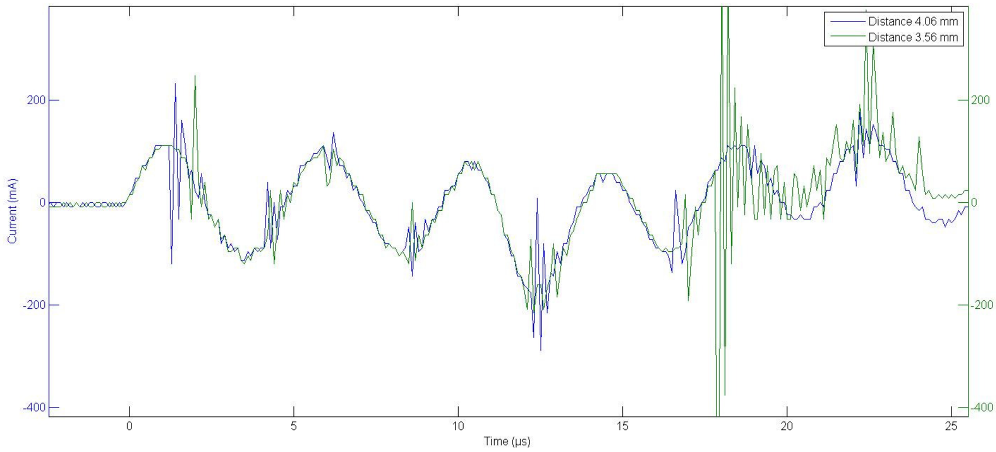

Figure 19: The first five periods of current as a function of time with aluminum. The interelectrode distances were 4.06 mm +/- 0.05 mm and 3.56 mm +/- 0.05 mm. The cut off distance was 4.56 mm +/- 0.05 mm. The frequency was 2 kHz.

The kind of material is also an important factor on the morphology of the plasma. When using a metal, all charge will immediately go to ground while surface charges will occur at dielectrics like quartz. In order to see how this influences the current output, at the same interelectrode distance the current is plotted (Fig. 20). Because of the unknown power loss in the cable and holder, for the interelectrode distance the cut off distance is taken. This assures a valid comparison between the two different materials.

In the figure it can be seen that the peaks occur at about the same time points. Only the amplitudes of the filaments differ significantly. Some differences can be adjusted to the fact that aluminum is a conductor and quartz a dielectric material. All charge transported by a filaments to a conductor will immediately be transported to the ground. When a filament reaches the surface of a dielectric, charge will build up on this surface of the dielectric. This will induce an electric field opposite to the initial electric field. Therefore the filament will break down faster at a dielectric than at a conductor, where no charge is build up. This explains the slightly stronger filaments of aluminum relative to the filaments measured by quartz as an second electrode.

