ELECTRICAL BREAKDOWN STUDIES OF PARTIAL PRESSURE ARGON UNDER KHZ RANGE PULSE VOLTAGES

by

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Abstract

Electronics operating in a partial vacuum may experience a gaseous breakdown when strong electric fields are present. The breakdown voltage for a gas decreases as the pressure decreases from atmospheric conditions and reaches a minimum. After this minimum breakdown voltage, it starts to increase as pressure further decreases for a given fixed electrode spacing. This idea was first expressed in the early 1900's by Paschen Law. An increase in operating frequency can also cause a breakdown to occur at lower applied voltage levels. In this work, the breakdown characteristics for Argon are studied in partial vacuum from 0.1 Torr to 3 Torr. First, a dc analysis is performed for electrodes with point-plane and point-point geometries. A pressure sweep analysis is then performed for the same electrode geometries with a unipolar pulsed signal for fixed frequency in the range of 20-200 kHz with a fixed duty cycle of 50%. A frequency sweep is then performed for a range of fixed pressures from 0.1 Torr to 3 Torr. Lastly, a duty cycle sweep is performed from 10% to 90% for the same range of fixed pressures and frequencies. Data is captured during each gaseous breakdown event for analysis. The breakdown voltage characteristics are discussed as a function of the applied signal and environmental pressure.

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List of Abbreviations

milliTorr	10^{-3} Torr = .13332 Pascals (760 Torr = 1atm)
kHz	kilohertz
cm	centimeter
dc	direct current
ac	alternating current
V_{bd}	breakdown voltage (the voltage that causes plasma to form)

Chapter 1: Introduction and Background

1.1 Need for Research

Normally, air acts as an excellent insulator, but under strong electric fields, it may begin to ionize and conduct electrical current in the form of a discharge. If the field strength becomes high enough, a breakdown may occur, producing glow discharge. This highly ionized gas is known as plasma, and is a good conductor, allowing charge to easily pass across the applied voltage. Partial discharges and corona are generally considered a problem because they present energy loss in power systems and the spectral content can be a source of interference for nearby electronics (EMI). These effects can further develop into a major problem at the component level, causing insulation deterioration and component failure; and, in some cases they can turn into fully developed, highly conductive arc, which can cause a total electrical breakdown of the system.

Applications in space exploration and the aerospace industry are requiring higher power demands with higher voltage levels and increasing frequency rates. The new generation of flight and space exploration vehicles is likely to utilize higher voltages than the traditional 28 V dc for onboard power distribution. Basically these increasing power demands mean either increasing the voltage of the power supply or the current, satisfying $P=IV$. Increasing the current would mean larger and heavier wires and interconnects. Increasing size and weight are generally two things that are to be avoided in flight vehicles. Therefore designers opt to increase voltage ratings to raise the power transfer. However, at low pressures, a voltage increase could lead to power loss through corona or lead to breakdown, which could damage the power system. This is due to the fact that air at 1 atmosphere (760 Torr) is considered a good insulator; but, at lower pressures, air does not act as such a good insulator.

The availability of switching power supplies operating at higher intermediate frequencies makes it important to consider the effects of these higher operating frequencies on the formation of corona and gaseous breakdown in partial vacuum conditions. Switched-mode power supplies (SMPS) switch a power transistor between saturation and cutoff with a variable duty cycle whose average is the desired output voltage. DC-DC converters also use a switching mechanism to obtain the desired dc voltage at the output. These systems operate at much higher frequencies than that of conventional 60 Hz power systems, and are usually in excess of 20 kHz [1].

The effects of the voltage signals used in such power systems need to be studied in a partial vacuum environment to better understand and predict their operation. In particular, it will be beneficial to know what will happen to the breakdown voltage as pressure is varied and frequency is varied for a square pulse train. Similarly, it is important to know what the effects are if the duty cycle is varied at typical pressures that may be encountered in an electronic system operating in a low pressure environment. Currently, there is little data for breakdown of Argon in the 20 kHz to 200 kHz range. In a previous work, breakdown characteristics of Helium and Nitrogen were gathered under the same experimental conditions as presented in this work [2]. Although Argon is not a very common gas encountered in aerospace applications, comparison of the breakdown characteristics for Argon to those of other gases can help to gain understanding of the breakdown mechanisms associated with kHz pulsed voltages in low pressure environments.

1.2 Air as an Insulator

Air is probably the most common insulator in use today. In power transmission systems, power lines are separated by sufficient distance to prevent arcing between them. Air surrounds all electrical equipment, and is in direct contact with electrical components such as terminal blocks, switches, and interconnects on circuit boards. Apart from being all around us, the other advantage of air as an insulator is that it is "self-restoring" meaning that after a breakdown, it will return to its previous state of being a good quality insulator [3]. This is in contrast to a solid dielectric, which will remain damaged after a breakdown has occurred through the material.

For air at 1 atmosphere, the dielectric strength is 30,000 V/cm. Dielectric strength is the theoretical maximum electrical field that the dielectric can withstand before breaking down and conducting a current. So, when 30 kV/cm is applied between two electrodes in air at atmospheric pressure, a breakdown will occur. For comparison, the dielectric strength for Kapton is 7700 volts per mil, which comes out to roughly 3 million V/cm [4]. So Kapton has about 100 times the dielectric strength of air. This is a rough comparison since, as will be discussed later, a very small current may actually flow in air for small applied fields.

Consider the case for two electrodes, an anode and a cathode, separated by a distance d. Although the dielectric strength of air is 30,000 V/cm at 1 atm, a change in pressure p will change its dielectric properties. If the pressure is decreased, then the breakdown voltage will decrease to a value where the breakdown voltage will be at a minimum. Any further decrease in pressure will cause the breakdown voltage to increase. This phenomenon is very important, and is expressed in Paschen Law, which will be discussed in more detail later.

1.3 Breakdown Mechanisms

An electrical discharge across an electrode gap can either be a partial breakdown, where corona effect may be observed where the electrical field is the highest, or a breakdown. Refer to Figure 1.1 below. For an electrode gap with no external voltage supplied, there will be background ionization in the air due to cosmic rays and radiation. Close to Earth's surface, there are approximately 1000 ion-electron pairs per cubic centimeter. If the gap voltage is slightly increased to maybe a few tens of volts, a very small amount of current will flow. This is because the free electrons will drift in the air towards the anode before they can recombine. Further voltage increase will produce no more current. The current will be saturated because the rate of ionization in the air is constant so the current is limited to about 10^{-15}A. The current can only be sustained by an external ionizing mechanism. For this reason, the current is said to be non-self-sustaining. More electrons need to be ionized to get an increase in current [3, 5].

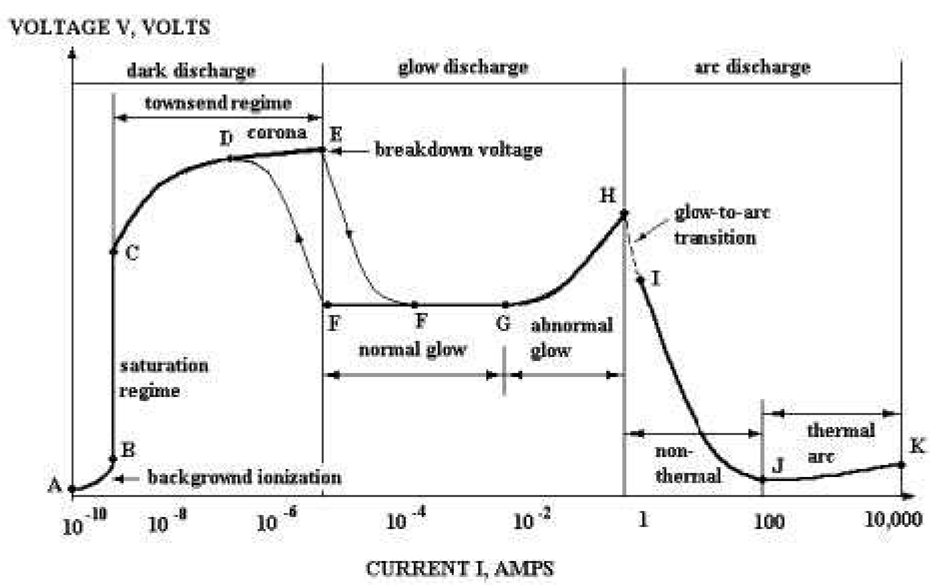


Figure 1.1: Voltage-current relationship for gaseous discharge [6].

As voltage is increased out of the saturation regime, there will be an exponential rise in current, and it will be on the order of micro-amps. This is known as the Townsend regime. More increase in voltage will cause a corona discharge, where the electrode surfaces may glow at the areas of highest electric field. This effect is sometime observable on high voltage power transmission lines and is generally not desirable since it represents a power loss.

In the corona region, there is a point at which a further increase in voltage will cause what is referred to as a breakdown. The voltage across the gap will suddenly drop and a larger current, on the order of 1mA, will flow. A conductive, electrically neutral, plasma will form between the electrodes and this region is known as the glow discharge region. The first part of the region is normal glow. The small change in voltage in this region will produce a large change in current because the "cathode fall" will tend to regulate the voltage to a constant value. Note that if the voltage is decreased then we will be back in townsend region; but, the I-V path back will not be the same as the path that was taken to get into the glow discharge region. This is known as a hysteresis curve.

At the glow discharge region, if the voltage is further increased, the discharge will enter the abnormal glow region. Here, the current increase is not exponential and requires a considerable increase in voltage. This is because the plasma starts to cover the entire cathode, so the plasma is not restricted to just the gap in between the electrodes. The voltage may increase up to a point where if the applied voltage is increased any more, the gap voltage will abruptly fall to a very small amount and a highly conductive arc will form across the channel. The voltage across the gap becomes very low as the current reaches into amps and even hundreds or thousands of amps, depending on the power supply output capability and the value of the current limiting resistor [5, 7].

A current-limiting resistor is always placed in series with the electrode gap. This is simply, a high-voltage resistor designed to limit the current to a certain value if a highly-conductive arc forms across the gap. So, for example, when the gap goes from the dark discharge region to the glow discharge region, the drop in the voltage level across the gap corresponds to a voltage increase in the current-limiting resistor.

1.4 Townsend Mechanism

As previously mentioned, a current on the order of 10^{-15} A can be obtained from background ionization. If the voltage is increased high enough, the gap will enter the Townsend region, and the current will be on the order of 1uA. For a Townsend discharge to occur there must be an electron avalanche. Avalanches are the fundamental building blocks for all types of discharges and breakdowns. When an electric field is applied across a gap, the electrons will follow the field lines toward the anode. If an electron gains enough energy, it may ionize a gas atom or molecule by colliding with it. In this situation, positive ions will be formed and the newly generated free electron together with the initial electron that collided with the molecule will proceed along the field lines and repeat the process many times. At a distance x from the cathode, the number of ionized electrons will have increased to n_x. We may now write an equation relating the change in electrons that have been ionized to the change in distance from the cathode [3].

$$dn(x) = \alpha n_x dx \quad (1)$$

The term alpha in the above equation is Townsend's first ionization coefficient. It is defined as the number of ionizing collisions made by and electron on average as it travels 1cm in the direction of the electric field. The nature of electron collisions is a statistical process and the term alpha is just an average value for the number of ionizations per unit length of electron drift along the field. In a uniform field, alpha is constant. n_0 is the initial number of electrons emitted from the cathode. It turns out that the number of electrons at distance x is given in the equation below.

$$n(x) = n_0 \exp(\alpha x) \tag{2}$$

As can be seen, equation 2 is an exponential function. This makes sense because an avalanche produces ionizations at an exponential rate due to electron impact process. So the number of ionizations at a distance x from the cathode is the product of the initial number of electrons and the exponential of the ionization rate, alpha, multiplied by the distance from the cathode.

It is important to remember that unlike a metal conductor, where the positive ions are bound together in a lattice-like structure, in a gas the ions may move. Even though they acquire much less velocity than free electrons, due to their much greater mass, they will still react to electric field lines. When positive ions hit the cathode surface, they may cause electrons from the cathode surface to combine with them and, in some cases, pull more than enough electrons from the cathode surface. Sometimes they may crash into the cathode surface hard enough to knock entire atoms out of the cathode surface. This is known as sputtering. This effect is due to a process called secondary ionization. Secondary ionization usually happens at a much smaller rate than first ionization and is expressed by the term γ. The number of secondary electrons at the cathode, beta, created by the first avalanche is given by the equation below [3].

$$\beta = \gamma(e^{\alpha d} - 1)n_0 \qquad (3)$$

If this process is not regulated, the ionization process will continue to form successive avalanches until there is a breakdown.

1.5 Glow Discharge

When an electrode gap is in the Townsend discharge region and the applied voltage is increased past threshold point E shown in Figure 1.1, the gap will enter the glow discharge region where the gap voltage is much less than in the Townsend region, and the current is now on the order of 1mA. This threshold voltage is known as the breakdown voltage, V_{bd}. This is the main quantity we are interested in finding during our experimentation. The term glow discharge was so named because parts of the discharge are luminous. The distribution of the various areas of glow discharge is shown below in Figure 1.2.

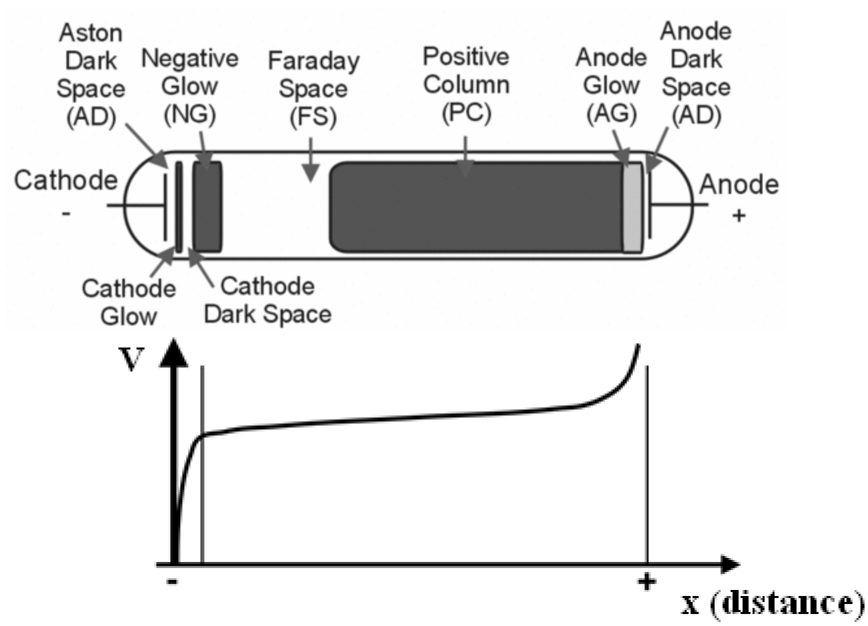


Figure 1.2: The glow discharge regions for a basic parallel plate electrode configuration.

