Identification of the Corona Point in Point-to-Plane Geometries in Atmospheric Air

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IDENTIFICATION OF THE CORONA POINT IN POINT-TO-PLANE GEOMETRIES

by

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B.S., ELECTRICAL ENGINEERING, UNIVERSITY OF NEW MEXICO, 2017

THESIS

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Identification of the Corona Point in Point-to-Plane Geometries

by

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M.S. Electrical Engineering, University of New Mexico, 2019

ABSTRACT

The minimum sustaining electric field for streamer propagation is directly correlated to the minimum electric field at the corona point. Corona is a product of non-uniform electric fields; the onset of corona occurs before electrical breakdown. As electric fields become increasingly uniform the required field strength to produce corona is increased as well. The field uniformity can be increased until a critical point in which electrical breakdown coincides with the onset of a positive corona, this is known as the corona point.

An experimental setup with a point to plane configuration allows precise changes in electric field uniformity, by gradually moving the point closer to the plane. Using a photomultiplier, the immediate onset of corona a positive can be determined. The potential on the electrode is slowly ramped up to ensure that the minimum amount of electric field to onset corona is measured.

The minimum value of the electric field required for streamer propagation, the sustaining field, can be used to determine a new breakdown criterion. While the Paschen curve is an excellent way to determine breakdown in uniform fields, it is a rough estimate in non-uniform fields. Using the sustaining field, one would be able to better estimate the value of electric field that would initiate breakdown. After determining the corona point experimentally, simulations were performed to determine the minimum electric field in the geometry. Replicating the experimental point to plane geometry with a spacing of 4.5mm between the electrode tip and the ground plane and a DC potential of 5.76kV. The resultant simulations gave a minimum electric field of 4.4kV/cm in agreement with other published works [1]. This leads to the determination that the corona point, in a point to plane geometry, may be a viable method for determining the sustaining field.
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Chapter 1

Introduction

1.1 Concept

Electrical breakdown in gases has been dominated by two models, Townsend Discharge and the Steamer Mechanism [2]. Townsend Discharge only applies in uniform electric fields, the simplest of forms being parallel plates, whereas the streamer mechanism is commonly used in non-uniform electric fields. The streamer mechanism explains that electrical breakdown in gases begins with the avalanche of electrons which then transition into a streamer, a separation of the charges from the electrode creating a ball of space charge that is propelled by the electric field. As the ball of charge increases in density, it enhances the local electric field at the head generating auxiliary avalanches that feed into it. This in turn increases the speed at which the streamer crosses the gap due to the process only requiring the avalanche of electrons. The avalanche to streamer transition was determined by both Meek and Raether from two different approaches, Meek for the cathode directed and Raether for the anode directed. Streamers are said to be either positive or negative polarity. A streamer is described by its direction of propagation in an electric field and is described as either positive (cathode directed) or negative (anode directed). Meek suggests that the avalanche becomes a streamer when the radial electric field created by the avalanche’s positive space charge reaches an order to that of the applied electric field [3]. Raether theorized that the avalanche will become a streamer when the number of electrons in the avalanche head $N_r$ is approximately equal to $10^8$ or $10^9$ [2]. Once the streamer is fully formed it will continue to propagate, through
a minimum electric field known as the sustaining field. If the electric field is increased beyond a threshold value, known as the instability field, it will cause the streamer thermalizes into a circuit limited arc. The instability field is the minimum electric field value from which the residual streamer channels can form into a circuit limited breakdown.

The instability field can be directly correlated to the corona point. The corona point is the exact transition point from when the onset of corona occurs at the same field uniformity as complete electrical breakdown. By varying the uniformity of the electric field, the corona point can be found for a specific setup, in this experiment a point to plane geometry was used. As the point would move closer to the ground plane, the electric field would experience more uniformity. Direct relationships between the corona point, the instability field, and the sustaining field, allows for a process in which they can be experimentally measured.

In the commonly used configuration of the point-to-plane electrode configuration used here, the streamer polarity can be correlated to the voltage applied to the point. That is, a negative voltage applied to the point is a negative streamer propagating toward the anode.

1.2 Previous Works

The streamer sustaining field is the minimum electric field required for an established streamer to maintain propagation. The magnitude of the sustaining field is well below the nominal dielectric strength of air (~ 32 kV/cm at Standard Temperature and Pressure STP). The concept of a minimum electric field for sustaining propagation of a streamer was first proposed by Acker and Penney [4] while investigating the conflicting models of

Wright hypothesized a model of a positive streamer as an extension of the electrode. That is, the conducting filament protruding into the gap acts as a conducting rod extending from the point electrode to the streamer tip as it propagates, severely distorting the potential distribution in the gap and producing a very high electric field region ahead of the propagating streamer tip – approximately the potential of the point. Dawson and Winn proposed a model for positive streamer propagation where the ionizing tip of the primary positive streamer assumed to be a spherical collection of positive charge, which, after leaving the high-field region near the anode, becomes isolated from the anode and advances as a result of photo-ionization and avalanche multiplication just ahead of the streamer tip. Their experiment launched a positive streamer from a point electrode which was re-energized as it passed through ring electrodes to which carefully timed negative pulses are applied. The fields associated with the streamer generation and then subsequent propagation are clearly differentiated. The potential of the streamer tip was hypothesized to be able to propagate through regions where the electric field was zero – known as the “zero field” hypothesis. The electric field in the low field region of the gap serves only to guide the path of the streamer tip.

The Acker and Penney experiment allowed streamers to propagate through holes in metal rings. In general, the experiment supported the Dawson and Winn model of an isolated net charge propagating along an electric field rather than that of Wright. Acker and Penney were the first to determine that a minimum field exists far from the cathode
necessary to sustain streamer propagation and determined the value for the positive streamer to be 4.6 kV/cm. The Acker and Penney data is reproduced below in Figure 1 showing the streamer completion criterion.