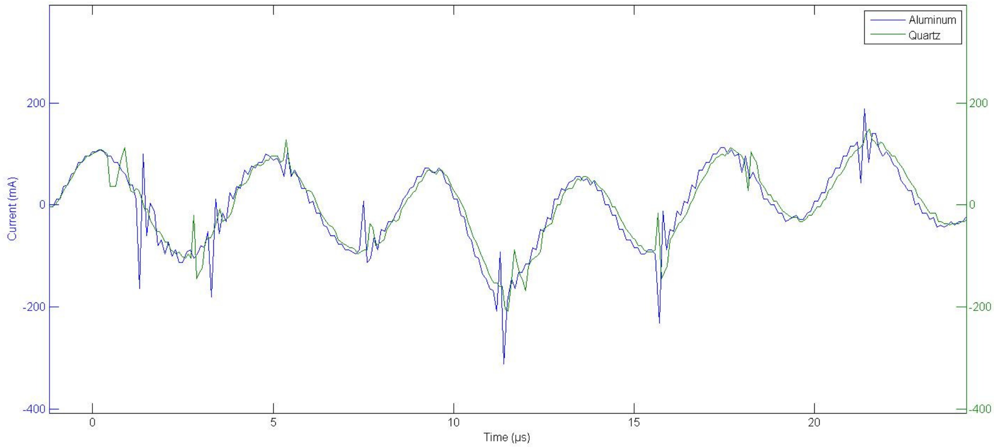

Figure 20: The first five periods of current as a function of time on aluminum and quartz. The interelectrode distance was equal to the cut off distance, for each material separately determined. For aluminum this was 4.56 mm +/- 0.05 mm, for quartz it was 4.23 mm +/- 0.05 mm. The frequency was 2 kHz.

To give a general image of the discharge, a picture with a normal CCD camera was made (Fig. 21). In order to collect enough light, an exposure time of a couple of seconds was necessary to take a good image. There are some filaments visible at the side of the quartz. In the middle of the quartz there is very little contrast. However, the measurements showed that the plasma there also consists of crowded filaments.

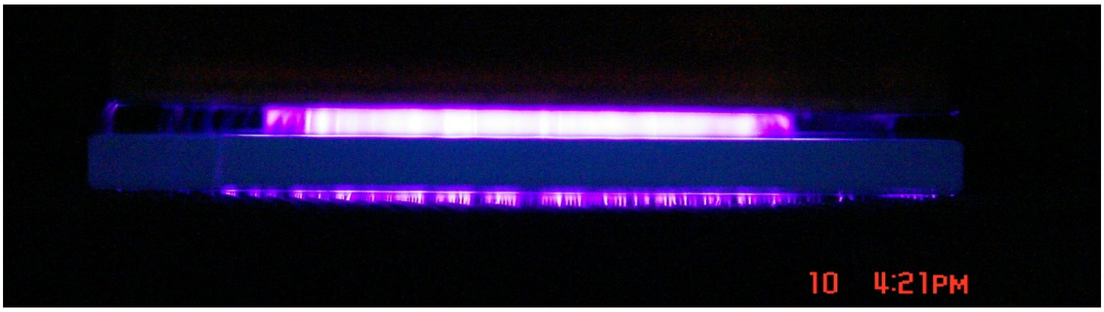

Figure 21: Discharge on the quartz at 2500 Hz. Also the discharge of the quartz on the mesh is visualized in the lower part of the picture.

Remarkable is the plasma between the quartz and the mesh. Because the mesh touched the quartz at both sides [A2], it was expected the charge would go to the mesh and the ground via the surface of the quartz. However, it turns out the induced electrical field by the copper electrode is high enough to create plasma from the quartz to the mesh.

Spectrum analysis

The highest peaks in the spectrum occur at 337 nm, 357 nm and 315 nm (Fig. 22). These peaks in the range of 300-400 nm indicate transitions in the second positive system of N_2 C→ B. [4] Because no intensity is observed below 310 nm, no significant OH emission is produced by the discharge. Therefore this peak is not observed any further. The peak at 357 nm indicates a transition between vibrational state 0 to vibrational state 1, indicated as (0,1) [4]. Other significant vibrational transitions are also indicated in the figure.

In general the plasma generated with a frequency f_2 of 2.5 has a higher intensity when compared with plasma generated with a frequency f_2 of 1 kHz. Almost all peaks are slightly higher at 2.5 kHz then 1 kHz (Fig. 22). Because a higher frequency means more of these cycles per unit of time, more micro discharges per unit of time will occur. Therefore the light intensity will be higher. The only exception is at the peak occurring at 337 nm. Then the intensity is higher for 1 kHz when compared with 2.5 kHz.

