Abstract

GARCIA, KEEGAN SIMONE. X-ray Generation and Exploring Triboelectric Effects. (Under the direction of John Muth.)

X-ray generating systems are an important tool in modern medicine for imaging and pathology. Modern x-ray generation systems are reliable and efficient, but command a high-price and high power requirement, creating a barrier-to-entry for this technology in poor or underdeveloped countries. An alternative means of generating x-rays was found through the phenomenon of triboluminescence. This phenomenon could be exercised through the peeling of inexpensive off-the-shelf scotch tape in a vacuum environment.

A tape-peeling triboluminescence system was designed and fabricated. The system consisted of two shafts, with one attached to a motor that could be used to unwind a roll of tape. The two shafts were secured inside a vacuum chamber, and a pair of magnetic disk couplers were used to couple rotation from the motor located outside the chamber.

The system was found to emit x-rays of a high enough intensity so that conventional dental x-ray film could be imaged. Additionally, the light and RF emissions from the triboluminescence system were investigated. These investigations gave new insight into the physical mechanisms behind triboluminescence and triboelectric effects.
Biography

Keegan Garcia was born in Tampa, Florida on August 23, 1988. He grew up in Palm Harbor, Florida and attended Palm Harbor University High School where he graduated in 2006 with an International Baccalaureate degree. He attended the University of Central Florida, where he developed an interests in physics, optics, and nanoelectronics. He graduated in May of 2010 with a Bachelor’s degree in Electrical Engineering with Honors. In the summer of 2010 he joined Dr. John Muth’s research group at North Carolina State University. Outside of science he has a passion for swimming, guitar, and automobiles.
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Joe Matthews for his support throughout my research. His continued support and advice allowed this project to be successful. Without him, I would not have been able to fabricate many of the components for this project nor would I have been able to troubleshoot the many issues with the vacuum system and chamber.

My family and friends for their continued support and motivation as I make my way through graduate school.

My fiancée Blair Remington, for being my biggest fan and cheerleader.
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Chapter 1

Introduction

1.1 X-ray Generation

X-ray generating machines are an important component of modern medicine. X-ray generating machines have a variety of uses in medical imaging, the pathology of the skeletal system, the detection of malformations in soft tissues, computerized axial tomography scans or fluoroscopy.

X-rays are a form of electromagnetic radiation, and range in wavelength from 0.01 to 10 nanometers. Typically x-rays are characterized by energy and penetrating ability, and they can be labeled either "soft" or "hard". Soft x-rays range in energy from 0.1 to 12 keV, and hard x-rays range in energy from 12 to 120 keV. Hard x-rays are used for most practiced medical applications because of the superior penetrating ability.

X-ray generation machines use a special type of vacuum tube that is known as a Coolidge tube. In a Coolidge tube, a high-voltage is established across the cathode and anode, creating a channel of conduction across the vacuum. This conduction channel allows electrons to be accelerated from the cathode into the vacuum and then be collected by the anode. When these electrons traveling at high velocity collide with the anode material, they decelerate suddenly and lose a great deal of energy. This energy drop is accompanied by the emission of electromagnetic radiation known as Bremsstrahlung, or braking radiation. The radiation spectrum of
Bremsstrahlung is dependent on the magnitude of the voltage used to accelerate the electrons and if high enough, can cause the generation of hard x-rays.

X-ray generation is also dependent on the material composition of the anode. The electrons high-velocity collision with atoms in the anode can cause an atom’s "'K’" shell electrons to jump to a higher energy orbital. The excited electrons will then transition back to the innermost "'K’" shell. The electron transition results in an intense x-ray radiation at the specific transition energies. These energies correlate to the energy level differences between the "'K’" shell level and the higher energy levels of the anode atom. Today’s x-ray generation machines make use of x-rays generated from both Bremsstrahlung and the electronic transition between atomic energy levels.

Besides vacuum tubes, other x-ray sources exist that are typically only used in specialized cases. Synchrotrons are widely used in research, and are capable of generating x-ray fluxes that are several orders of magnitude greater than those of vacuum tubes. Yet synchrotrons’s high cost to build and maintain limit their practicality in medical use. Some materials (such as $^{55}$Fe or $^{137}$Cs) exhibit radioactive decay that produces photons of energies in the x-ray region. However, the flux of x-rays from radioactive decay is not directly controllable, making accurate exposure and dose control difficult for medical purposes.

Since x-rays were discovered in 1895 by German physicist Wilhelm Röntgen, the means of generation for medical purposes has changed little. Modern x-ray vacuum tubes have several distinct advantages over their older counterparts. Modern systems maintain very high electron beam power densities (corresponding to power ratings up to 100kW), and are engineered for much higher anode temperature capacities, giving today’s systems an increased efficiency. Today’s systems also allow for very small focal spot sizes down to 1mm$^2$ for increased resolution.