Figure 1.2 shows the luminous and dark spaces that form during a glow discharge for a simple parallel plate setup. There are basically two main luminous regions, the cathode glow and negative glow. Cathode glow appears to be on the cathode surface. Negative glow forms between a dark space and Faraday space and is the brighter of the two luminous regions. Anode glow may also form on the anode surface. As can be seen from Figure 1.2, most of the voltage is across the region between the cathode and negative glow (also known as Crookes space), and this drop in potential energy is referred to as cathode fall. This is because a space charge of positive ions accumulates directly in front of the cathode. Positive ions strike the cathode surface, releasing electrons. The electrons will travel from the cathode to the anode and must pass through this cloud of positive ions. Passing through this region costs a lot of potential energy, as some of the electrons will recombine with the positive ions; but, when the remaining electrons make it out, they will have sufficient energy to ionize molecules and excite other electrons to generate light emission. This ionization region is the negative glow region and is typically the brightest plasma in the normal glow. It should be noted that the cathode fall voltage in the normal glow region is mainly dependent on the gas and cathode material used. It is only slightly dependent on pressure.

After electrons pass through the negative glow region, they move towards the anode quite slowly because they no longer have the energy to ionize any more molecules; they used up most of their energy in the negative glow region. This region is the Faraday dark space which extends from the negative glow to the positive column. There is no light emission in this space. The anode tends to repel positive ions in the positive column. There forms a thin space in between the anode and positive column known as a sheath. This sheath is a space charge of electrons and is from where the anode draws the electron current. The voltage across this sheath is called the anode fall and is usually much less than the cathode fall [7, 8, 9, 10].

If the current is increased out of the normal glow region, the cathode fall potential will increase and become abnormal. The electrons entering the negative glow region do so with higher velocity. The borders between glow regions and dark regions become more sharply distinguishable and glow tends to cover the cathode surface as the Aston dark space is compressed. Actually, all of the dark space is compressed because the ionization regions are becoming larger. This effect is noticeable during experiments as the glow will cover much of the electrode area and most of the gap space. If voltage is increased too much past this point, an arc breakdown will occur. This will be avoided during the experiments [7].

1.6 Paschen Law

Paschen law is used to express the breakdown voltage as a function of the product of pressure p and distance d (electrode spacing). Basically, there is a product, pd, of pressure and distance that will give the minimum breakdown voltage for a given gas. Any deviation above or below this pd value will result in a higher breakdown voltage. This is because at really low pressures, there are very few particles in the air. The mean free path is large so electron collisions are relatively infrequent, making it harder for an electron avalanche to occur. Therefore, the applied voltage must be very high to form a conducting channel. Increasing pressure above the point where the minimum breakdown voltage occurs causes an increasing breakdown voltage because there are so many particles in the air that the effective dielectric strength has increased so that it takes a high voltage to ionize them.

Equations 4 and 5 explain that the breakdown voltage, V_{bd}, is a function of pressure and distance. In equation 5, a and b are gas specific constants. They modify the shape of the curve over a range of *pd* values. Figure 1.3 shows what a typical Paschen Curve might look like for some various gases [11].

$$V_{bd} = F(pd) \tag{4}$$

$$V = \frac{a(pd)}{\ln(pd)+b} \tag{5}$$

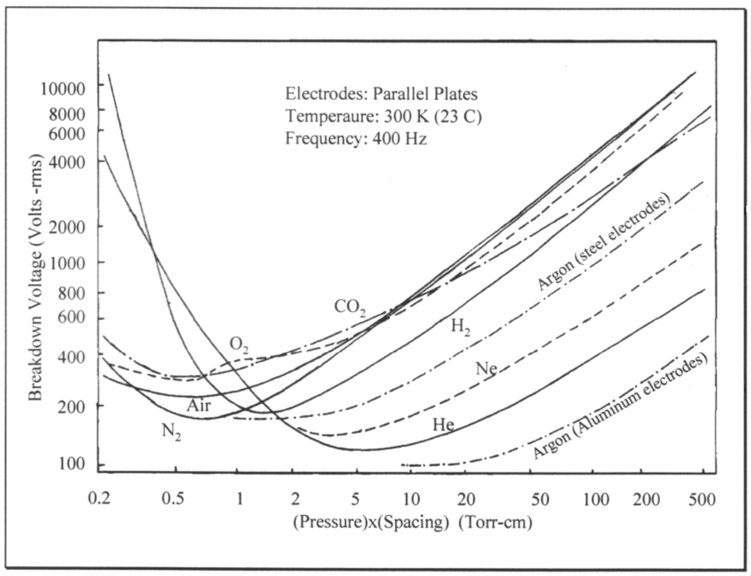


Figure 1.3: Paschen Curves for various gases [2].

1.7 Streamer Mechanism

There is another breakdown theory, aside from townsend mechanism, known as streamer, or channel mechanism. There has been much discussion as to which mechanism governs the breakdown process but now both mechanisms are accepted to operate under their own favorable conditions. Under some effects, such as corona, it seems that both mechanisms may operate. The avalanche process is intrinsic to both mechanisms of breakdown.

Townsend mechanism seems to govern only at low to moderate *pd* values, less than 200 Torr-cm. For large *pd* values say over 4000 Torr-cm, Townsend theory does not seem to accurately describe the breakdown event. Lightning is one such example. Streamer theory states that a thin ionized channel, or a streamer, forms from the anode to the cathode due to the primary and intense avalanche which leaves a thin channel of positive ions. When the avalanche crosses the gap, the electrons are swept into the anode and the positive ions remain in a cone-shaped volume extending across the gap. A dense space-charge field is concentrated near the anode but the density is less everywhere in the gap. The gas surrounding the avalanche has photo-electrons produced by the photons emitted from the densely ionized gas that makes up the avalanche stem. These photo-electrons initiate auxiliary avalanches which are directed by the external field as well as the space-charge field. Positive ions left behind by these avalanches branch off, lengthen, and intensify the space charge of the main avalanche toward the cathode. The process continues and develops a self-propagating channel which will extend from the anode to the cathode. Eventually, a path of highly ionized gas forms a conductive bridge across the entire gap [5]. It is important to note that the *pd* value during the experiments presented in this work do not exceed 3 Torr-cm so townsend mechanism gives an adequate description of the breakdown process.

1.8 Uniform and Non-uniform Fields

All of the effects of breakdown discussed can happen for electrodes with uniform or non-uniform fields. The difference is where the effects are most likely to happen. Getting an idea of the fields for different electrode configurations will help predict where a breakdown is most likely to occur.

Consider two electrodes separated by some distance. Their electric field lines may look something like what is shown in Figure 1.4. The electric field lines are perpendicular to the electrode surfaces and parallel to each other. They point from the positive plate to the negative plate. This figure ignores fringing effect that may take place at the edges.

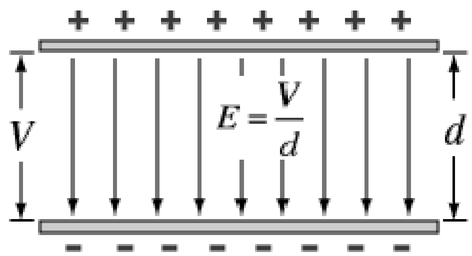


Figure 1.4: Electric field lines for parallel plate electrode configuration [12].

Not many real-life situations have electrodes that produce a uniform electric field. It is more likely that for a practical electrode configuration, there will be a non-uniform field. For this breakdown study, a point-to-point setup and point-to-plane setup will be used. The electric fields for these setups are not uniform. To get an idea of what the field will look like, computer simulation was performed. Results were obtained for both electrode setups and are shown in Figures 1.5 and 1.6. Note that for simulation purposes, the wires connecting to the anode and cathode are not shown. In the experimental setup, copper wire is actually connected to the end opposite the tip of the point electrode and the end opposite of the plate for the plane electrode.

In Figure 1.5, the lines represent the equipotential lines and the shades of color represent the electric field strength, with blue corresponding to lower E field, and red corresponding to the highest E field. Notice that the highest E field occurs where the equipotential lines are most closely spaced. This corresponds to the red region between the tip of the anode and the surface of the cathode. Sharp points and edges tend to produce the highest electric fields because the gradient of the equipotential lines is very high at such areas. One can also notice a little peaking of E field around the corners of the cathode and anode.

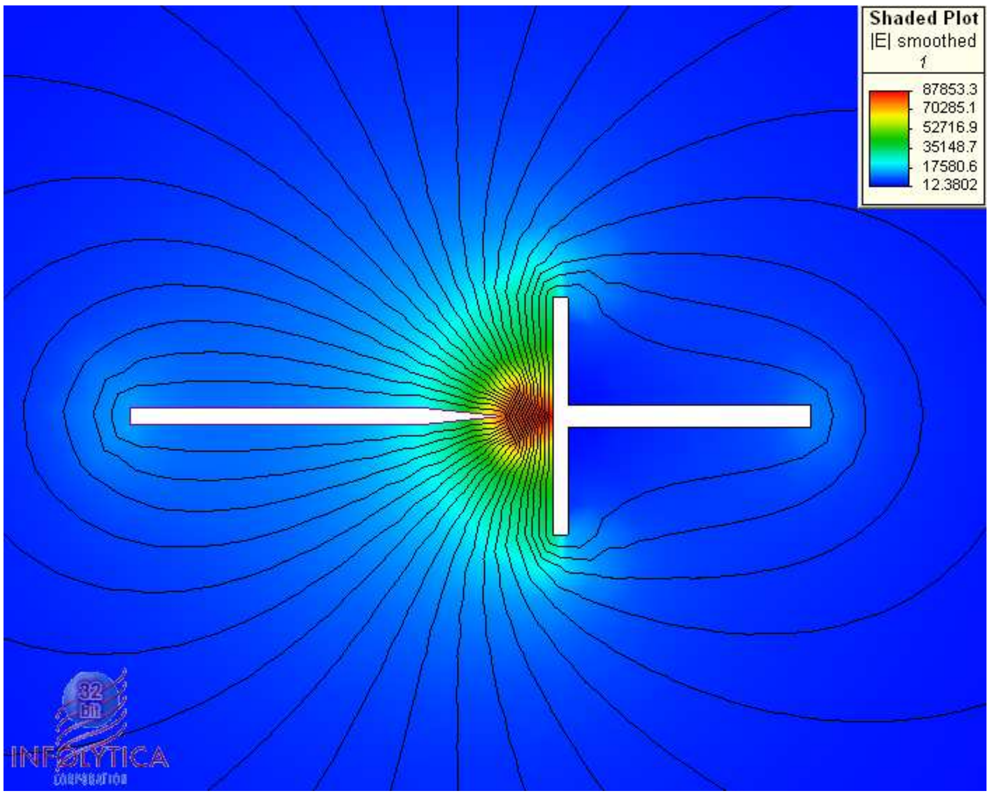


Figure 1.5: Computer simulation of electric fields for point-to-point setup [13].

Figure 1.6 is the simulation for the point-to-point electrode configuration. Here, the electric field is highest in between the electrode tips where the equipotential line gradient is the highest. During experiments, the areas on the electrodes with high fields tend to have the brightest glow.

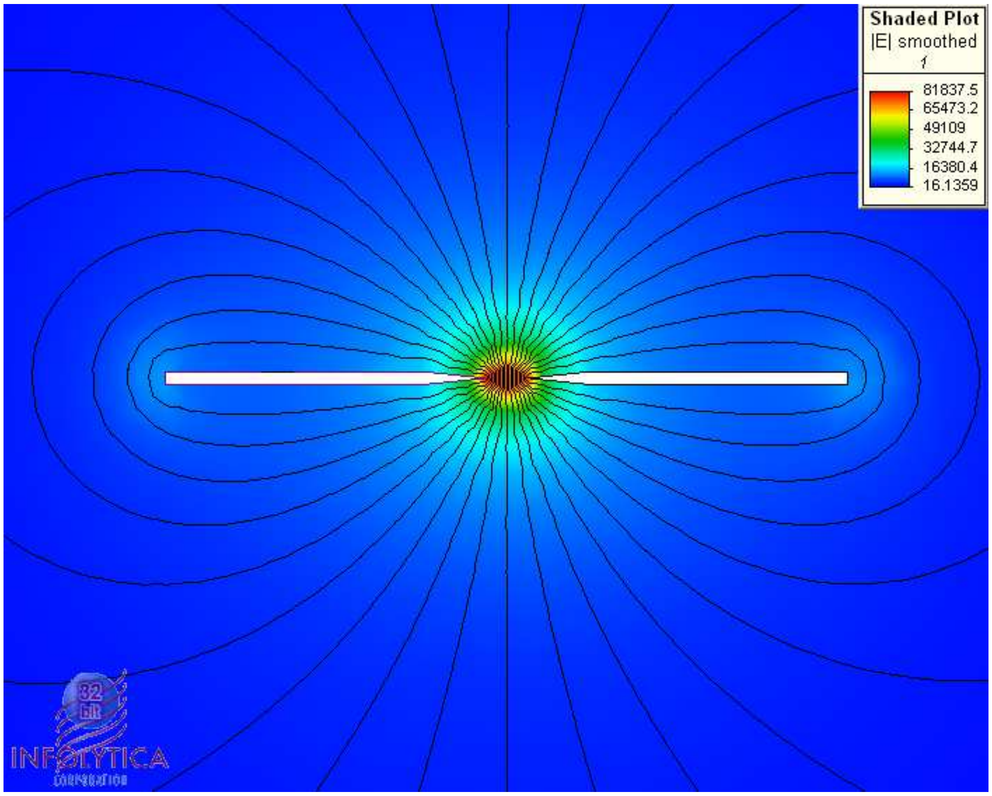


Figure 1.6: Computer simulation of electric fields for point-to-plane setup [13].