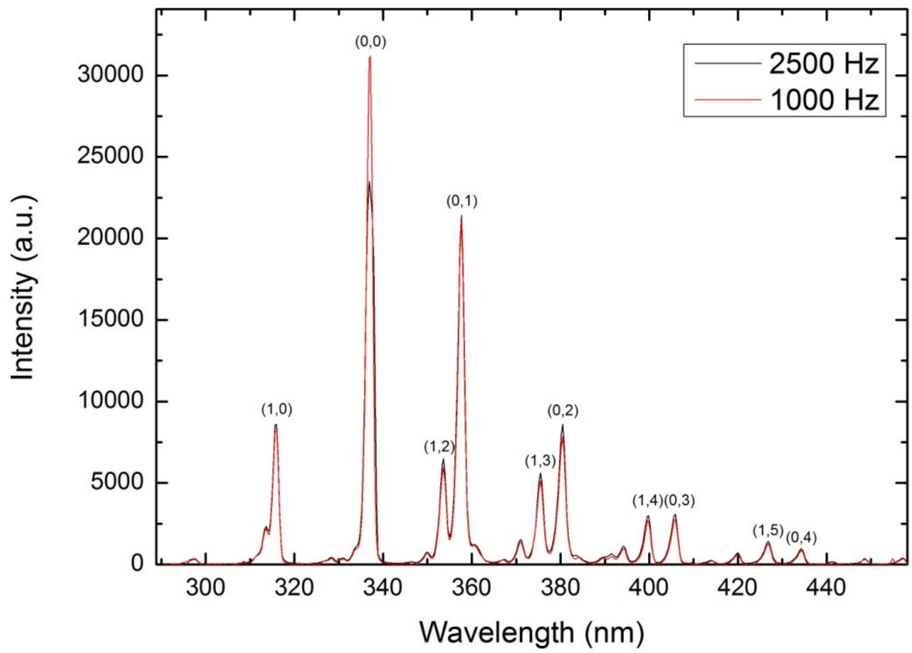

Figure 22: Spectrum of the plasma in the range where significant peaks appeared at two different frequencies

In order to calculate the gas temperature of the plasma the rotational emission spectrum at 337 nm is used to calculate the temperature (Fig. 23). This is done for a frequency f_2 of 1500 Hz. The filament temperature in the plasma was 330K +/- 20K. This uncertainty is determined by analyzing simulated spectra at higher and lower temperatures (Fig. 24). According to Kuchenbecker the gas is heated more effectively in the filaments compared with the total volume of the plasma [3]. Therefore the average gas temperature is lower than this filaments temperature, because only the emitted light of the filaments is analyzed by this method. A safe plasma jet applied on human tissue should not exceed 313K [12]. In order to validate whether this plasma is suited for treatment, spatial research on local temperatures of the tissue is necessary.