![Figure 1: Acker-Penny data showing that the streamer is not self-propelling [4]](image)

The Winn-Dawson and Acker-Penney experiments greatly informed the development of the streamer theory used today. The Winn and Dawson model proposed that the streamer tip gains energy in the high field region of the gap at the point and later dissipates some of this energy in propagating through the low field region of the gap (a few millimeters from the point to the cathode). This was a key element in the energy balance approach used in nascent computer simulations of Gallimberti [7]. Acker and Penney disproved a key element of the “zero field” hypothesis of Winn-Dawson by noting that the “value of the electric field far from the point significantly affects the distance a streamer propagates rather than just guiding the path of the streamer” [4]. Their experiments with rings indicate that the potential at the streamer tip is not significantly different than the field in
the gap, except perhaps close to the streamer head. This has been validated by simulation [8].

Phelps used a now classic experimental setup where streamers were launched in a highly divergent field (point electrode) and then advance into an approximately uniform field region between charged parallel plate electrodes [9]. The potential of the pin electrode and the background electric field are decoupled. Phelps’s early measurements yielded values between 6 and 7 kV/cm for the positive streamer sustaining field in atmospheric air. Further validation was provided with contemporary computer simulations by Gallimberti, concluding a background electric field of 7 kV/cm was sufficient for stable streamer propagation and, more importantly, advanced the energy budget argument for an isolated system. At the sustaining field, the streamers acquire just enough energy through their interaction with the field to supply the losses incurred in ionization and excitation as they advance.

It appears that by 1976, it was accepted that positive streamers, once produced by a suitable pointed electrode, propagate indefinitely in the direction of the electric field if its strength is equal to or greater than a critical value known as the sustaining (or stability) field with a value of between “4 and 5 kV/cm” [9]. Because of the considerable uncertainty in both computational and experimental results, this range continues to be quoted [8].

Perhaps the most widely accepted experimental verification of the sustaining field for the positive streamer is the experiment of Allen and Ghaffar [1]. Using an experimental setup similar to Phelps [9] [10], but with the addition of advanced diagnostics, measured a
minimum sustaining field of 4.4 kV/cm as well as a comprehensive comparison of previous experiments from literature, reproduced in Table 1 below.

Figure 2: Experimental setup used by Allen and Ghaffer [1]

<table>
<thead>
<tr>
<th>Reference</th>
<th>Sustaining Field (kV/cm)</th>
<th>Electrode Gap Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phelps and Griffins [10]</td>
<td>4.87</td>
<td>Plane-parallel, 90 mm</td>
</tr>
<tr>
<td>Allen and Boutlendj [12]</td>
<td>4.9</td>
<td>Plane-parallel, 660,470,210 mm</td>
</tr>
<tr>
<td>Acker and Penney [4]</td>
<td>4.60</td>
<td>Non-uniform, 31.7 mm</td>
</tr>
<tr>
<td>Bye, et al. [13]</td>
<td>4.7</td>
<td>Non-uniform, 450 mm</td>
</tr>
<tr>
<td>Allen and Dring [14]</td>
<td>4.14</td>
<td>Non-uniform, 600 mm</td>
</tr>
<tr>
<td>Geldenhuys [15]</td>
<td>4.64, 4.894</td>
<td>Non-uniform, 500 mm</td>
</tr>
</tbody>
</table>

Table 1: Positive streamer propagation fields
Allen notes the principal experimental difference was the nature of the voltage applied to the point streamer source and its position. Allen and Ghaffar provide an extensive examination of existing literature (including previous Allen results) and conclude that the value of 4.4 kV/cm is the minimum value for atmospheric air.

In [10] [12], the application of a direct voltage to the point resulted in very high fields for propagation, it appears probable that a local glow discharge was set up, reducing the electric field around the conducting volume and so requiring a higher applied field for a streamer to develop. In assessing the work of Bye [13], Allen and Dring [14] and Geldenhuys [15], all of whom measured the field immediately ahead of streamers in a corona discharge just reaching the plane of a rod-plane system, Allen and Ghaffar suggests the technique suffers from the comparatively large spread in the values due to the statistical variation of the corona under impulse conditions. Allen and Ghaffar conclude their assessment with clear statement: “that the value of 4.4 kV/cm represents the field required for the propagation of a streamer of minimum attainable energy in the absence of space charge due to branching, and that this value is, therefore, a threshold characteristic of a single streamer” [1].
Chapter 2

Breakdown, Streamers, Corona, and the Sustaining Field

2.1 BREAKDOWN IN GASES

Electrical breakdown in gases is one of the most common forms of electrical breakdown, it has been widely studied and implemented into modern technologies. Two major mechanisms for electrical breakdown are the Townsend breakdown (successive avalanches predominantly originating from the cathode) and the streamer mechanism. The most common condition under which electrical breakdown may occur tends to drive the mechanism away from the Townsend to the streamer mechanism. These conditions include the degree of non-uniformity of the electric fields, time dependent electric fields, and degree of overvoltage.