1.9 Corona Discharge

1.9.1. Corona Basics

Corona discharge takes place immediately prior to the breakdown. The breakdown voltage is also known as the corona initiation voltage, shown as point E in Figure 1.1. When breakdown occurs across the entire gap, there will be a glow discharge. After breakdown occurs, the voltage must be decreased to the extinction voltage to stop corona from forming. The path to the extinction voltage follows the hysteresis curve and the extinction voltage corresponds to point D.

Corona discharges will occur only if the field is sharply non-uniform, meaning the field-strength near one or both of the electrodes is much larger than elsewhere in the gap. Therefore, corona is most likely to occur at sharp edges or points, where the electric field is the highest. Corona discharge is a self-sustained electrical discharge where an electrical field confines the ionization processes to regions close to high-field electrodes or insulation. So the ionization process does not bridge the electrode gap [14].

There are two types of coronas discussed in literature, namely, positive and negative coronas. Which type of corona that will be formed is dependent on the polarity of the applied voltage, grounded anode or grounded cathode. For the experiments presented in this study, the cathode is grounded. Therefore the type of corona that may form during experiments should be positive corona since the power supply will be sourcing a positive voltage with respect to ground.

1.9.2. Positive Corona

Before positive corona forms, there is a small region surrounding the anode where the electric field strength is high enough to ionize the gas by collision. If a free electron is driven towards the anode, an electron avalanche will occur. During this process, more and more positive ions are formed. The positive ions near the anode eventually form an extension of the anode, a streamer, directed towards the cathode. Meanwhile, secondary avalanches are directed towards the large cloud of ions in front of the anode. These secondary avalanches are streamers and if the gap voltage is further increased a cloud of electrons may form directly in front of the anode. This forms a glow on the anode and is visible. If the voltage is increased too much past this point, then this equilibrium condition will be disturbed and a breakdown will occur, where conductive plasma will span the electrode gap [3, 9, 15].

1.9.3. Negative Corona

Just prior to corona formation, the electrons at the cathode experience a rapid pulsating mode known as Trichel pulse corona. Each one of these pulses correspond to a major electron avalanche in the ionization zone, which extends from the cathode surface to a distance where the electric field becomes too weak for ionization by collision to overcome electron attachment. Beyond this distance, an increasing number of ionized electrons get attached to the gas molecules and produce negative ions that drift away slowly from the cathode towards the anode. If the voltage is further increased, the Trichel pulses increase at a more frequent rate towards a critical value where a steady negative glow is formed [3, 15].

1.10 AC Effects

Electrode gaps under an ac signal will behave differently than those under a dc signal application. The application of an ac signal means that the electric field reverses polarity during every cycle. The 60 Hz sine wave that is supplied by power companies to the mains is one such example. This signal reverses polarity sixty times per second. At higher frequencies, the electrons in the gap will oscillate at an increasing rate. Some of them may fail to reach the anode during the half cycle in which they were ionized. So they will remain in the gap and tend to neutralize positive ions. Pfeiffer proposed in his work on breakdown at 75 kHz to MHz range that this effect governs the behavior of particles during the breakdown process. This could be why breakdown voltage tends to decrease as the frequency is increased [8]. In another work, it was found that the breakdown voltage decreases as the frequency increases, and that the breakdown voltage decreases when an ac signal is applied versus a dc signal [2].

1.11 Breakdown Under an Impulse Voltage

For the case of steady or slowly varying electric fields, an initiatory electron can be easily found from natural sources such as cosmic rays or detachment from negative ions. However, during an impulse voltage of short duration, approximately 1 μs or less, there may not be an initiatory "seed" electron available to start the avalanche process. Therefore a higher voltage is required to start the breakdown process for an impulse than for a low frequency signal [3].

1.12 Unipolar Pulsed Breakdown

For a unipolar pulsed signal, as shown in Figure 1.7, there is no field reversal as in the ac situation. The applied voltage is from zero to some positive value. Charges will experience a force upon them for the high duration of the pulse and experience no force on them when the signal falls to zero. This may cause the breakdown voltage to decrease. Note that this is the type of signal that will be applied to the experiments presented in this work, not an ac signal, because the polarity of the applied signal never reverses.

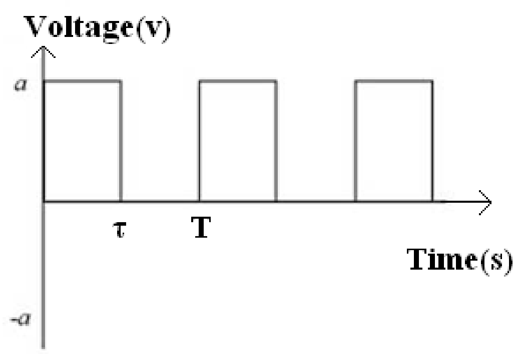


Figure 1.7: Unipolar pulse train voltage signal

In a previous work, it was found that the breakdown voltage decreases as the pulse train frequency increases for Helium and Nitrogen [2]. Previously collected data for Helium is shown in Figure 1.8. However, the rate of decrease was different for the two gases. For Helium, the trend seems to match the decreasing double-exponential function. For Nitrogen, the trend seems to match a decreasing linear function. This difference may be accounted to the fact that Nitrogen is molecular and Helium is atomic. Experimental data needs to be collected for Argon to help draw conclusions and see if the type of gas determines what kind of trend-lines will result during a frequency sweep.

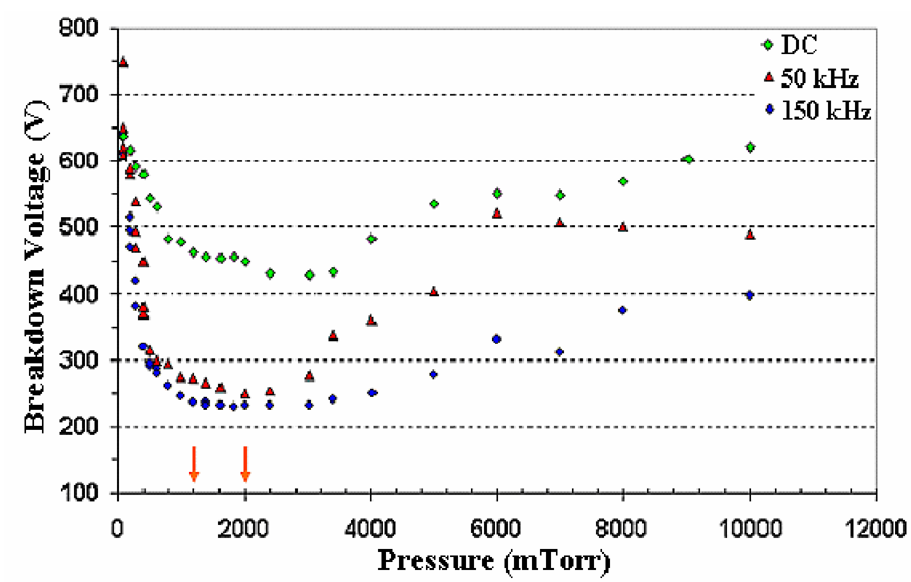


Figure 1.8: Data for Helium conducted for point-point electrode setup (d=1cm) [2]

Chapter 2: Experimental Objectives

The purpose of this experiment is to observe the breakdown characteristics for Argon for dc and repetitive pulse train applied voltage signals for two different electrode geometries. Breakdown studies will be performed for a point-plane setup and a point-point setup. The dc breakdown effects will be observed for varying pressure. The effect of a unipolar pulse train with varying frequency on breakdown voltage for an electrode gap will be observed over a range of pressures. The effect of varying the duty cycle for a given pulse train on breakdown voltage will also be observed over a range of frequencies and pressures. So, in summary, it is desired to know what will happen to the breakdown voltage of Argon as pressure, frequency, and duty cycle is varied. This information will allow conclusions to be drawn upon the effectiveness of Argon as an insulator under different conditions.

This work will study the formation of plasma and attempt to draw conclusions and see how well the results match Paschen Law. By holding the gap distance constant, we can set *pd* by varying the pressure and observing the breakdown voltage. The resulting plots should show data trends similar to Paschen curves.

Chapter 3: Experimental Procedure

3.1 Experimental Setup

To accomplish the tasks mentioned above, an experimental setup as shown in Figure 3.1 is utilized. The setup consists of an electrode fixture placed inside a cylindrical vacuum chamber, equipped with gas inlet/outlet valves, capable of sustaining pressure as low as 40 milliTorr. Diagnostics equipment, including a high-voltage probe, current probe, and photo-multiplier tube (PMT), is installed in the setup. Data acquisition equipment, including a Tektronix oscilloscope connected to a PC, is used to record data from the diagnostics equipment. Electrical connections to the electrodes are made through sealed gaskets in the vacuum chamber. Pressure is controlled inside the chamber by the valve installed in between the vacuum pump and the gas inlet port on the chamber.

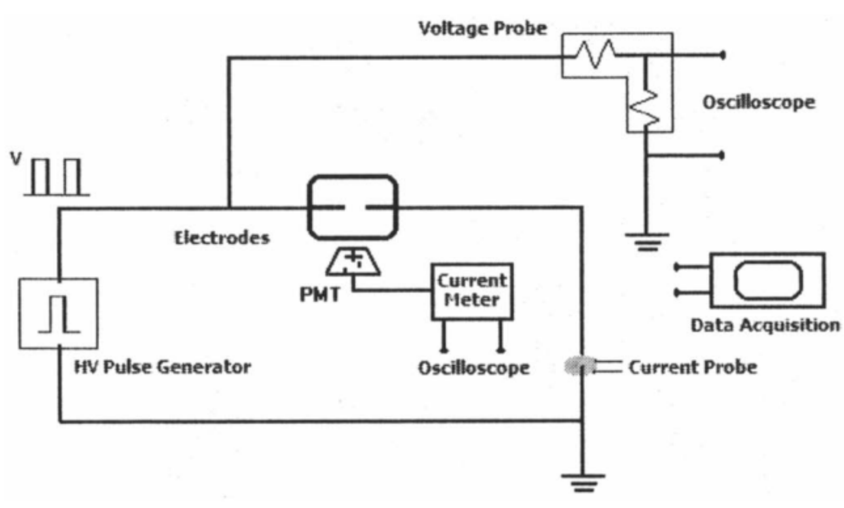


Figure 3.1: Basic experimental setup

A CVC SDC-100 high-voltage dc power supply is used for the dc experiments. The maximum current capability for this power supply is 750mA. It is internally limited by a current-limiting resistor. Since we are mostly interested in the transition from the dark discharge to glow discharge region, the current should never reach such a high value. The breakdown study with a pulse train of varying frequency will be set up as well. The HV dc power supply is connected to a DEI PVX-415 pulse generator along with a small-amplitude square wave from a BK Precision function generator. The DEI "pulser" basically acts like a gated switch, where a small square wave signal from the function generator is used to gate the much larger dc voltage. The resulting output from the pulse generator is square-wave pulse train capable of high voltage, varying frequency, and varying duty cycle.

In order to capture the data during the experiments, a data acquisition system has been set up. A high voltage Tektronix 1000x voltage probe in conjunction with a Tektronix digital oscilloscope is used to record the electrode gap voltage. Also connected to the oscilloscope is the PMT and current probe. The PMT responds to light emission and is used to trigger the scope at the time of breakdown. The current probe is used to verify that a plasma channel has indeed formed at the time of breakdown. The data captured on the oscilloscope is downloaded onto a PC through a GPIB data acquisition port. The data is collected in Tektronix acquisition software and then imported into Excel spreadsheets. Data analysis is then performed on the collected data.

3.2 Argon as the Operating Gas

Argon will be the principal gas used in all experiments. Breakdown studies have been performed in previous work for Helium and Nitrogen [2, 16]. As previously mentioned, in order to understand how the atomic and molecular properties affect the breakdown voltage, data for Argon is desired. Therefore, Argon is the gas of interest for this work.

It is possible that air from outside the vacuum chamber may leak inside. However this amount leaking in should be sufficiently low such that Argon is established as the main gas in the chamber. Before experiments are performed, the chamber is purged by inserting a large amount of Argon and then pumping out most of it out. The desired pressure is then set by controlling the gas inlet valve which regulates the flow of Argon. The experiments are performed between 0.1 Torr and 3 Torr. Actually, there will be a small flow of Argon during the experiments. This ensures that any contaminants entering from outside the chamber or produced from sputtering of the electrode surface will be evacuated, so that there will be nearly pure Argon in the chamber.

3.3 The Electrode Geometries

Two different electrode geometries are used for this experiment. One is a point-plane configuration and the other is a point-point configuration. Refer to Figure 3.2 to view the point-plane configuration with an electrode spacing of 0.9 cm. The plate is made out of copper and the point is made out of stainless steel. This configuration is used to simulate a conductor edge or point above a ground plane. Note that the plane is connected to earth ground and the point is connected to the high side of power supply.

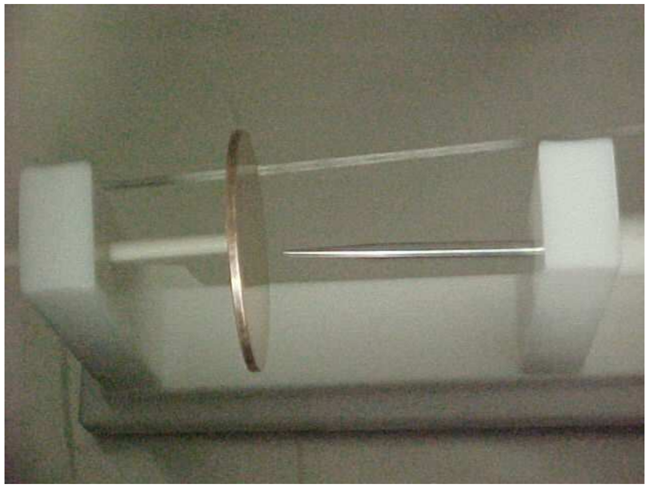


Figure 3.2: Point-plane setup with electrode spacing of 0.9 cm

The point-point configuration is used to simulate two connectors, such as those in a wiring harness that may not be connected but are close to each other. The electrode spacing for the point-point setup is 1 cm. This setup includes two very sharp electrodes made out of stainless steel as can be seen in Figure 3.3. The estimated tip radius for these electrodes is 0.25 mm and a close-up picture can be seen in Figure 3.4. Note that sometimes, the pointed electrode tips need to be sharpened and polished. This is due to the fact that during breakdown events, sputtering can erode the electrode tips and make them more rounded. Also, the tips can become discolored or burned looking which can cause an increase in the breakdown voltage since a damaged tip is not as good of a conductor as a tip with a smooth and polished surface. This issue will be discussed more in the results section for the point-point experiments. The close up image in Figure 3.4 is just after sharpening and polishing. The tip appears to be fairly sharp.