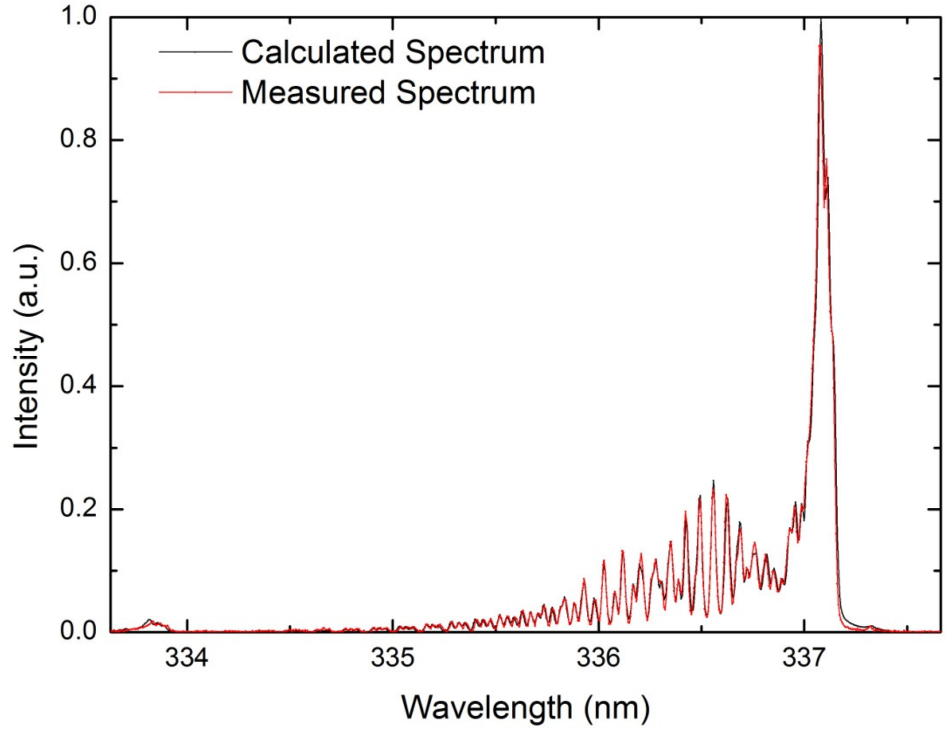

Figure 23: High resolution spectrum at 337 nanometer showing the emission of N_2

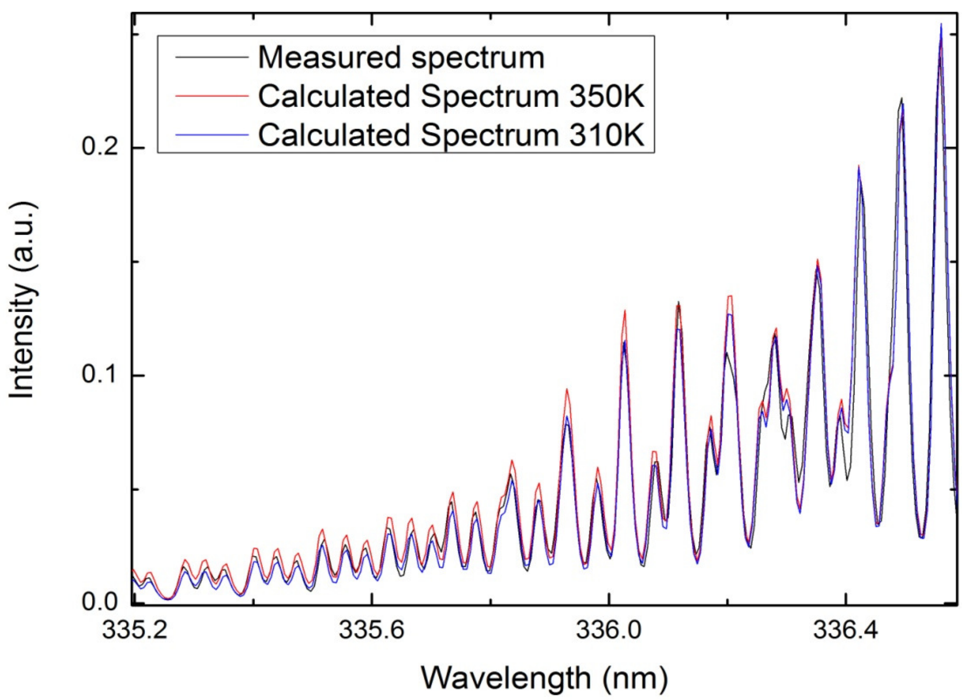

Figure 24: High resolution emission spectrum at 337 nanometer showing the emission of N_2. This figure shows the calculated spectra at 310K (blue line) and at 350K (red line) and compares the spectra with the measured spectrum.

Conclusion

The goal of this research was to characterize the DBD discharge in air under atmospheric pressure in terms of electrical and optical parameters. Previous research pointed out that treatments such as wound sterilization and blood coagulation are already successful applied. Nevertheless the setup was never characterized in detail. In this work we analyzed the voltage and current output as a function of time for different frequencies, by using different materials as second electrode, by varying the interelectrode distance and by analyzing the spectrum.