2.1.1 Electron Avalanche

The electron avalanche begins with the any free electrons accelerated by the applied electric fields. These electrons are accelerated in the external electric field until they collide with other neutral gas molecules. The collision excites additional electrons which are in turn also accelerated by the electric field. This continues to occur at an exponential rate, which can be estimated by the following equation

\[ n(d) = n_0 e^{\alpha d} \]

where \( d \) is the distance from the avalanche initiation, \( n_0 \) is the number of initiation electrons, and \( \alpha \) is the Townsend first ionization coefficient which describes the number of electrons generated per unit length.
2.1.2 Uniform Fields – Townsend Avalanche

The most common model for electrical breakdown in uniform electric fields is Townsend Avalanche. The model begins with an electron avalanche, as mentioned in the section above. This process continues exponentially creating more and more free electrons. As the collisions occur electrons are excited generating free ions. The freed ions are accelerated back towards the cathode bombarding it and releasing more electrons, that continue into additional avalanches. Avalanches build up until they can pass enough charge to reach circuit limited electrical breakdown.

2.1.2.1 The Paschen Curve

The Paschen curve is a well-known depiction of the applied voltage at which electrical breakdown occurs (also known as the sparking voltage) as a function of $pd$ - the product of pressure $p$ and gap distance, $d$. This quantity is known as the similarity parameter. The Paschen curve may be generated for any gas and each curve has the same general shape.

Figure 3: The Paschen curve, a plot of sparking voltage as a function of the produce of pressure and gap distance, applies to uniform electric field conditions. The curve has a characteristic shape which varies somewhat by gas species [16].
In the evaluation of electrical breakdown, the Paschen curve must be treated with caution. First, it can invoke panic because at its minimum, the sparking voltage is on the order of a few hundred volts; much lower than the kilovolts breakdown observed at other points in the curve. More importantly, however, the Paschen curve is valid only for uniform electric field conditions with no time dependence – which is not the case in most real-world systems.

This dependence on uniform field conditions is related to the mechanism by which electrical breakdown occurs. At the Paschen Minimum, electrical breakdown occurs by the Townsend mechanism of successive electron avalanches with new carriers generated by ion bombardment of the cathode.

Confusion regarding the Paschen curve is quite understandable since electrical breakdown phenomena’s generally scale with $pd$ because the similarity parameter is essentially a measure of the number of collisions that a charged particle undergoes in an electric field which produces new charge carriers.

2.1.3 Non-Uniform Fields – Streamer Mechanism

In non-uniform electric fields, the Townsend method does not apply as well. What is more commonly thought to occur is the streamer mechanism. The streamer mechanism varies in the breakdown process, it begins with an abundance of successive avalanches that transition into a streamer before ion bombardment of the cathode can occur. These avalanches transitions into a streamer, described in section 2.1.3.1, which then become a fully thermalized arc. The streamer mechanism was theorized by Meek and Raether,
when they discovered that the breakdown in gaps with spacings around 1 cm would occur in time scales of less than a microsecond. The Townsend method, however, requires the successive avalanches to occur limited to the drift velocity of the ions which take up to 10μs to occur in these geometries [2].

2.1.3.1 Streamers

The electron avalanche continues to propagate and grow as it crosses the gap. As the avalanche builds up the electrons begin to separate into a head of charge, this is the transition to a streamer. Two separate theories were proposed independently of each other to determine the criteria for electron avalanche to streamer transition. Meek proposed, for an avalanche, that once the electric field generated by the head of charge $E_r$ reached the order of the applied electric field $E_0$ then the avalanche would transition to a streamer. Raether theorized that for a negative avalanche the transition would occur when the number of electrons in the head of charge reached a critical value of approximately $N_{cr} \approx 10^8$. Both theories for streamer onset are essentially equivalent. Once the avalanche transitions to a streamer it can cross the gap and lead to sparking.

2.2 Sustaining Field

The streamer is a separation from the electrode in the form of a ball of charge. As the head of the streamer increases it begins to propagate faster across the gap. It was once believed that the streamer was self-propelling and could continue to cross the gap without an external electric field, or a zero field value [6]. This was later reexamined by Acker and Penney in 1969, as they discovered that the streamer would in fact die out in a zero
field [4]. This minimum electric field required for the streamer to continue propagation is known as the *sustaining field*.

### 2.3 Corona

A corona discharge is a streamer that is confined in space because the electrical field between the two conductors falls below the streamer sustaining field. Corona is a visible, audible, low energy discharge that occurs in regions of high field enhancements [2]. It is easily detectable in sharp edges of electrical conductors by its signature purple glow around the region. It is also common to hear a hissing sound which is generated by the periodical nature of the local ionization.

#### 2.3.1 Corona Formation

Corona occurs only in non-uniform electric fields and specifically in regions of enhanced fields. This is due to the nature in which it occurs, the high field regions allow for ionization but as the field decreases in intensity a full ionization channel is unable to form. In the literature, corona is sometimes referred to by the confusing terminology of “corona breakdown”. This is not a proper description due to the misleading fact that it would imply corona forms a low impedance channel, instead corona is a high impedance loss in the range of μA to mA. Figure 4 below shows the signature purple glow that is created when corona forms.
\textbf{2.3.2 Corona Point}

For highly non-uniform geometries, corona precedes a breakdown. In evaluating the potential for electrical breakdown, the “corona point” provides a critical criterion – even in the absence of a full understanding of electrical breakdown and corona formation under high frequency conditions. As the electric field become more uniform corona no longer forms, this is due to the lack of field enhancement regions.

An experiment by Uhlmann with concentric cylinders done in 1929 showed how corona precedes the full electrical breakdown in nonuniform electric fields [17]. With a fixed outer conductor radius, Uhlmann applied a voltage between the inner and outer conductors and measured both the breakdown voltage (solid lines) and the corona onset voltage (dashed line) in Figure 5 below. For the fixed outer cylinder radius, as the inner radius gets smaller, the degree of non-uniformity increases. The non-uniform electric field allows a corona to form at the small radius but not at the larger radius. This also
means that when there is high degree of non-uniformity, as the voltage is increased, a corona precedes the electrical breakdown whereas in more uniform electric fields, breakdown occurs directly implying that any streamers crossing the gap transitions immediately into a circuit limited breakdown. The point on the graph where the corona onset curve and the electrical breakdown curve meet is known as the *Corona Point*.