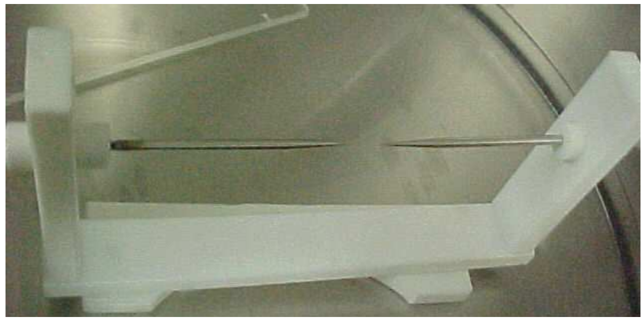


Figure 3.3: Point-point setup with electrode spacing of 1 cm

Figure 3.4: Close up image of the pointed electrode tip

3.4 Experimental Sets

Four different kinds of tests are performed for each electrode configuration geometry. The first test is a dc pressure sweep, which is used as a baseline comparison. This type of applied signal is shown in Figure 3.5(a). The next test is a pressure sweep with three fixed frequencies with 50% cycle, as shown in Table 3.1. The third test is a fixed pressure frequency sweep for frequency values shown in Table 3.2. The duty cycle here is also kept at 50%. The last test is a duty cycle sweep, and it includes pressure and frequency values as shown in Table 3.3. The pulse train signal is represented by Figure 3.5(b) and the equation for duty cycle is given below.

$$D = \frac{\tau}{T} * 100\% \tag{6}$$

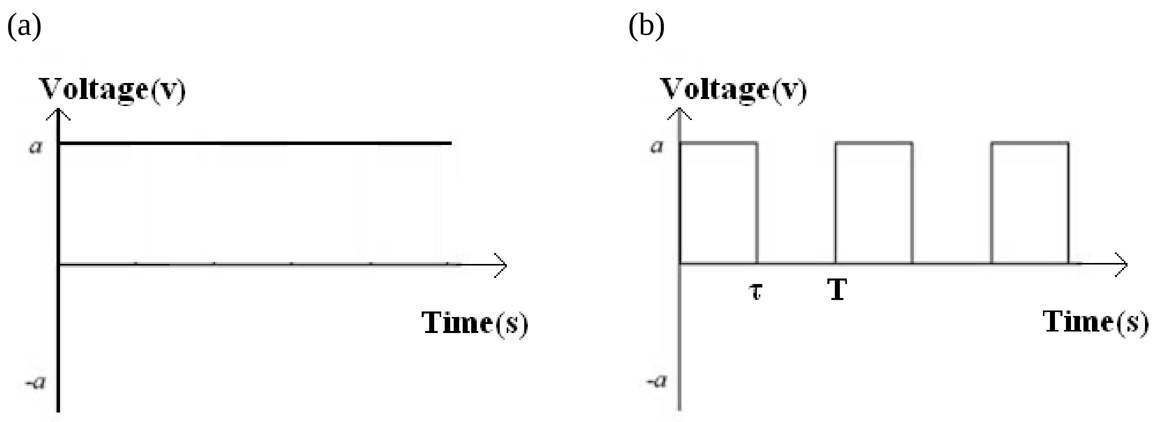


Figure 3.5: dc (a) and unipolar pulse train (b) voltage signals

Table 3.1: Pressure Sweep Experiments

	Frequency	Pressure Sweep
Point to Plane Setup	20kHz	0.1Torr to 2.4 Torr
	50kHz	
	100kHz	
Point to Point Setup	20kHz	
	50kHz	
	100kHz	

Table 3.2: Frequency Sweep Experiments

	Pressure	Frequency Sweep
Point to Plane Setup	400mTorr	20kHz to 200kHz
	800mTorr	
	1.2Torr	
Point to Point Setup	400mTorr	
	800mTorr	
	1.2Torr	

Table 3.3: Duty Cycle Experiments

	Pressure	Frequency	Duty Cycle
Point to Plane Setup	400mTorr	20kHz	10%-90%
		50kHz	
		100kHz	
	800mTorr	20kHz	
		50kHz	
		100kHz	
Point to Point Setup	400mTorr	20kHz	
		50kHz	
		100kHz	
	800mTorr	20kHz	
		50kHz	
		100kHz	

For all experiments, one of the variables (pressure, frequency, or duty cycle) is incrementally swept from a minimum to a maximum to observe the breakdown effect. At each increment, three to five tests are done and the data is captured for analysis. The three to five sets of data at each increment are then averaged to form a single data point for as will be shown in Chapter 4.

For pressure sweep experiments, the pressure is incrementally swept from 0.1 Torr to 3.0 Torr. However, for some tests, the breakdown voltage gets very high above 2 Torr, so the last test might be at that pressure. This is because, as the pressure increases above the *pd* value that gives the minimum breakdown voltage, the breakdown voltage will become higher and higher. When this happens the glow becomes more concentrated and more intense. In order to avoid damaging the electrodes, some experimental tests sets may stop at 2.0 Torr.

Chapter 4: Experimental Results and Discussion

Experimental results for the point-plane and point-point setups are presented. The dc analysis is performed. Figure 4.1 shows a sample of the captured data for one test at the time of breakdown during a dc experiment. The gap voltage is approximately 375 volts prior to breakdown. When the breakdown occurs, the gap voltage falls to approximately 225 volts and then levels out at 250 volts. The breakdown event happens in about 10 to 20 μs. The light emission is also shown in Figure 4.1. Once the breakdown event occurs, visible light is formed, as an indication that the electrode gap has gone from the dark discharge region to the glow discharge region, and plasma has been formed. Note that the data shown for the light emission has been scaled so that it can be seen in relation to the gap voltage. The data captured for the light emission is actually much less in magnitude.

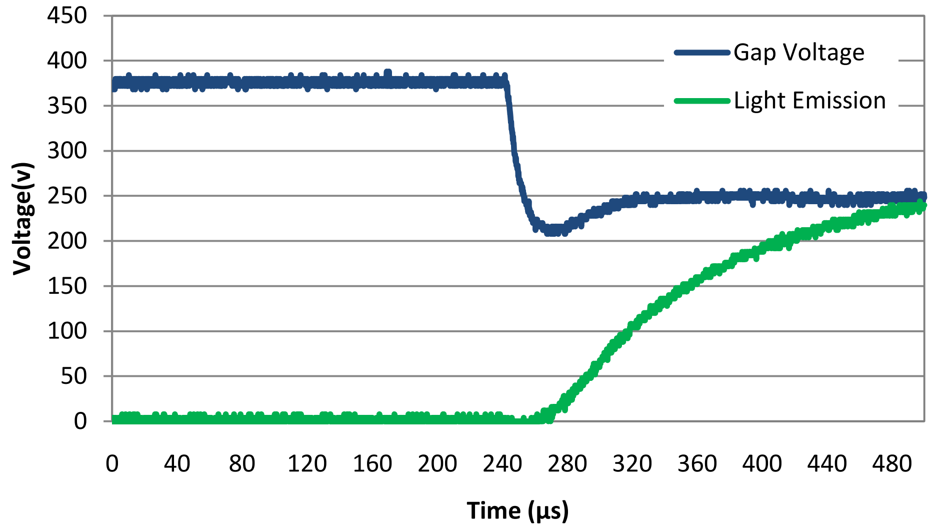
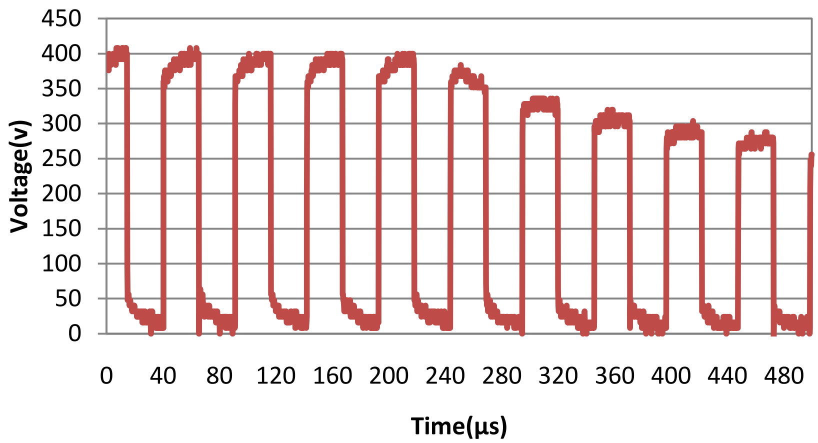
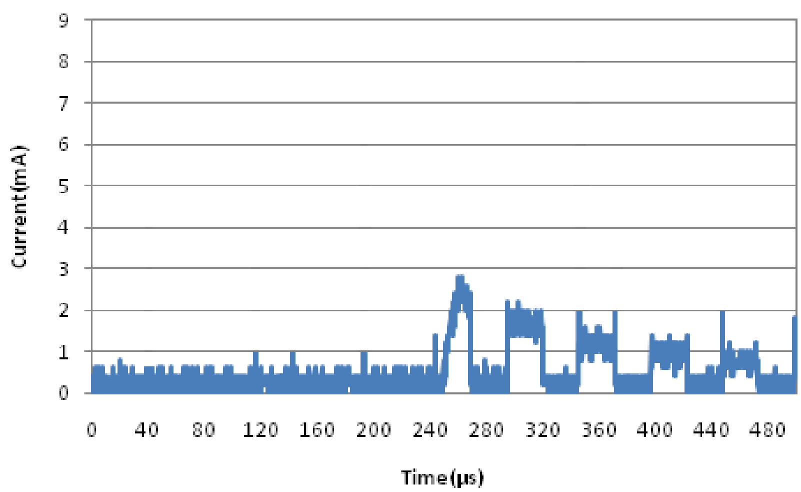


Figure 4.1: Breakdown waveform for dc analysis.

After the dc analysis has been performed, the pulse train experiments can take place. Figures 4.2(a) and (b) show a sample of captured data from one of the pressure sweep experiments. The pulse magnitude in Figure 4.2(a) reaches 400 volts prior to breakdown and then drops to well below 300 volts. This along with the light emission data (not shown here) is an indication that the breakdown event has indeed occurred. Figure 4.2(b) shows the current waveform captured by the current probe. Prior to breakdown, the current appears to be nearly zero. There is some noise due to radiated emissions from other electrical equipment (lights, vacuum pump, etc). However, notice that at approximately 250 µs, a square wave pulse train is visible. This matches the same time the gap voltage drop occurs in Figure 4.2(a). So, a measurable amount of current, on the order of a couple of milliamps, occurs once the breakdown event takes place and a plasma channel is formed, spanning the electrode gap.



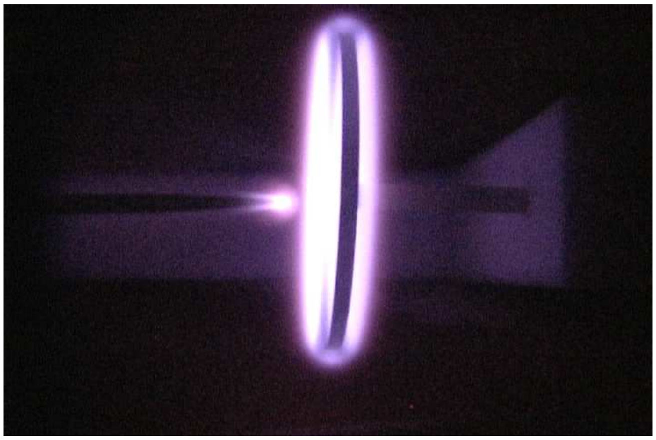
(a)



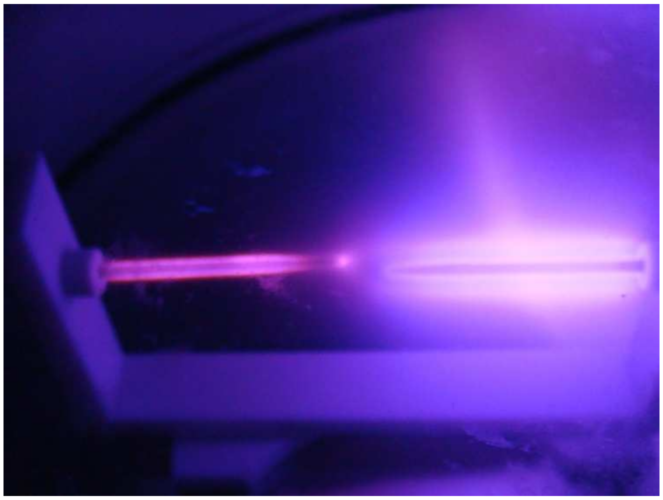
(b)

Figure 4.2: Captured Voltage (a) and Current (b) waveforms during unipolar pulse train experiment.

Figures 4.3(a) and (b) are images of the electrodes after breakdown. Notice how the plasma glow is very bright at the pointed surfaces. In Figure 4.3(a), the negative glow is very bright on the cathode surface, the copper plate electrode, and bright at the tip of the point electrode. Notice in Figure 4.3(b) how the glow has covered much of the electrodes. This is an indication that the electrode gap is in the abnormal glow region. As the applied voltage is increased, the scope will trigger at the time of breakdown, which is immediately prior to the time the gap enters the glow region. So these images are probably captured well after the time of breakdown but they give an idea as to where the electric field is the highest. These images correspond to the electric field simulations shown in Figures 1.5 and 1.6.