The effect of altering the frequency can be explained by looking at the output of the microcap model (Fig. 4). Two main effects can be seen in both the model and the measured output. The smallest frequency component corresponds with the repetition frequency f_2 and is the same as the input frequency. The second effect is the shift of frequency f_3 proportional to the frequency f_2. In order to see which frequencies are suited for treatment, more applied research has to be done with variation of frequency to see what effect it has on for example UV radiation or other chemical or biomedical processes.

When looking at the cut off distance for different frequencies, it can be seen the cut off distance increases until a saturation distance at a constant frequency, about 1 kHz. For aluminum a drop in cut off distance can be seen for higher frequencies than this saturation distance. The maximal voltage as a function of frequency follows the same trend for both glass and aluminum. There was no drop in maximum voltage observed at frequencies higher than 1 kHz. This indicates that the maximal voltage is an important factor in explaining the cut off distance behavior. The change of frequency also plays an important role.

Earlier researched showed that the current of a homogeneous plasma should not contain filaments at all. By looking at figures of the current homogeneity for this plasma cannot be confirmed. Results indicate that the plasma is a collection randomly distributed filaments. There was also a lot of ringing and noise in the current and voltage output, especially just after a filament occurred. Adjustments to this device are therefore required in order to control and homogeneously apply this plasma on human tissue. It also turns out the induced electrical field is high enough to create a plasma between the mesh and the quartz. This is surprising, because the charge was expected to go to mesh and ground via the surface of the quartz directly.

The visible emission spectrum of the plasma is dominated by rotational bands of N_2. By determining a high resolution emission spectrum of N_2 the filament temperature of the gas was calculated to be 330K +/- 20K. The average gas temperature is lower, because the temperature of a filament is significantly larger than the temperature of the surrounding gas. In order to safely apply this plasma to human tissue more accurate measurements of the average gas temperatures and tissue temperature should be performed. To ensure a homogeneous treatment of tissue a glow discharge should be formed without the presence of intense filaments. This will mean a safe, cold and equal treatment of the tissue.

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Appendix

[A1]

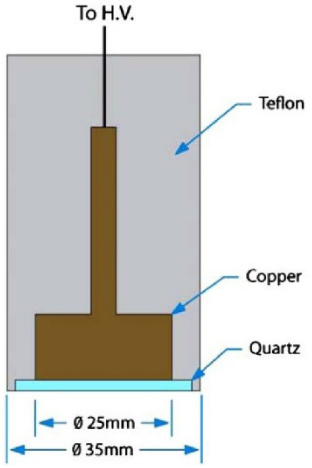

Figure 25: An illustration of the electrode, the Teflon and quartz

[A2]

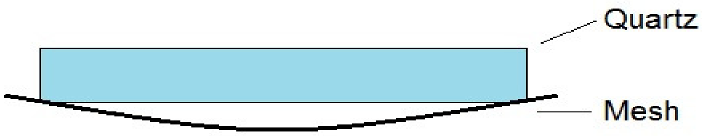

Figure 26: Illustration of the contact of the mesh and the quartz, causing plasma between the quartz and the mesh.

[A3]

Table 1: Components and specifications of the electrical scheme. Italic values are not measured but estimated or approximated.

Component	Abbreviation	Part of setup	Controllable	Typical values
Switch2	SW2	2	Frequency f_2	50-3500 Hz
Switch2	SW2	2	Pulse width	1-10 µs
Capacitance Gap	C_{gap}	3	Interelectrode distance	1-50 pF
Resistance Plasma	R_{plasma}	3	Interelectrode distance	0.5-1.1 MΩ
Transformer		2	Fixed	*15*-90 mH
Capacitance 1	C_1	2	Fixed	*1.1 mF*
Capacitance 2	C_2	2	Fixed	*20 pF*

[A4]