X-ray generating machines’ high cost and high power requirement create a barrier-to-entry for poor or underdeveloped countries. A typical modern day X-ray generation machine can cost as much as 50,000 USD and - as previously mentioned - may have a power requirement as high as 100kW. These requirements make these machines a costly, and possibly impractical tool in
poorer nations. However, it’s undeniable that X-rays would serve as as an invaluable medical tool and need to ’somehow’ be brought to these countries.

1.2 An X-ray Tube Alternative

1.2.1 Use of Triboluminescence

This thesis investigates an alternative method to generate x-rays. Fundamentally, this requires the generation of an electric field large enough to create the high voltages seen in today’s modern x-ray generation systems. One solution makes use of a phenomenon known as Triboluminescence. Triboluminescence is the mechanism by which when two contacting surfaces are separated, a difference in charge is created between the two surfaces which then recombines and results in light being emitted. The presence of this light emission has been scientifically known for many years [15] and corresponds to the discharge from gas ionization. Recently, it has been found that the electromagnetic radiation emitted changes under vacuum. Not only is light generated, but so are X-rays [3,20]. This radiation is thought to be generated in a similar means to today’s current x-ray generation systems: through Bremsstrahlung mechanisms.

1.2.2 System Objectives

An x-ray generation system utilizing the phenomenon of Triboluminescence should meet several key requirements to be considered suitable for use. These main requirements have been listed below:

- Generate X-rays - Arguably the most important criteria; it must be proven that a system can in fact generate X-rays.

- Image using X-rays - In order to be considered a useful replacement to today’s X-ray generation systems, the triboluminescent system must be able to expose a radiograph.
• Mechanically Powered - The system must not require high voltages, and should be mechanically powered.

• Low Cost - The system will need to be able to be constructed with a minimum amount of funding. This will be approximated to below 500 USD.

1.3 Goals of Research

1.3.1 Investigate Triboluminescence of Scotch Tape

The goal of this research is to investigate the use of scotch tape as a means to mechanically separate charge and induce a strong electric field. This strong electric field should create a high enough voltage such that the separated charge is accelerated in vacuum and then decelerated rapidly to produce x-rays.

The goal of this research project is to create a peeling-tape triboluminescence system with the purpose of generating X-ray radiation and to develop an understanding of the mechanisms by which these X-rays are generated. The structure of the report is as follows:

Chapter 1 is the introduction.

Chapter 2 provides a review of the fundamental physics of triboluminescence and x-ray generation.

Chapter 3 is a review of other pressure-sensitive adhesive based x-ray systems.

Chapter 4 discusses the experiment construction and methods used.

Chapter 5 presents the experimental results and analyzes the performance of the peeling-tape triboluminescence system. This includes the analysis of the intensity and spectrum of the light generated, the verification of X-ray generation, and the analysis of any RF signals produced.

Chapter 6 outlines suggestions for future work.

Chapter 7 is the conclusion.
References


Chapter 2

Background

This chapter discusses the physics of triboluminescence and other triboelectric effects. The peeling tape system used to study these triboelectric effects resembles the simplified diagram in Figure 2.1.

In Figure 2.1, an uptake cylinder forces the peeling of tape. When these layers of tape are separated, charge densities are exposed on the freshly peeled sections of tape. Subsequently, these charge densities discharge and produce various types of radiation. This chapter will explain and illustrate the mechanisms that generate this radiation.

2.1 Tribology

Tribology is the science of the interaction and mechanisms behind contacting surfaces in relative motion. Traditionally, the study of tribology has more applied to mechanically-focused engineering disciplines such as friction, lubrication and wear. This chapter focuses on the narrower subset of tribology known as triboelectricity with a focus on how triboelectricity produces triboluminescence and other effects. Triboluminescence describes the photon emission that accompanies the separation of two contacting surfaces.
2.1.1 Surfaces and Charge

When two solid surfaces interact and come into contact with one another, charge can transfer from one surface to another [14] in a process known as contact electrification. This results in a positive or negative charge developing on the surface of a material. The tendency of these materials to develop either a positive or negative charge is outlined in lists known as triboelectric series [10, 16, 26]. Materials such as glass or asbestos top these triboelectric series as materials that have a high tendency of developing positive charge while materials such as rubber and Teflon sit on the bottom and have a high tendency of developing negative charge.

The triboelectric series created with certain sets of materials is not always unidirectional [10]. Some sets of materials form what is known as a cyclic triboelectric series. These series are unique in that the materials in the series are seen as becoming ‘more negative’ or ‘more positive’ depending on the direction in which one cycles through the materials in the series. The existence of a cyclic series suggests that contact electrification is not dependent on a single central physical property or mechanism.

The cyclic nature of these triboelectric series suggests that contact electrification can in-
Table 2.1: Example triboelectric series adapted from a compilation of triboelectric sources [10].