(a)



(b)

Figure 4.3: Images for the plasma formed during experiments for the point-plane(a) and point-point(b) electrode configurations

4.1: Point-Plane Experiments

4.1.1: Breakdown Results for dc signal

The dc analysis for the point-plane setup is shown in Figure 4.4. The overall shape of the curve is similar to a Paschen curve as expected. At the low pressure, 0.1 Torr, the breakdown voltage is very high, in excess of 450 volts. As pressure is swept from 0.1 Torr to the 3 Torr, the breakdown voltage decreases to a minimum at approximately 0.5 Torr. The corresponding breakdown voltage at this pressure is about 360 volts. Note that the data point at 1 Torr is actually the lowest voltage but it appears to be an anomaly, since it does not really fit the rest of the data. As can be seen in Figure 4.4, the pressure plays a huge role in the breakdown voltage because an increase from 0.1 Torr to 0.5 Torr results in lowering the breakdown voltage by about 100 volts. As pressure is increased above 0.5 Torr, the overall trend shows an increasing breakdown voltage, which is as expected. At 3 Torr, the breakdown voltage reaches 525 volts.

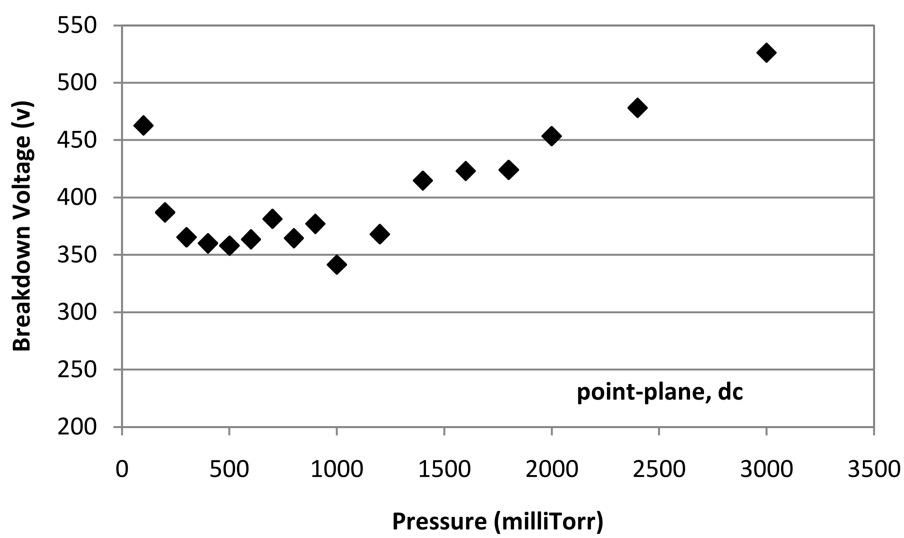


Figure 4.4: dc analysis for point-plane electrode configuration

4.1.2: Pressure Sweep Breakdown Results

The results for the 20 kHz fixed frequency pressure sweep is shown in Figure 4.5. Notice that the minimum breakdown voltage is considerably less than that for the dc breakdown. The minimum breakdown voltage is 325 volts for a 20 kHz pulse train. This agrees with earlier observations that the dc breakdown should be higher than that for a pulse train with fixed frequency. The breakdown voltage is about 11% lower for the pulse train than the dc signal.

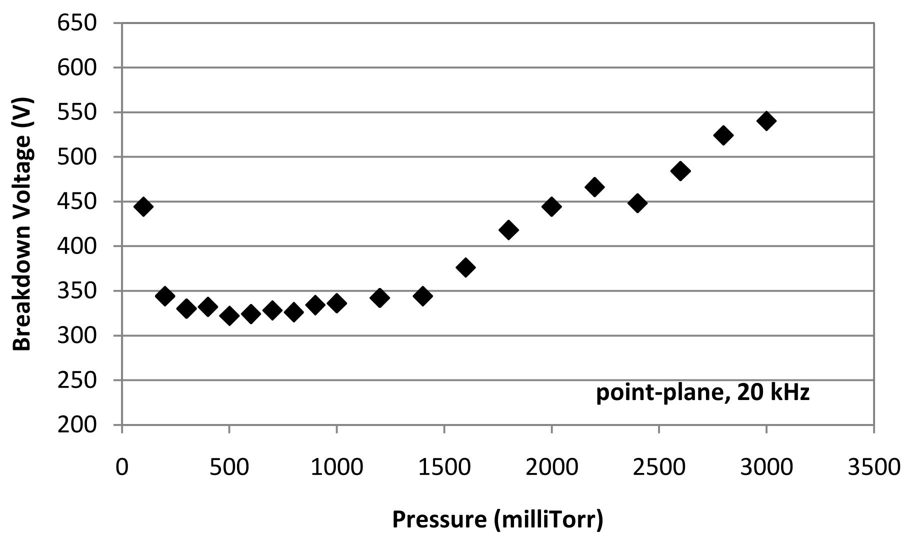


Figure 4.5: 20kHz Pressure Sweep for point-plane electrode configuration

Figure 4.6 shows the data for the 50 kHz fixed frequency pressure sweep experiment. The minimum breakdown is about 315 volts. Figure 4.7 also shows that the minimum breakdown voltage is about 315 volts. This value is less than that for the 20 kHz experiment, which is expected since it agrees with earlier observations that the breakdown voltage decreases as the frequency is increased.

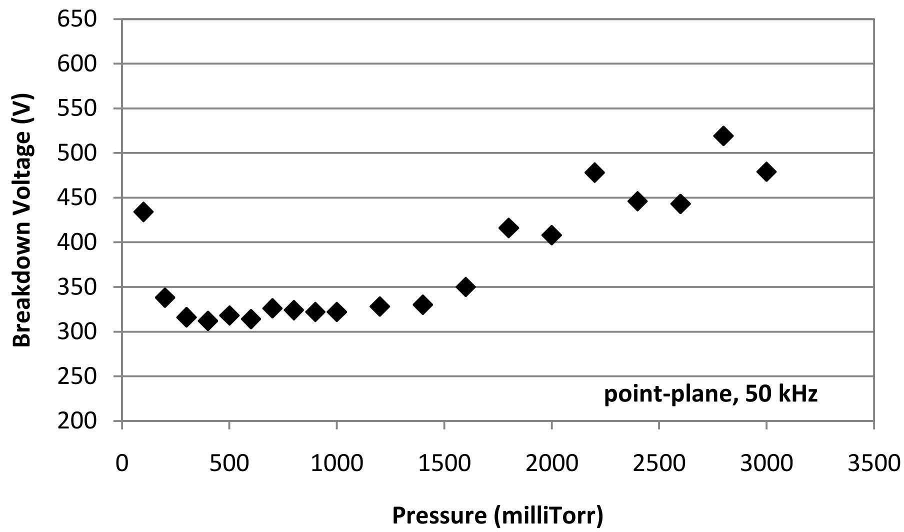


Figure 4.6: 50 kHz Pressure Sweep for point-plane electrode configuration

Figure 4.7 shows the 100 kHz pressure sweep experimental data. On average, the breakdown voltage appears to be less from 0.1 Torr to 1.4 Torr when compared to the 50 kHz data. This supports the claim that frequency is inversely determinate on breakdown voltage. However, notice that past, 1.4 Torr, the breakdown voltage increases at a faster rate for 100 kHz data than for the 50 kHz data. It is undetermined why this happens. Perhaps this could be due to hotspots that can form on the electrode surfaces. Higher pressure can cause an intense glow that could be forming on spots on the copper plate other than directly across the point electrode. This may be affecting the breakdown voltage.

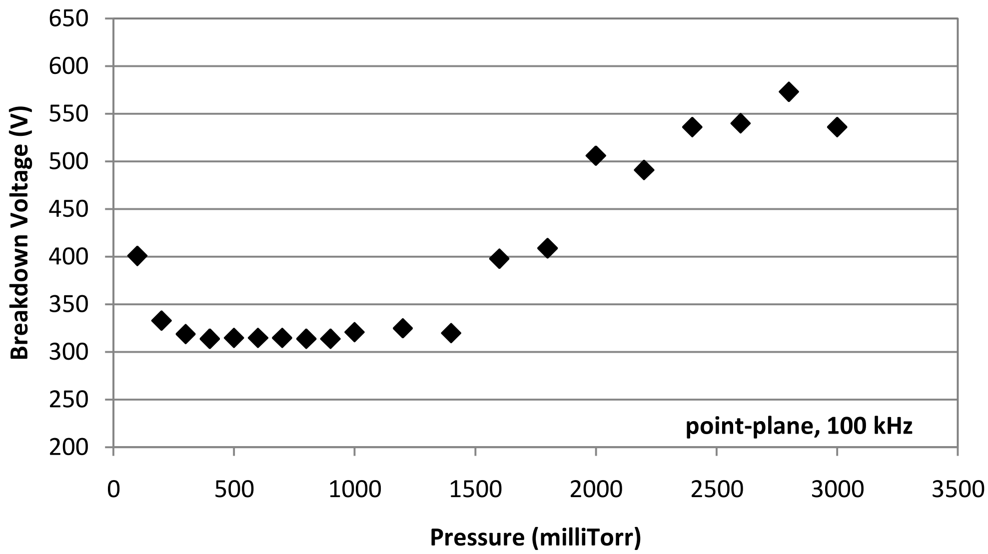


Figure 4.7: 100 kHz Pressure Sweep for point-plane electrode configuration

4.1.3. Frequency Sweep Breakdown Results

After the pressure sweep is performed, the frequency sweep at fixed pressure is performed for the point-plane electrode configuration. Figure 4.8 shows the frequency sweep at 400 milliTorr. From 20 kHz to 200 kHz, the breakdown voltage falls from 340 volts to 305 volts. This is a significant difference, about a 10% drop in breakdown voltage.

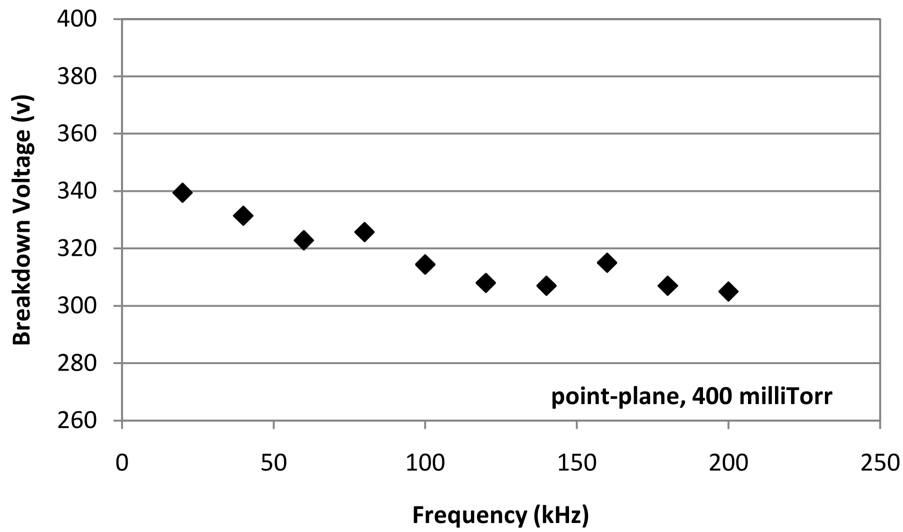


Figure 4.8: 400 milliTorr Frequency sweep for point-plane electrode configuration

At 0.8 Torr, there is only a slight overall decrease in breakdown voltage as the frequency is swept as shown in Figure 4.9. The 1.2 Torr frequency sweep in Figure 4.10 shows even less of a decreasing trend. This could be due to instabilities or hot spots at higher pressures.

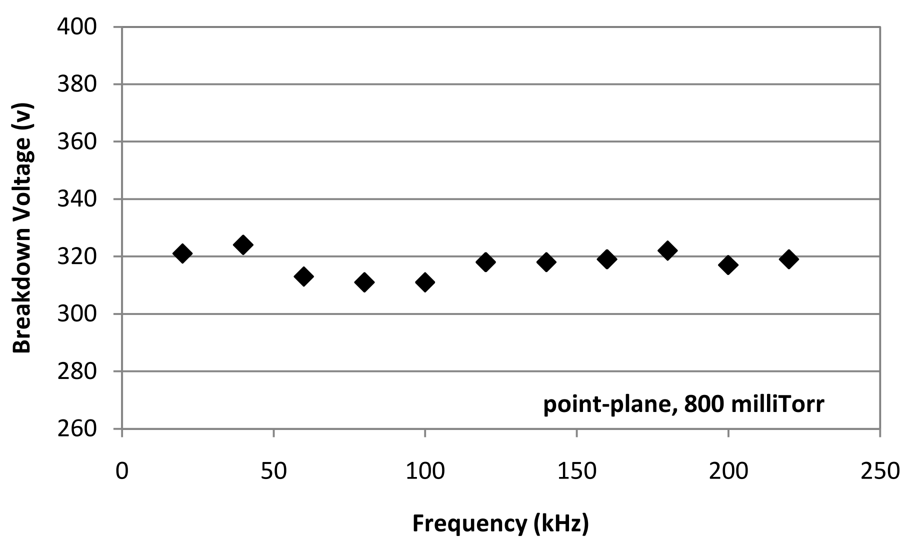


Figure 4.9: 800 milliTorr Frequency sweep for point-plane electrode configuration

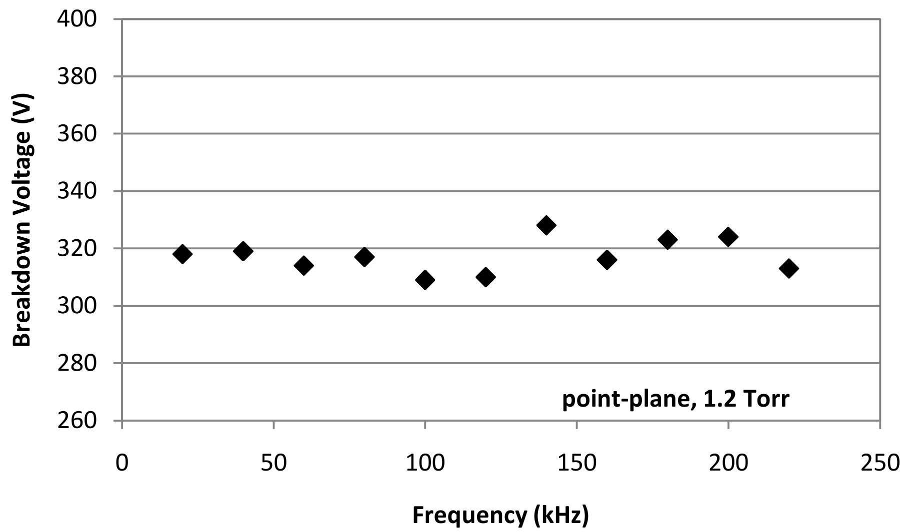


Figure 4.10: 1.2 Torr Frequency sweep for point-plane electrode configuration

4.1.3. Duty Cycle Sweep Breakdown Results

The duty cycle sweep for fixed pressure and frequency is then performed. Figure 4.11 is for the duty cycle sweep at 0.4 Torr and 20 kHz. For a low duty cycle of 10%, the signal resembles an impulse. The breakdown voltage required for this duty cycle is relatively high. Once the duty cycle is increased past this point, the breakdown voltage begins to decrease to a minimum at 40%. The breakdown voltage increases to a maximum at 90%. At 90%, the breakdown voltage is large, due to the fact that this duty cycle resembles almost a dc signal. The breakdown voltage here is 355 volts, which is very close to the 360 volts at 0.4 Torr shown in the dc breakdown data in Figure 4.4. The breakdown voltage for a dc signal should be larger than that for a time-varying voltage signal as previously stated. In Figure 4.12, the 50 kHz data, there is a substantial difference between the minimum breakdown voltage at 30% and the maximum at 90%. The breakdown voltage drops by nearly 13% from the maximum to the minimum. The data at 20 kHz and 100 kHz shows that a 7-8% decrease occurs from the breakdown voltage at 90% duty cycle and the minimum breakdown voltage.