![Corona Point](image)

**Figure 5:** Voltage measurements on corona onset and electrical breakdown between concentric cylinders with varying inner cylinder radii. The smallest radii produce enough non-uniformities that a corona precedes the breakdown. The Corona Point is where electrical breakdown and corona onset occur at the same time. [16]

The Corona Point gives us a criterion for evaluating the probability of electrical breakdown in a non-uniform geometry. That is, a corona may be formed near a sharp point, but the electric field everywhere in the gap must be greater than the sustaining field for the corona to transition to a breakdown arc.
Chapter 3

Experimental Setup

3.1 EXPERIMENTAL SETUP

A custom designed experimental apparatus was made to measure the corona point in a point to plane geometry. The setup as shown below used several forms of data collection all correlated to determine the precise value at which the corona point occurs. The electric field value for corona onset can be varied by the changes in electric field uniformity, to change the uniformity of the electric field a point to plane setup with a variable gap distance is used. As the tip of the electrode is moved closer to the ground plane the electric field becomes more uniform. This occurs because the high field point (the electrode tip) moves closer to the ground plane which reduces the amount of distance for variation in the electric field, meaning that the enhanced field value at the tip also becomes the local field value at the ground plane. Variation in the gap distance is achieved by using a micrometer mount with the electrode attached. This was calibrated by zeroing out the micrometer and manually adjusting the gap distance by varying the micrometer stop until the electrode was in full contact with the ground plane. The four main diagnostics used to determine corona onset and electrical breakdown were, a P6015 high voltage probe, a Current Viewing Resistor (CVR), a Fast-Current Transformer (FCT), and a Photo Multiplier Tube (PMT). Their exact connections to the experiment are shown below in Figure 6.
Difficulties arose in the precision and timing of the signals. To determine the onset of corona in the system a high sensitivity light measurement was required, this was accomplished with a PMT. The onset of corona gives minimal light emission which would normally be overpowered by the naturally occurring light in the laboratory, to remove this background light the experiment was in closed in a shadowbox, a structure comprised of an optical mount metal base and 5 black hardboards, and then covered with a Throlabs BK5 black out sheet. Once encased in the dark space the PMT was set to trigger the DSA 70604 oscilloscope when light emission from the corona would first occur. When triggering the scope, it would be apparent that corona had occurred due to the small milliamp current measured by the FCT. A second triggering method was used to collect when breakdown would occur across the gap. This was done by triggering off the CVR on the ground side of the geometry. The CVR would see spikes in current when the gap would breakdown, this is due to the large amounts of current that passes through the gap when breakdown occurs.
3.1.1 Chamber

To ensure a controlled environment the point plane configuration was encased in a 3D printed chamber with windows on each side to allow for diagnostics. The chamber was created using a Form Labs Form2 3D printer with the tough resin from a custom designed 3D model [18]. The chamber measured 90mm x 90mm x 110mm with a total internal volume of 0.891 Liters. The custom chamber was specifically designed to allow for pressurization. This was done by including gaskets at material intersections, such as the side windows and the ground plane. A small rubber gasket was used at the electrode orifice to allow for movement while still maintaining the internal pressure. To allow for smoother movement silica grease was applied to the electrode. Three custom 3/8th inch National Pipe Thread (NPT) threaded holes were printed onto the top of the chamber to allow for commercial pipe fittings to be added. The chamber was filled with a DC Current Viewing Resistor PMM01 Photomultiplier Tube Fast Current Transformer P6015 High Voltage Probe Current Viewing Resistor PMM01 Photomultiplier Tube
compressed gas to remove the humidity from the system and to set the inside to an absolute pressure for easy repeatably of the environment. To pressurize the inside chamber compressed dry air was used, using an inline pressure regulator and gauge the inside chamber pressure was set to 1 atm (or 760 torr). This is known as atmospheric pressure due its commonality with the natural pressure at sea level. This was a requirement to the system, to avoid using estimated scaling laws, since Albuquerque New Mexico is approximately 5,352 feet above sea level with an average air pressure of 0.87 atm or 650 torr. To ensure that the pressure would not exceed the structural limits of the 3D printed chamber pressure relief values as shown in Figure 6 were used. The actual structural limits of the chamber where unknown but testing was done by pressurizing the chamber up to 2 psi and no damage was seen.

![Figure 8: CAD model cross section of 3D printed chamber. Showing the point to plane setup inside the chamber](image-url)
The chamber was fitted with a window on each side to allow for a direct line of sight into the point to plane geometry. The windows were fitted with UV fused silica purchased from Thorlabs to ensure that the maximum amount of light transmission occurs. The largest available windows were chosen to allow for maximum viewing, the windows measured 2 inches in diameter and 12mm in thickness. UV fused silica was chosen due to its high transmission at the desirable wavelengths (300nm – 400nm) as can be seen in Figure 9 below. One window was used to allow for visual inspection into the chamber, either by eye or with open shutter camera. The second window was specifically used to allow the Photomultiplier Tube (PMT) to have direct low loss line of sight to the electrode tip.

![Uncoated UV Fused Silica (10 mm Thick)](https://example.com/uncoated-silica.png)

Figure 9: Transmission of wavelengths through UV fused silica windows [19].