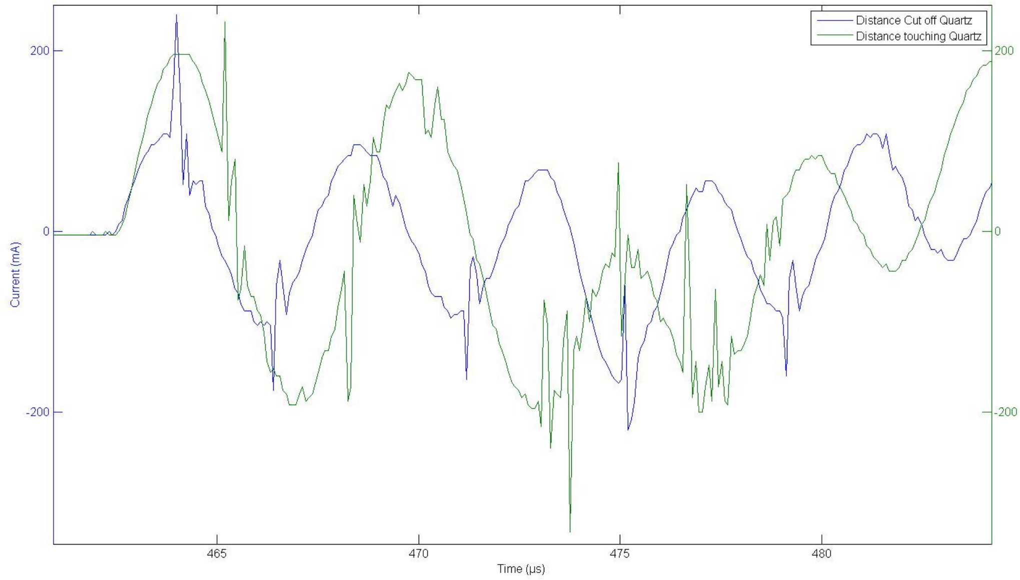

Figure 27: The first four periods of current as a function of time with quartz. The interelectrode distances were the cut off distance 4.23 mm +/- 0.05 mm and 0 mm (touching). The frequency was 2 kHz.

[A5]

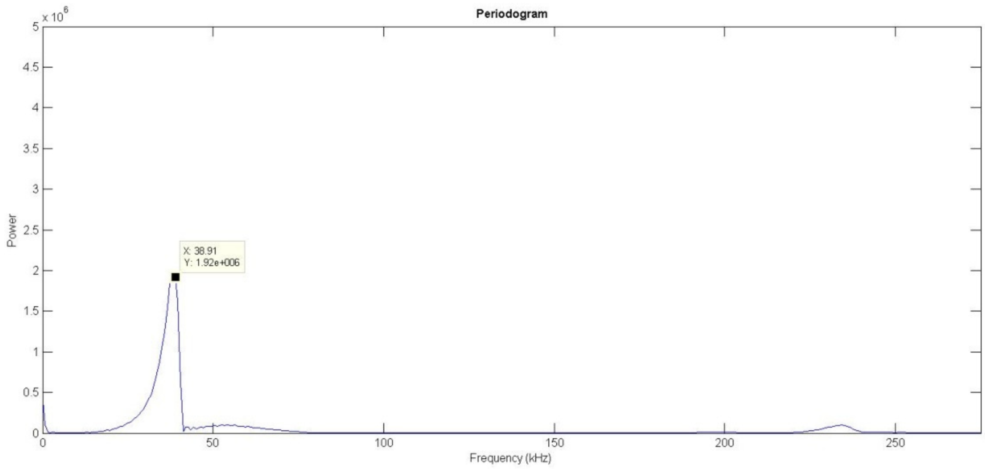

Figure 28: Periodogram of the plasma at 50 Hz, at a distance of 4.08 mm +/- 0.05 mm, which was 0.5 mm behind cut off distance. This is calculated with a Fast Fourier Transform.