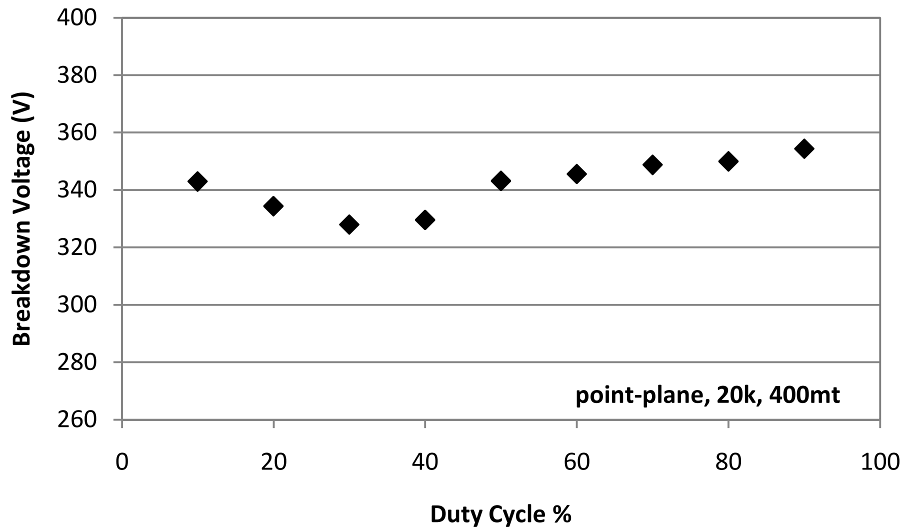


Figure 4.11: Duty Cycle sweep for 20 kHz and 400 milliTorr for point-plane setup

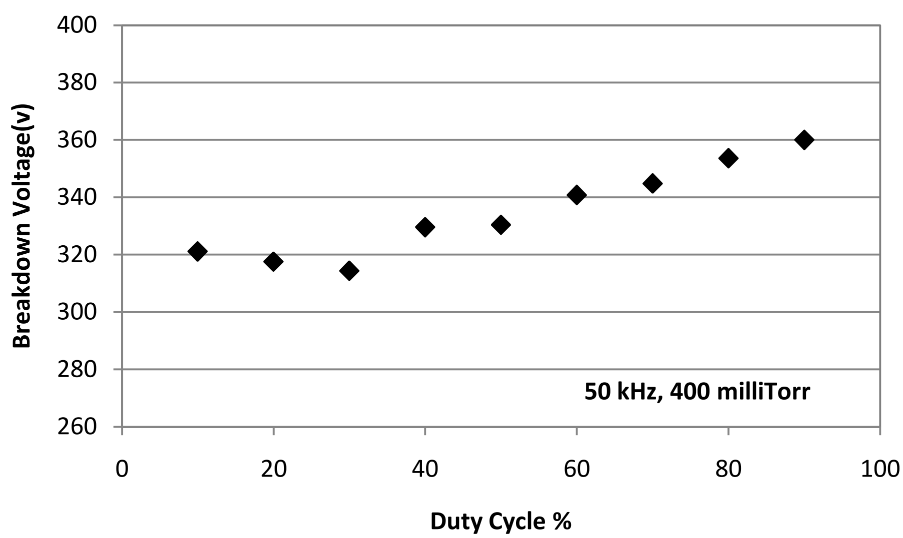


Figure 4.12: Duty Cycle sweep for 50 kHz and 400 milliTorr for point-plane setup

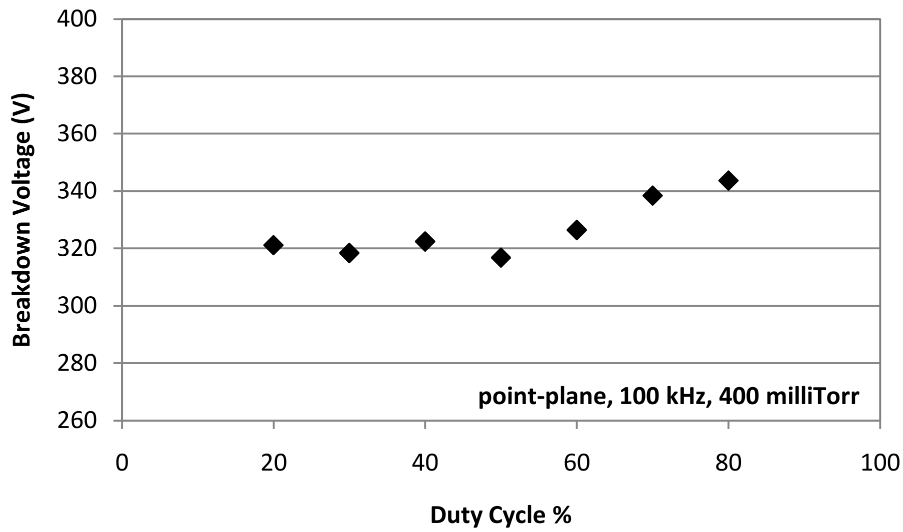


Figure 4.13: Duty Cycle sweep for 100 kHz and 400 milliTorr for point-plane setup

The duty cycle sweep is also performed at 1.2 Torr. Figure 4.14 shows a very high breakdown voltage at 50%. It seems to be an anomaly and it is undetermined why the breakdown voltage is so high for this point. Besides the point at 50%, the plot shows a decrease in breakdown voltage from 10% to 20%. Then the breakdown voltage gradually rises towards the 90% mark. Figure 4.15 also shows a relatively high breakdown voltage at 50%. Perhaps there is some special effect that is happening at 50%. Besides that point, the 50 kHz data roughly follows the trend for 20 kHz in Figure 4.14.

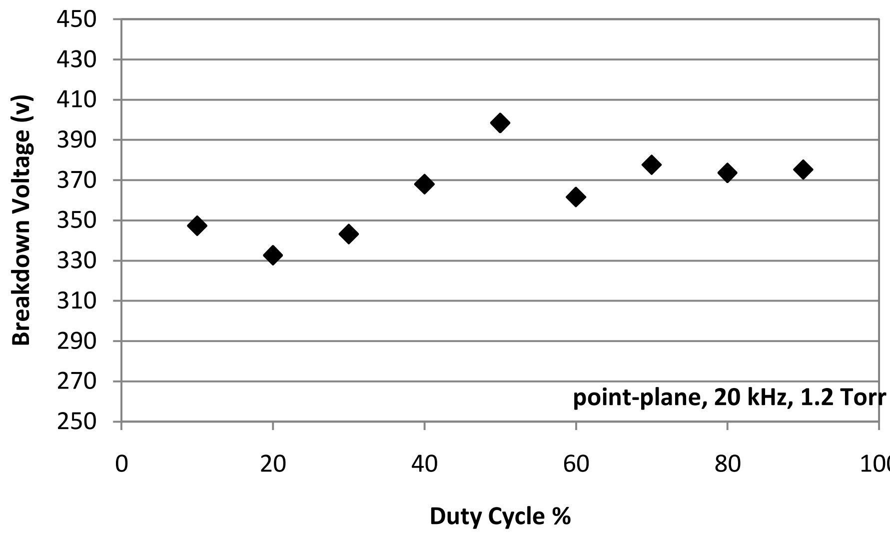


Figure 4.14: Duty Cycle sweep for 20 kHz and 1.2 Torr for point-plane setup

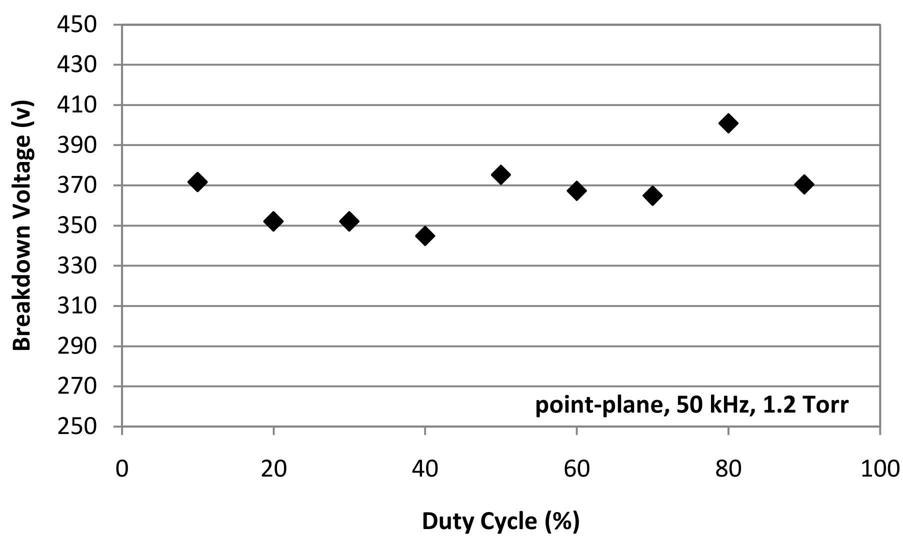


Figure 4.15: Duty Cycle sweep for 50 kHz and 1.2 Torr for point-plane setup

For the duty cycle sweep at 1.2 Torr shown in Figure 4.16, the breakdown voltage was high at 20% and then dropped by about 15 volts at 30% to 40 %. There was then a breakdown voltage increase from 50% to 80%. The breakdown voltage dropped slightly from 80% to 90%.

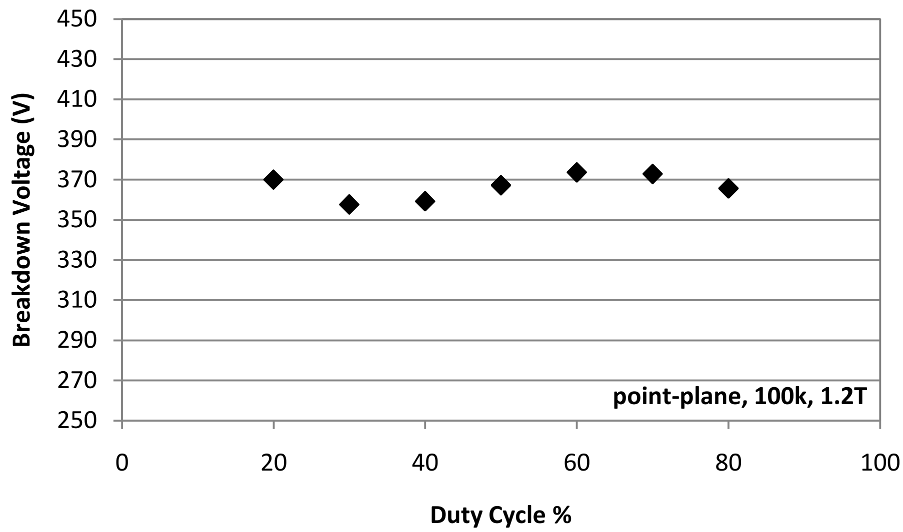


Figure 4.16: Duty Cycle sweep for 100 kHz and 1.2 Torr for point-plane setup

4.2: Point to Point Experiments

4.2.1: Breakdown Results for dc signal

The dc analysis is shown in Figure 4.17. The overall shape of the curve is similar to a Paschen curve. The minimum breakdown voltage is approximately 460 volts.