### 3.1.2 Electrodes

The electrodes were created using 3/8” tight tolerance brass rod with a rounded end and was spaced a variable distance from a brass ground plane that was 90mm x 90mm and 1/8th inch thick. To further focus the electric fields on the electrode a tungsten welding
The electrode was attached to the end as seen in Figure 11 below, this allowed for a much finer point with less ablation during breakdown events. The tip was inserted into the brass electrode by drilling tight fit holes and heating the brass expanding the hole, this ensures a good electrical connection and tight bond. The tip of the brass rod was rounded with a 3/8” radius to allow field shaping and to reduce coronal losses premature to the tungsten tip. Before inserting the tungsten tip into the brass electrode shaft, the tungsten tip was shaped into a fine point. This was done using a welding electrode sharpener attachment on a Dremel. The attachment sharpens the tungsten into a fine point by rotating a grinding disk and pressing the electrode against it at an angle. The angle incident on the disk is the angle applied to the tip of the electrode. The electrode used was sharpened with a 42° cone giving an approximate cone height of 2 mm. After the tip was machined, pictures were taken with a ProZoom PZT-6.5 microscope and an Ultra-cam II camera attachment to ensure the precise nature of the machining. Measurements were also performed on the microscope; this was calibrated using a ruler and the built-in software on the camera.

The value of the electric field around the tip of the tungsten electrode is extremely non-uniform due to the field enhancements that occur. This sharp tip makes the electric field difficult to predict analytically. A simplified approximation is \( E_{\text{tip}} \approx \frac{V}{5r} \) where \( V \) is the potential on the tip and \( r \) is the radius of the tip apex [20].
Figure 10: Electrode used, made of brass with a tungsten welding electrode inserted into the tip.

Figure 11: Electrode Tip with measurements overlaid on top, showing a 1.5mm radius, a 41.99° angle, and a 2.18mm cone height.
3.1.3 Power Supply

The electrodes were biased with Acopian power supplies, 30kV and a 2.5mA current limit; this is the maximum output power of the supply. The voltage on the electrode was ramped up as slowly as possible to allow time for the corona formation at each increment. The power supply was ramped at a rate of 0.01kV/100ms or 0.1kV/1s.

![Acopian Rack Mount High Voltage Power Supply](image)

**Figure 12: Acopian Rack Mount High Voltage Power Supply (30kV DC and 2.5mA output)**

The ramping process was done using the external supply control on the back of the power supply. The supply allows for an input voltage of 0-5.1V mapped to the high voltage output of 0-30kV. To utilize the external supply control a National Instruments USB-6001 DAQ was used. The USB-6001 DAQ allows for analog outputs of -10V-10V with respect to the ground input through two different analog outputs. The DAQ was grounded to the power supply control reference ground and one of the analog outputs was connected to the external supply voltage programmer. Outputting an analog voltage between 0-5.1V from the DAQ allowed for full control of power supply. The DAQ has a
14-bit Digital to Analog Converter (DAC) used to generate the analog output voltages, this gives a discrete voltage step of 1.2mV. The USB-6001 was also capable of analog inputs with 14-bit resolution. Alongside the external voltage controls the power supplies also offered an external voltage reference scaled at 10,000:1 volt. This allowed for the USB-6001 to read the high voltage output of the power supply with reasonable accuracy. As well as the external reference voltage for the high voltage output the power supply also had a reference voltage for the current supplied. The reference output was connected to one of the analog inputs of the USB-6001 to give insight into the current supplied, the reference was scaled as 1V/mA with a maximum output current of 2.5mA. The USB-6001 is a national instruments device designed to be utilized with LabVIEW. To control the USB-6001 a LabVIEW program was created that is discussed in more detail in the proceeding sections.

![USB-6001 DAQ](image)

Figure 13: National Instruments USB-6001 DAQ used to control the power supplies from LabVIEW.
3.1.4 Voltage Probe

The voltage of the electrode was measured using a Tektronix P6015 high voltage probe. The Tektronix P6015 is a commonly used high voltage probe in pulsed power measurements. It allows for simple measurement of DC voltages up to 20kV well above the maximum voltage required for breakdown in the gap. The probe had an internal capacitance of 3pF and resistance of 100MΩ. This 100MΩ resistance was used as a ballast across the gap as can be seen in Figure 7. To ensure a good electrical connection the electrode was physically attached to the P6015 high voltage probe by screwing on the end via a 10-32 threaded hole. The high voltage probe allowed for a better measurement of the electrode voltage compared to the power supply. The power supply indicated the supplied instantaneous voltage, while the P6015 high voltage probe allowed for a time resolved depiction of the voltage applied on the electrode. Giving a visual of when breakdown occurred, due to the voltage waveform dropping significantly during breakdown.
3.1.5 CVR

The current through the ground plane was measured using a current viewing resistor commonly known as a CVR. The specific product used was a T&M Research Products model SSDN-414-01. A precise, low inductance, and small resistance of 0.0997Ω is put in series between the large plane electrode and the system ground. By measuring the voltage across the resistor, it is possible to calculate the current through it using Ohm’s law. This allows for indication of streamers crossing the gap. As the corona pulses, streamers are emitted and they travel across the gap, the CVR can detect these current pulses. These small pulses are only discernable qualitatively and not quantitative due to their low value and close relation to the system noise. The CVR was mostly used to measure the breakdown current and verify that breakdown had occurred. When the gap
breaks down a large spike of current is generated due to the resistance of the gap dropping quickly.

Figure 15: A picture of the CVR used, shown connected in series with the ground plane.