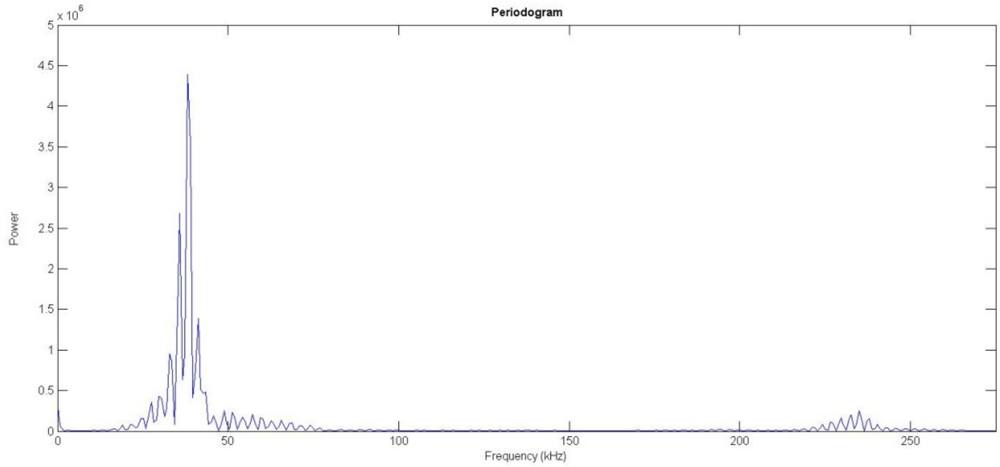

Figure 30: Periodogram of the plasma at 2500 Hz, at a distance of 4.99 mm +/- 0.05 mm, which was 0.5 mm behind cut off distance. This is calculated with a Fast Fourier Transform.

[A6]

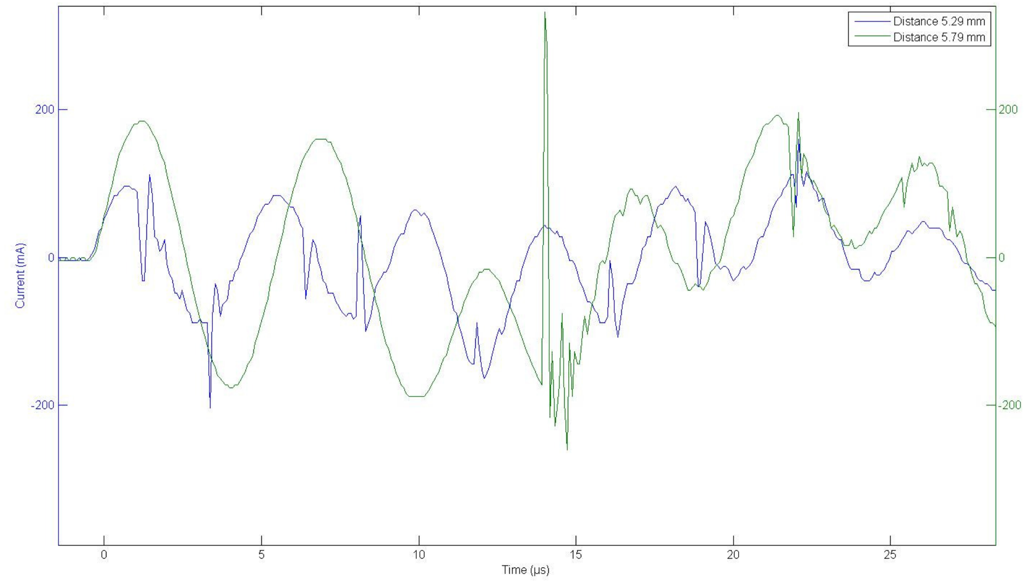

Figure 31: The first four periods of current as a function of time with quartz. The interelectrode distances were the cut off 5.29 mm +/- 0.05 mm and 5.79 mm +/- 0.05 mm. The frequency was 500 Hz.