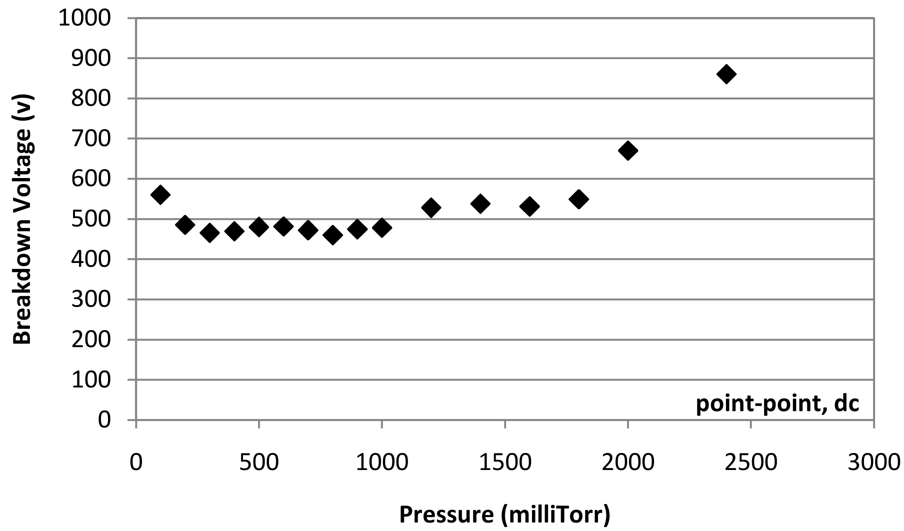


Figure 4.17: dc breakdown results for point-point electrode configuration

4.2.2: Pressure Sweep Breakdown Results

The pressure sweep for a fixed frequency pulse train of 20 kHz is shown below in Figure 4.18. Note that for the pressure sweeps for the point-point electrode configuration, data was collected at 20 kHz, 50 kHz, and 100 kHz. Then the electrodes were re-surfaced on the tips. Once the tips were sharpened and polished, it had a slight effect on the breakdown characteristics. The 20 kHz experiment was performed again with the re-surfaced setup to see the effect. The breakdown voltage increased some because a sharper tip may have been not as rounded and smooth as it previously was. As can be seen in the Figure 4.18, the voltage difference between the two setups was as high as 50 volts in some places. This indicates that the sharpness of the electrode tips plays an important role on the breakdown voltage. However, all other experiments for point-point electrodes were done with the same re-surfaced setup with the sharpened and polished tips. So comparisons can be made with all of the data for the re-surfaced setup, including the dc data, which was also performed with the re-surfaced electrodes.

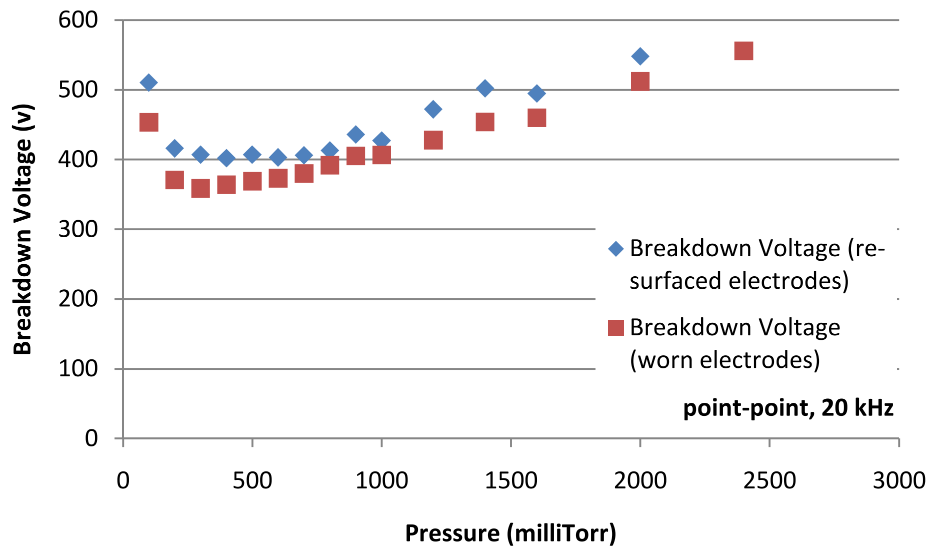


Figure 4.18: 20 kHz Pressure sweep for point-point setup with data for the worn electrodes and the re-surfaced electrodes

For 20 kHz breakdown data on the re-surfaced setup, shown in Figure 4.19, the minimum breakdown voltage is about 400 volts, which is 60 volts lower than the minimum breakdown voltage for the dc analysis. So the minimum breakdown voltage is 13% less for the 20 kHz pulse train than for dc.

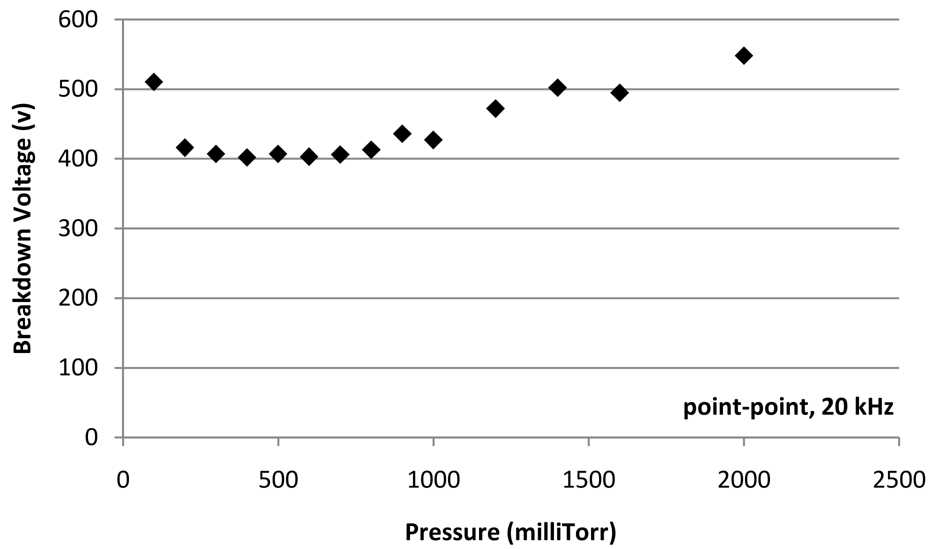


Figure 4.19: 20 kHz Pressure sweep for point-point setup (re-surfaced electrodes)

For figures 4.20 and 4.21, it appears that the minimum breakdown voltage actually goes up as frequency is increased from 50 kHz to 100 kHz. This is probably due to increasing wear on the electrode tips which prompted the need to re-surface the electrodes.

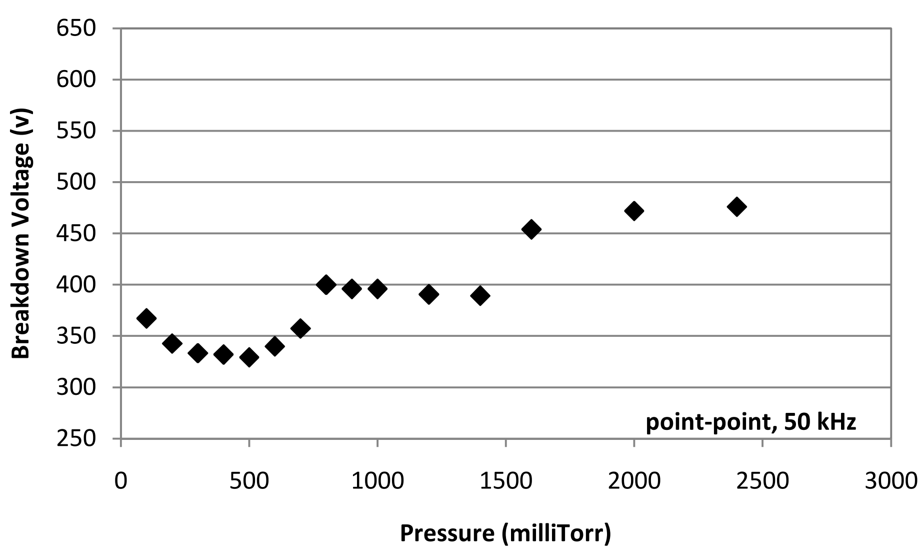


Figure 4.20: 50 kHz Pressure sweep for point-point setup (worn electrodes)

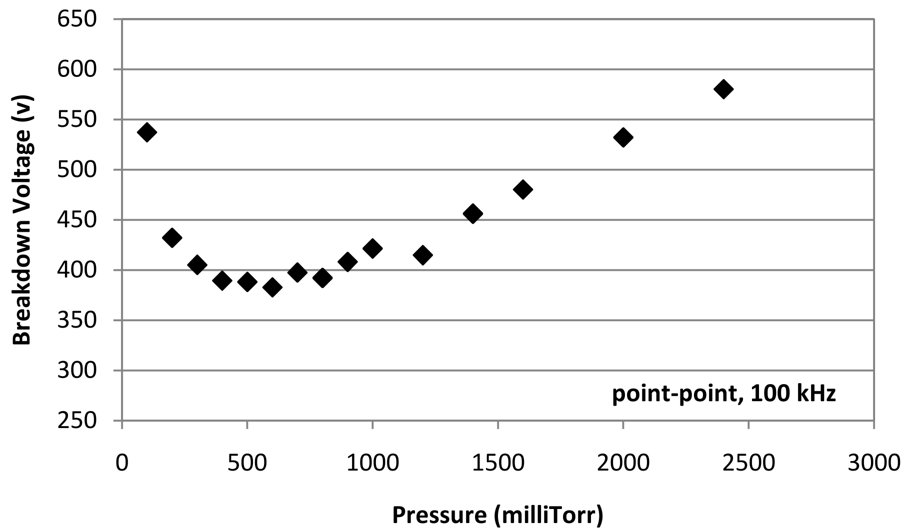


Figure 4.21: 100 kHz Pressure sweep for point-point setup (worn electrodes)

4.2.3: Frequency Sweep Breakdown Results

The frequency sweep for 0.4 Torr is shown below in Figure 4.22 and it shows a decreasing trend for the breakdown voltage as a function of frequency. The data at 0.8 Torr and 1.2 Torr show a similar trend as shown in Figures 4.23 and 4.24. So all of the frequency sweep data indicates an overall decrease in breakdown voltage as the frequency is increased. The data at 1.2 Torr shows about a 10% decrease in breakdown voltage as the frequency is increased from 20 kHz to 200 kHz. This inverse relationship between frequency and breakdown voltage is as expected.

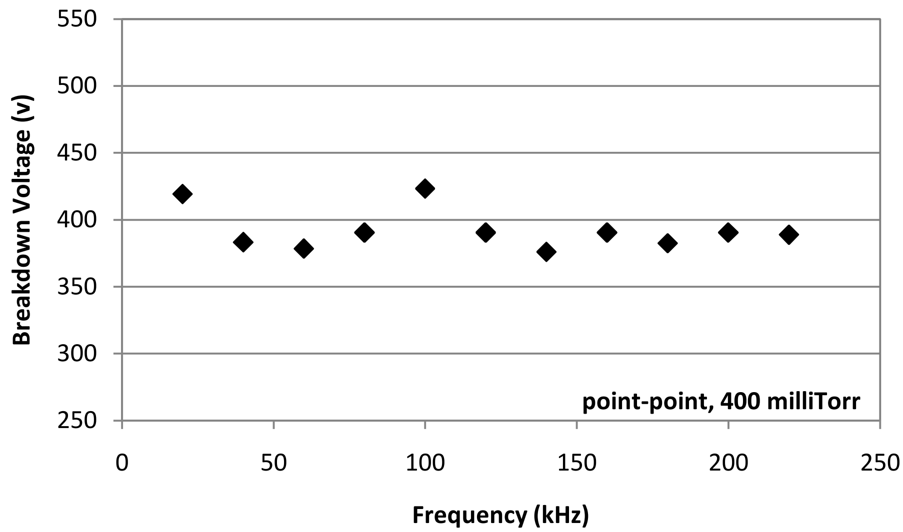


Figure 4.22: Frequency sweep at 400 milliTorr for point-point electrode configuration

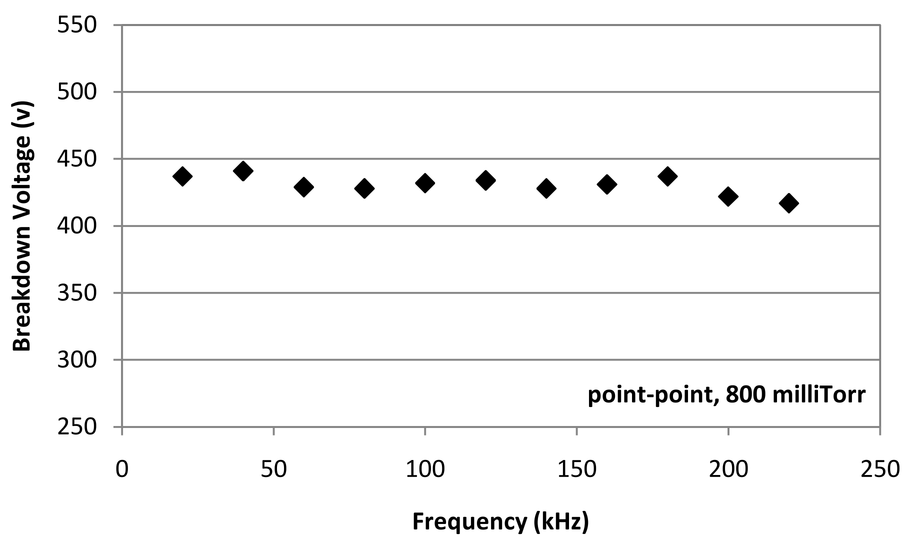


Figure 4.23: Frequency sweep at 800 milliTorr for point-point electrode configuration

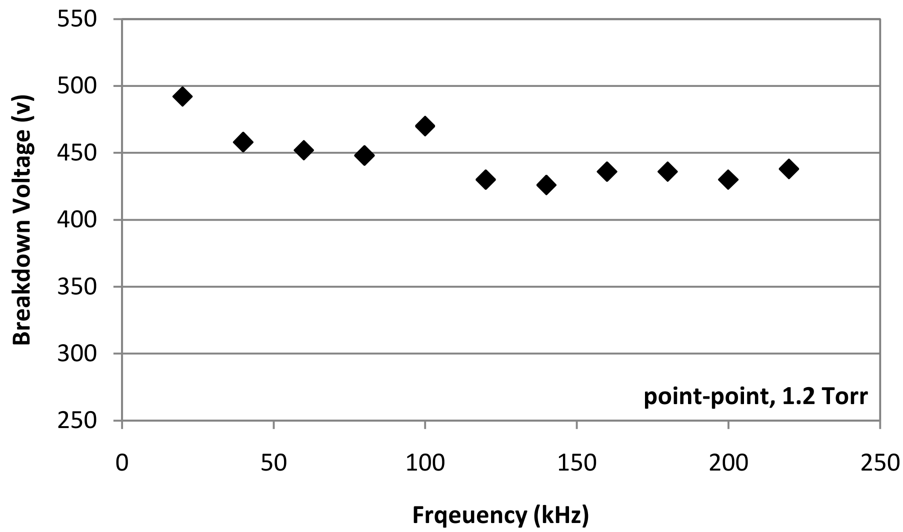


Figure 4.24: Frequency sweep at 1.2 Torr for point-point electrode configuration

4.2.4: Duty Cycle Sweep Breakdown Results

The duty cycle analysis is performed for the point-point electrode configuration. For the 400 milliTorr duty cycle experiments at 20 kHz, shown in Figure 4.25, the breakdown voltage seems to stay at 420 to 440 volts from 10 to 40%. It then decreases to a minimum of 375 volts at 60%. The breakdown voltage then increases to 440 volts at 90%. So the breakdown voltage decreases by almost 15% from a 90% duty cycle to 60% duty cycle.