3.1.6 FCT

Data capture of the corona require precise measurements of current. The power supply displays the given amount of supplied current in a low-resolution form. This is not adequate to give insight into how much and when current is passing through the electrode. To measure the precise amount of current flowing through the electrode a Bergoz Fast Current Transformer (commonly called an FCT) was used. The model of Bergoz FCT used was the FCT-055-0.50-WB with 0.5V/A gain and a 1.5GHz bandwidth. The FCT was placed with the electrode passing through it, this allowed the FCT to
measure the current flowing in through the electrode, most commonly the current required to produce the corona streamers. The FCT was chosen due to its ability to quickly capture the low current pulses that occur from corona. Current pulses as lows a few milli amps were easily captured flowing through the electrode. The FCT was a non-intrusive way to measure the current. Another benefit to the FCT was its ability to handle the larger amounts of current that would pass through it when breakdown occurred, although unmeasurable due to clipping, the FCT was not damaged by such events.

![FCT Image]

Figure 16: Bergoz Fast Current Transformer

3.1.7 Photomultiplier

To determine when corona had occurred a PM001 Throlabs photomultiplier tube was used as seen in Figure 17.
The photomultiplier tube would detect the faint light emission that occurs when corona first appeared. It was placed with a direct line of sight to the tip of the electrode. The PM001 is sensitive in the 300 nm - 500 nm range as can be seen in Figure 18. This is the dominant wavelength of light emitted from the electrode when corona occurs, 300 nm – 400 nm as according to spectrum captured by Grum and Costa in 1976 [21]. The photomultiplier works by creating a cascade of electrons to create a current and therefore output a voltage. The photomultiplier was mounted to the pressure chamber by custom printing a 3D window flange it could mount to. Because the photomultiplier is not designed to be pressurized it could not be mounted with a direct path to the inside of the chamber. To allow for the photomultiplier to still have a line of sight into the pressurized area a window was placed between the optical input of the multiplier and the chamber. This allowed for a separation of the pressure from the photomultiplier. The window as
mentioned in section 3.1.1, provided minimal attenuation to the light created by the corona and should not have affected the sensitivity of the photomultiplier.

![Spectral Response](image)

**Figure 18: PM001 Spectral Response [22]**

![Corona emission](image)

**Figure 19: Spectral emission of corona in air [21]**
Difficulties arise when reaching extremely sensitive triggering from a photomultiplier. The photomultiplier can be triggered from any amount of leakage light that enters the experimental setup, since the amount of light produced by the corona is extremely dim.

To ensure that proper triggering of the scope occurred from the corona light, pulses of current were also visible as noted in Figure 21. As can be seen in Figure 20 there are no pulses of current, this implies that the photomultiplier was triggered from light that leaked into the experimental setup.

![Figure 20: Example of False Trigger from Photomultiplier](image)

Figure 20: Example of False Trigger from Photomultiplier
Figure 21: Example of True Tigger from Photomultiplier, with respective current pulse.

3.1.8 Oscilloscope

Data was collected with a Tektronix DSA 70604 oscilloscope, with three separate channels. The DSA 70604 has a sample rate of 25GS/s and a bandwidth of 6GHz. The high sampling rate and bandwidth are necessary for capturing the onset of corona and the breakdown pulses with good resolution. In order to support the 1MΩ input impedance of the Tektronix P6015 a second scope was used. The PicoScope 3205D has a sampling rate of 5GS/s and a bandwidth of 100MHz. Although the PicoScope has a much smaller bandwidth and sampling rate it is adequate since it was only used to capture the voltage ramp which occurs at 0.1kV/1s. To ensure that the two scopes would capture the data at the same time the PicoScope was set to trigger at the same time as the DSSA 70604. To accomplish this the AUX OUT of the DSA 70604 was connected to channel 1 of the PicoScope. The AUX OUT of the DSA 70604 is set to 5V or HIGH until the scope is triggered at this point the output drops to 0V or a LOW state. Using this change in signal the PicoScope was set to trigger on the falling edge of its channel 1. To ensure that both
waveforms aligned the scopes had to be manually set with the same time scales and delays.

![Oscilloscopes used and connection diagram](image)

**Figure 22: Oscilloscopes used and connection diagram**

The DSA 70604 was used to capture the data from the FCT on channel 3, the CVR on channel 2, and the Photomultiplier Tube on channel 4. To properly calibrate the channels external attenuation had to be applied to the FCT and to the CVR. The FCT has a datasheet given gain of 0.5V/A, this implied an external amplification of 2 times or -6dB to be set on the scope for the correct current value. The CVR had a given precision resistance value of 0.0997Ω this implied for an external attenuation of 100 or 40 dB, this is calculated using ohms law to determine how the measured voltage relates to the current. The PMT did not require an external attenuation as its output is a 0-5V signal, well within the scopes input range. On the PicoScope the P6015 high voltage probe was measured with an external attenuation of 1000 or 60dB.

### 3.1.9 Triggering

As the gap distance was varied in multiple waveforms were collected for both, corona onset and full electrical breakdown. Two different triggering methods had to be used because of the vast differences in the waveforms. For the corona onset the oscilloscope
was triggered from the FCT (Channel 2). The rising edge of the channel was used to
trigger the scope because of its high reliability. The FCT measures the current passing
through the electrode and was a straightforward approach to triggering, because if no
current is passing through the electrode then there would not be corona.

Because of the vast difference in the signals obtained a different triggering method had to
be used for full electrical breakdown. When electrical breakdown occurs, the impedance
of the gap greatly drops. This is due to the plasma channel that is created, this in turn
allows large amounts of current to flow through the gap. To properly measure these large
currents the CVR on the ground side of the gap had to be used. The CVR could easily
handle the currents passing through the gap. Triggering for the breakdown voltage was
done on the rising edge of the CVR. The CVR would only have a large rising edge if
there were large amounts of current flowing through the gap, only possible if breakdown
occurred.