[A7]

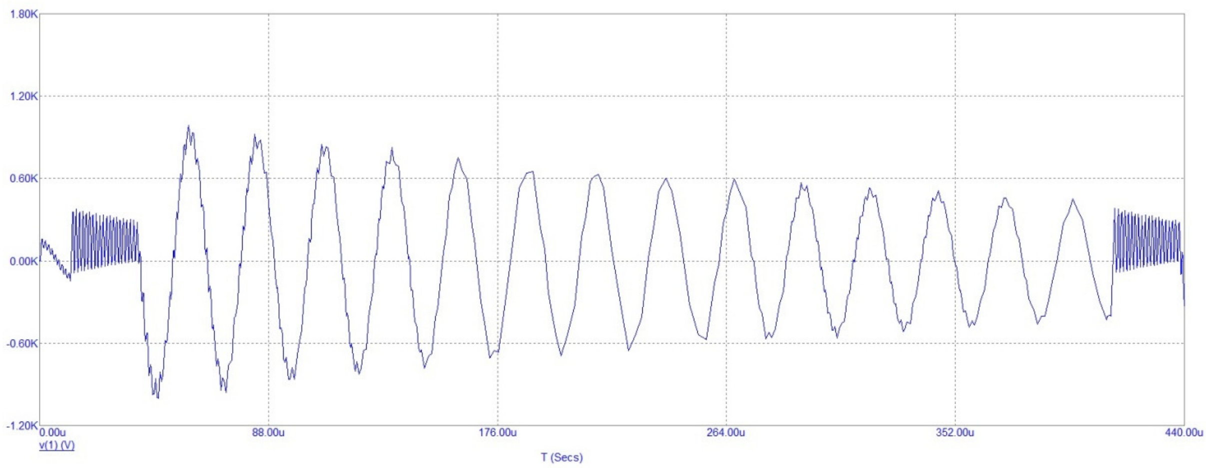

Figure 32: Model voltage output with C_{gap} is equal to 1pF and R_{plasma} equal to 1.1 MΩ.

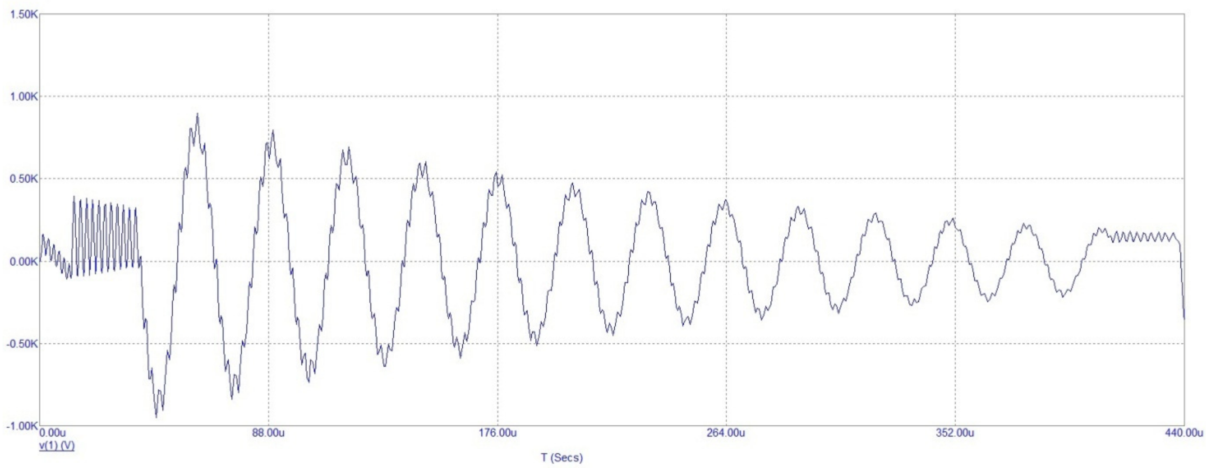

Figure 33: Model voltage output with C_{gap} is equal to 50pF and R_{plasma} equal to 0.5 MΩ.