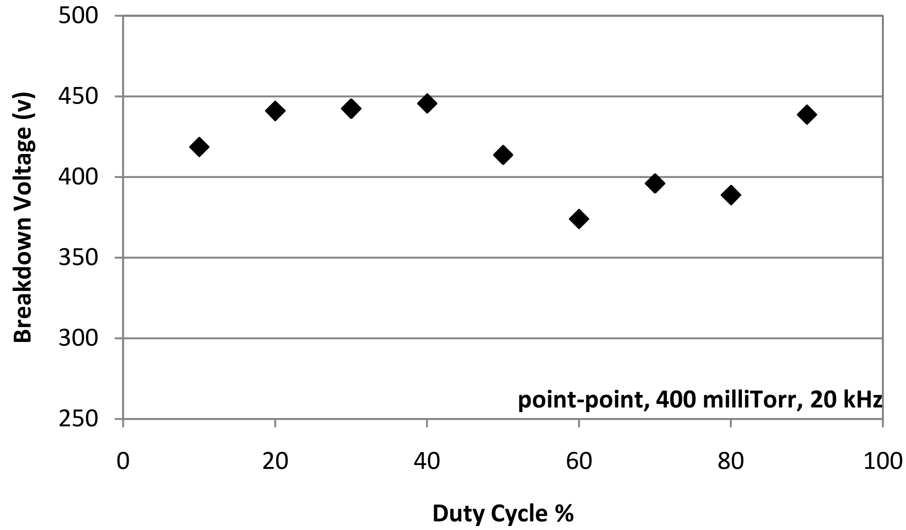


Figure 4.25: Duty cycle sweep at 20 kHz and 400 milliTorr for point-point setup

For the experiments at 50 kHz and 100 kHz, the minimum breakdown voltage occurs at 20 % and increases above and below this value, as shown in Figures 4.26 and 4.27. At 50 kHz, there is a difference in breakdown voltage of about 70 volts from the minimum value to the value at 90%. At 100 kHz, the voltage difference is about 55 volts. So in these cases, a change in duty cycle can have a 13-17% decrease in breakdown voltage.

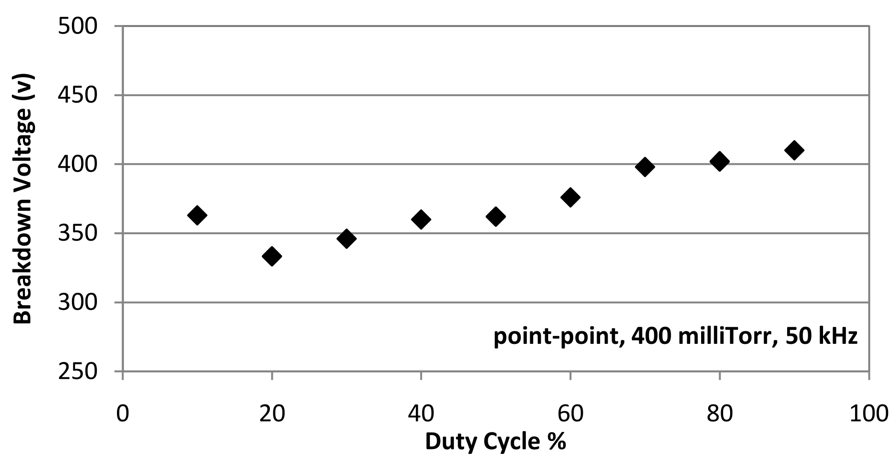


Figure 4.26: Duty cycle sweep at 50 kHz and 400 milliTorr for point-point setup

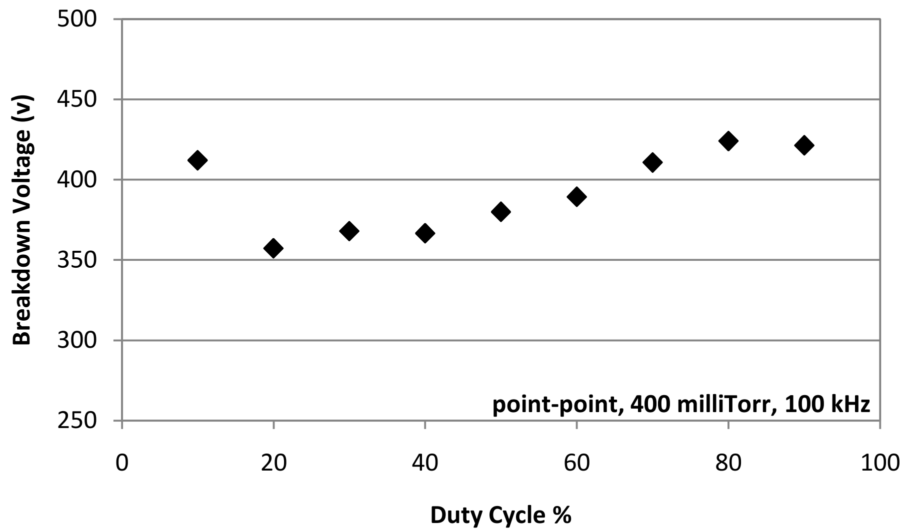


Figure 4.27: Duty cycle sweep at 100 kHz and 400 milliTorr for point-point setup

The duty cycle sweeps at 800 milliTorr show a similar trend as the data for 400 milliTorr. The breakdown voltage is high at low duty cycle. It then decreases to a minimum as the duty cycle is increased. Then, as the duty cycle approaches 90%, the breakdown voltage increases. The minimum breakdown voltage appears to be at 20% for 20 kHz and 50 kHz as shown in Figures 4.28 and 4.29. At 50 kHz, the breakdown voltage at 10% is about 455 volts. At 20% duty cycle, it falls by about 100 volts, yielding a 22% decrease. At 90% duty cycle, the breakdown voltage increases from the minimum by 19% to 440 volts. There appears to be a substantial change in the breakdown voltage based on the duty cycle.

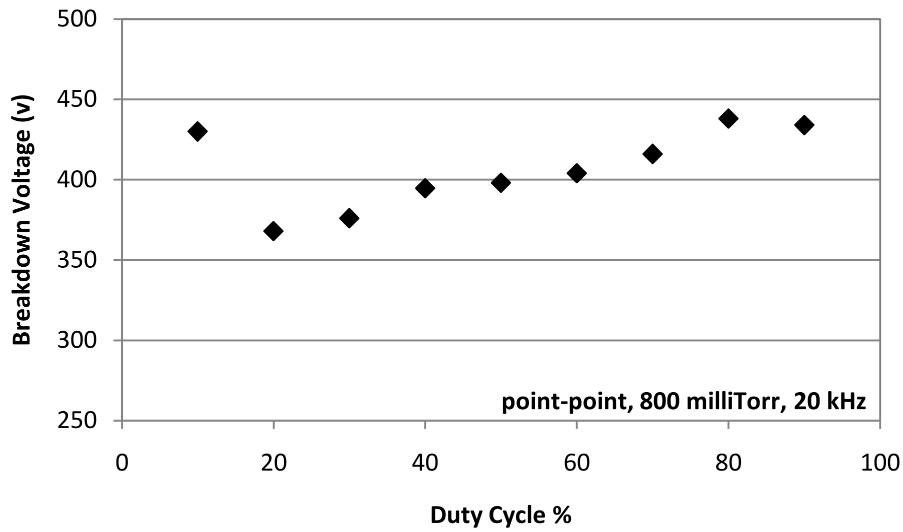


Figure 4.28: Duty cycle sweep at 20 kHz and 800 milliTorr for point-point setup

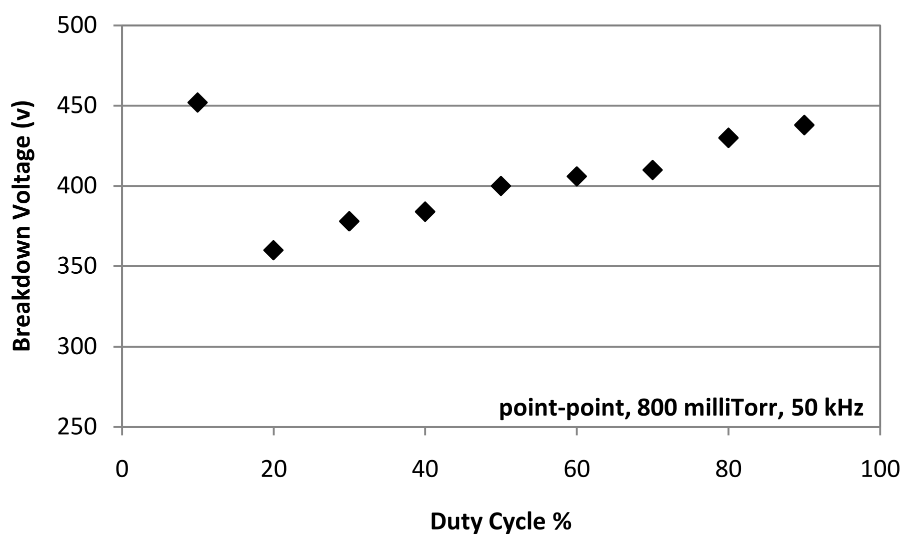


Figure 4.29: Duty cycle sweep at 50 kHz and 800 milliTorr for point-point setup

For 100 kHz, the breakdown voltage stays nearly constant from 20 % to 60 %, around 405 volts and then rises towards 90% to almost 450 volts. The percent decrease from the maximum to minimum breakdown voltage is 10%. The breakdown voltage at the extremes, 10% and 90% is expected to be higher than everywhere else, so the data generally supports this claim.

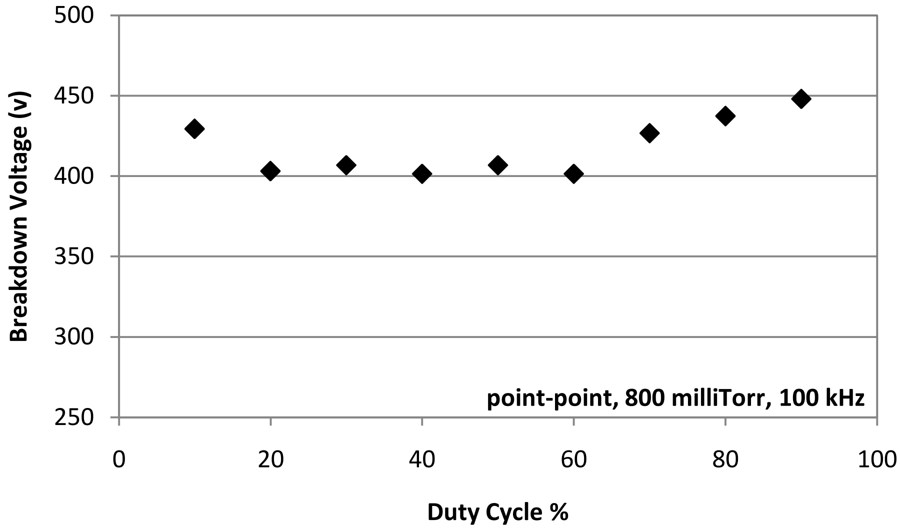


Figure 4.30: Duty cycle sweep at 100 kHz and 800 milliTorr for point-point setup

Conclusions and Future Work

The experimental results presented some interesting findings and confirmed some earlier theories on breakdown in kHz range. In both cases, for the point-plane and point-point electrode configurations, the dc data presents a higher breakdown voltage when compared to the pulse train experimental results. The breakdown voltage decreases by over 10% for both electrode configurations.

All of the pressure sweep plots show a trend that is in agreement with Paschen law. A minimum breakdown voltage was observed where any substantial increase of pressure above or below this point results in a higher breakdown voltage. Comparison of the fixed frequency pressure sweeps of the point-plane experiments show that the minimum breakdown voltage decreases as the frequency is increased. This helps support the claim that breakdown voltage decreases as the frequency increases. The same comparison was harder to make for the point-point pressure sweep data, since some of the pressure sweeps were performed on worn electrode tips. However, the frequency sweeps for the point-point experiments proved to be quite conclusive.

The frequency sweeps, especially those for the point-point data, show a clear inverse relationship between frequency and breakdown voltage. The frequency can have a significant impact on the breakdown voltage for an electrode gap. A decrease in breakdown voltage of nearly 10% is observed in some of the experimental data as the frequency was swept from 20 kHz to 200 kHz. This supports earlier observations on the frequency dependence of breakdown voltage.

The duty cycle test shows that as duty cycle is increased from 10% to 90%, the breakdown voltage starts high at 10%, decreases to a minimum at somewhere between 20 to 60% and then increases up to 90%. At 10%, the breakdown voltage is relatively high because the signal resembles an impulse, which is thought to require a higher breakdown voltage than a repetitive signal with higher duty cycle. At 90%, the breakdown voltage is large due to the fact that this duty cycle almost resembles a dc signal. The breakdown voltage for a dc signal should be larger than that for a time-varying voltage signal. The decrease in breakdown voltage from the maximum to the minimum is as between 10-20% in most cases.

With the data collected for Argon in this work, future work could include analyzing the data for the Argon experiments alongside those for Nitrogen and Helium. This work could be used to better understand the mechanisms causing breakdown. The effect of the type of gas, whether atomic or molecular, as well as the weight of the particles, can be studied to better understand the breakdown mechanism.

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