3.1.10 LabVIEW
The experiment was operated using a rackmount PC with LabVIEW installed. To
properly control the power supply and collect the data captured by the oscilloscope a
custom LabVIEW program was created. The program consisted of two main Virtual
Instruments (VI’s) running in parallel, one to control the high voltage power supply and
the second to interface with the oscilloscope and retrieve the data to be processed. To
properly collect the data captured on the oscilloscope the computer was interfaced with a
GPIB cable. The GPIB, also known as IEEE 488, is a short-range digital interface that
allows for fast data transfer from compatible devices. Using the LabVIEW supplied
Tektronix 7000 series scope drivers and sub VI’s the program would collect the captured data points and process them to be displayed on a graph.

One second feature of the LabVIEW program was to combine the collected data points from the Tektronix oscilloscope and the PicoScope. Since two separate oscilloscopes were used with two different capture resolutions, the data had to be combined in LabVIEW. A two-step process was used to import and combine the captured waveforms. The first step of the process required the use of PicoScope 6 software that was supplied with the PicoScope, the software was used to capture the data from the PicoScope and save it in .csv form to the rack PC. The software was set to collect the waveform on the same time division as the Tektronix scope and with the maximum allowed sampling rate of 2 GS/s. Once the scope was triggered the collected waveform was saved to the desktop to allow for the second step of the process to take place. The second step of the process was to combine the waveforms captured by the two separate scopes into a single file. This was done inside the LabVIEW program by first, reading the data from the Tektronix scope and second reading the saved .csv file generated by the PicoScope 6. Once the data was combined it was saved as a text file to allows for quick loading of data.

The second VI was used to control the power supply. The power supply allowed for remote control though analog voltages. To generate the analog voltage required for the supplies a National Instruments USB-6001 DAQ was used. This was controlled through the LabVIEW program, providing full control of the power supply. The LabVIEW VI allowed for a multitude of parameters to be set when controlling the power supplies. To generate the ramping of the voltages the VI allowed for the user to set a ramp rate by
setting the size of a single voltage step and the time between steps. This allows for
custom ramp rates to be created by the user of the program. As well as being able to ramp
the voltage, the program allowed for a fixed set voltage on the supply, a value between 0-
30kV could be entered and the supply would be set to that voltage. The program also
included safety features for simplified control of the system. As the VI would ramp the
voltage a feedback was read to detect breakdown. To detect breakdown the VI would
monitor the power supply voltage and current outputs, if there was a spike in the current
between measurements the VI would assume breakdown and shut off the supply. A
second breakdown detection mechanism was used, this was done by monitoring the
voltage output by the power supply and comparing samples. The VI would compare the
measured voltage sample to the previous one, if the difference was greater than the user
set threshold the VI would assume breakdown and shut off the power supply. The VI was
also used to set the gain voltage of the photomultiplier tube. This was done by generating
an analog voltage from the same USB-6001 DAQ that controlled the power supplies. The
VI allowed for the user to set an analog voltage value between 0-1.8V to be output to the
photomultiplier. This value would be set and held for as long as the VI was running.
3.2 DATA COLLECTION PROCESS

Each collected data set began with setting the gap distance with the micrometer. After the gap distance had been set, gas was flowed through the chamber to remove humidity and clear out any impurities in the chamber. After gas was flowed through the chamber it would be sealed and maintained at the 760 torr absolute pressure. Every shot required the two oscilloscopes to be set to single capture with the appropriate triggering method, triggering off the FCT or PMT for corona onset or triggering off the CVR for breakdown. After the gap distance, pressure, and scopes were all set the power supply would be ramped slowly until the DSA 70604 scope would trigger. Once the scope would trigger the data would be read from the scope into the LabVIEW program and then saved into a text file. The LabVIEW program would also read and display the maximum voltage of
the first 1000 data points captured and this number would be manually entered to an excel datasheet, this was to help speed up the data collection process. Only the first 1000 data points of the capture would be used because when breakdown would occur noise would be introduced into the system causing non-real voltage measurements.
Chapter 4

Results

4.1 Experimental Results

The recorded values are the maximum voltage obtained by the P6015 High Voltage probe. The data was plotted with the same respect as the Uhlmann [17] data as seen in Figure 5 to allow for an easy visualization of the corona onset versus the full electrical breakdown. The Y-axis shows the maximum recorded voltage at the given X value, the gap distance.

Figure 24: Experimental data collected at 760 Torr pressure with dry air. Ramp rate of 0.01kV/100ms
As the gap distance closes the corona onset and electrical breakdown curves converge to a single point. They are approximately equal at a 4.5mm gap distance. This indicates that the corona and electrical breakdown are occurring so closely they cannot be distinguished. This corona point, in the data shown in Figure 24, is approximately at 4.5mm and 5.75kV. The actual corona point gives no viable information into the minimum electric field required for streamer to arc transition. Simulating the same geometry as the experimental setup will allow for insight into the minimum field in the geometry, this minimum field is the hypothesized instability field and sustaining field.

### 4.2 Simulations

The minimum electric field in a non-uniform geometry can be difficult to calculate analytically. To gain an estimate Computer Simulation Technologies’ (CST’s) electrostatic solver or low frequency solver was used. The experiment geometries were modeled, and the electric field was measured at its minimum and maximum points.

#### 4.2.1 Point to Plane Experimental Results Simulation

After the corona point was measured experimentally to determine the minimum electric field for breakdown at the given gap distance and potential, simulations were done. The experimental geometry was replicated in the CST electrostatic solver. The simulation was set with two parametric values, the gap distance between the electrode and the ground plane, and second the potential applied to the electrode pin. The CST electrostatic solver allows for quick simulations with minimal user input. To simplify the simulation all conductors in the simulation were declared Perfect Electrical Conductors (PEC) with no losses. The bounding box of the simulation was set to open; this implies no limits to the
simulation up until the bound box boundary. The model was created with the same geometry as the experimental setup. To increase the similarity between the model and the physical setup the electrode model was created with the measured values and was not terminated into a finite point. Instead the tip of the electrode in the model is flattened to simulate the same imperfections that occurred in the physical electrode. The electrode tip was given a 0.016mm radius at its point to reduce any mesh anomalies that would occur with a finite point. This was chosen to allow for quick simulations, in the desired precision, without any errors. As can be seen in Figure 25 below the mesh was enhanced in CST near the electrode to create a smoother curve for the electric field plot. This was done by applying local mesh properties to a hidden rectangle that encompassed the electrode tip and the gap.

![Figure 25: Screenshot of CST simulation model and mesh](image)

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Using the experimentally measured corona point values of 5.75kV at 4.5mm gap distance the minimum electric field simulated at 4.4kV/cm nearest to the ground plane as expected. Figure 26 below shows the variation in the electric field uniformity in the geometry. Figure 26 is the electric field plotted along a straight-line emerging from the tip of the electrode to the ground plane, this is the most direct path between the electrode and the ground plane. The sharp point of the electrode enhances the electric field and hence generates much higher electric fields than anywhere else in the experiment. This is prominent in on the right-hand side of Figure 26, as this is the field value closest to the electrode tip.

![Figure 26: Electric field from tip of electrode to the ground plane with a gap distance of 4.5mm and a potential of 5.75kV. Y-axis units in V/m and X-axis unit in mm.](image)

Simulation of the corona point gives insight into which value the minimum electric field must reach to achieve breakdown. When collecting data each point is an average of 10
data samples. This means there is a range in which corona onset occurred, and therefore a range for the corona point. The standard deviation between point for values collected at 4.5mm is 0.48 kV. This implies that the minimum electric field, or measured sustaining field varies from 4 kV/cm to 4.9 kV/cm.

<table>
<thead>
<tr>
<th>Gap Distance (cm)</th>
<th>Voltage (kV)</th>
<th>Min Field (kV/cm)</th>
<th>Max (kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45 (-σ)</td>
<td>5.28</td>
<td>4</td>
<td>13</td>
</tr>
<tr>
<td>0.45</td>
<td>5.76</td>
<td>4.4</td>
<td>14.2</td>
</tr>
<tr>
<td>0.45 (+σ)</td>
<td>6.24</td>
<td>4.9</td>
<td>15.4</td>
</tr>
</tbody>
</table>

Table 2: Corona point and standard deviation from average, plus and minus.

Additional points of the experimental data were also simulated to determine if any correlations could be found. The minimum electric field varied dramatically in the corona onset data, this could be due to the statistical nature of the corona. It was hypothesized that the minimum field at any point in corona onset curve would be the sustain field. Until more precision can be achieved it is not possible to make this determination.

<table>
<thead>
<tr>
<th>Gap Distance (cm)</th>
<th>Voltage (kV)</th>
<th>Min Field (kV/cm)</th>
<th>Max (kV/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>4.9</td>
<td>3.6</td>
<td>20</td>
</tr>
<tr>
<td>0.55</td>
<td>5.6</td>
<td>4.6</td>
<td>22.5</td>
</tr>
<tr>
<td>0.5</td>
<td>5.7</td>
<td>5.26</td>
<td>24.6</td>
</tr>
</tbody>
</table>

Table 3: Minimum and maximum electric field of corona onset points
4.2.2 Ulhmann’s Concentric Cylinders

In an effort to compare the corona point with other data, simulations of Ulhmann’s concentric cylinders (see Figure 5) was also performed [17]. To increase the accuracy of reading the graph online data extraction software was used [23]. Once the given data points were chosen a simulation of the coaxial cylinder geometry was done. The cylinders are made of PEC to simplify the simulation, and to reduce computation time the simulation was done with quadrant symmetry. The minimum and maximum electric field was collected from a line spanning the distance from the inner conductor to the inside radius of the outer conductor.

![Simulation geometry of concentric cylinders used, with mesh showing.](image)

The minimum electric field calculated was done with an inner conductor radius of 0.43cm and an outer conductor of 5 cm. The inner conductor was set to a voltage of 52kV, and a plot of the electric field was created. The electric field was plotted along a
straight line between the two conductors, and the minimum field was calculated to be 4.3kV/cm. Extremely close in value to that of the point to plane geometry.

![Plot of the electric field along a straight line between the two conductors.](image)

**Figure 28**: Plot of the electric field along a straight line between the two conductors.

In Figure 28 the electric field goes to zero at the end of the plot. This is due to meshing errors that cause the measurement to pass inside inner conductor. Because the conductor is made of PEC there is no electric field inside, hence the zero-field value.
Chapter 5

Conclusions

5.1 Sustaining Field

The calculated minimum electric field was well within the range of referenced values from Allen and Ghaffar [1]. The most commonly referred value for the sustaining field is 4.4kV/cm. This is the same value for the minimum electric field calculated with the same geometry as the corona point in the experimental setup. This is also extremely close to the value calculated from Uhlmanns geometry which had a minimum electric field of 4.3kV/cm at the corona point. This would imply that the sustaining field and corona point have a direct correlation, and the minimum electric field at the corona point is most probably the sustaining field.

5.2 Future Works

The research and experimental setup begun during this thesis work can be pursued in a variety of ways. Interesting research would be experimenting with different gasses such as Nitrogen and Sulfur Hexafluoride (SF6). These gasses are commonly used in a wide range of devices and providing information on their sustaining field can support computational and theoretical evaluation of these systems. In addition to other gases, using different pressures could also give insight into the differences in the sustaining field further improving our ability to predict breakdown in non-uniform electric fields when the Paschen curve is invalid.
References