<table>
<thead>
<tr>
<th>Example Triboelectric Series</th>
<th>More Positive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human Hands</td>
<td></td>
</tr>
<tr>
<td>Asbestos</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td></td>
</tr>
<tr>
<td>Mica</td>
<td></td>
</tr>
<tr>
<td>Nylon</td>
<td></td>
</tr>
<tr>
<td>Wool</td>
<td></td>
</tr>
<tr>
<td>Silk</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td></td>
</tr>
<tr>
<td>Cotton</td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td></td>
</tr>
<tr>
<td>Gold</td>
<td></td>
</tr>
<tr>
<td>Natural Rubber</td>
<td></td>
</tr>
<tr>
<td>Polyethylene</td>
<td></td>
</tr>
<tr>
<td>Teflon</td>
<td>More Negative</td>
</tr>
</tbody>
</table>

volve either the transfer of an electron (−) or the transfer of an ion (+ or −). Specifically for the contact electrification of insulators, experimental observations do not agree with bulk electronic properties, and suggest that ionic transfer is the mechanism of choice [23]. McCarty and Whitesides consider contact electrification occurring between two insulators: nylon and polyethylene. According to the traditional triboelectric series, nylon would receive a positive charge while polyethylene would receive a negative charge. If electron transfer is considered, the steps leading to charge separation would require several eV; this includes the removal of an electron from nylon, separating charge across an interface (granted, this can be provided through mechanical separation), and adding an electron to an alkane like polyethylene. Even with the energy introduced through mechanical separation, this total electron transfer would be an endothermic process, with an energy requirement much higher than the thermal energy at room temperature (kT ≈ 0.026 eV), and thus would not be able to occur without the addition of heat.

The idea of electron transfer being a mechanism for contact electrification can only truly be justified between metals or materials with very small band gaps. In such cases, electron transfer can be explained by electrons flowing from differences in contact potential. An illustration of the mechanisms of electron transfer can be seen in Figure 2.2.
An alternative to electron transfer is ionic transfer. In this theory, contact electrification between insulators is the result of the transfer of mobile ions between surfaces of the materials. Several experimental studies support this theory [13, 28], but this research will look at studies performed by Diaz [9, 11]. Diaz performed several studies on ion transfer between ion-containing polymers. These ion-containing polymers contained one type of immobile ion that was covalently bound to the polymer, with the other type of ion mobile and free to transfer to another material. The polarity of these covalently-bound ions had a big influence on the charge acquired by the polymer. Diaz found that when placed in contact with a non-ionic insulator, the polymer always maintained the same sign of charge as the covalently bound ion contained within. The magnitude of the charge on the polymer surface was found to be proportional to the concentration of ions bound to the polymer. This suggests that the covalently bound ions stayed with the polymer and the mobile ions transferred to the other surface, resulting in a separation of charge. This ion transfer mechanism is illustrated in Figure 2.3.
Mechanisms of Ion Transfer

Although contact electrification is a pervasive mechanism, its details are incompletely understood. However, in this thesis ionic transfer is assumed to be the correct mechanism of charge transfer.

Figure 2.4 above illustrates the mechanism of ion-transfer. Each mobile ion on the surface of a material has a vibrational potential energy associated with it. These energies are comprised of short-range surface interactions (such as van der Waals forces) and long-range interactions (such as coulombic forces). When the surfaces are in contact, the mobile ion shared between them occupies an energy state in a single potential energy well. As the two surfaces are separated, the potential well changes shape due to the presence of mobile ions on the surface of both materials. The result is the formation of dual potential wells that are non-equal in energy potential. The energy potential of the covalently-bonded mobile ion will be lower in magnitude due to the coulombic interaction.
Consider the behavior of the ion before the two materials are separated; the ion’s movement will be limited to the single potential well. As the materials are separated and the potential wells begin to split, the ion may be free to move between the two wells until the barrier becomes sufficiently high. At some distance, this barrier will eventually serve to bound the ion within one of the formed potential wells. As distance increases, each surface will maintain a potential well. The distribution of charge in the potential well is dependent on the extent that the charge is mobile and is determined by electrostatics. The energy required to separate the potential wells and to displace one charged surface with respect to the other is provided mechanically.

2.2 Charge Separation and Triboluminescence

The separated charge may be recombined through several different methods. These methods include the tunneling of ions and the dielectric breakdown of the surrounding gas. Charge is assumed to be kinetically bound in deep potential wells after separation, so this section will focus on the dielectric breakdown of the surrounding gas. This dielectric breakdown leads to triboluminescence and the generation of light.

Consider the previous example mentioned in 2.4. As two materials are separated, two potential wells are formed at the materials’ surfaces. These potentials wells define the regions by which charge is bound on the surface of the material. One of these charge regions will be
positive, the other, negative. Without any mechanisms for charge recombination (or mobility of charge since the materials are insulating), the charge density remain the same on both surfaces regardless of separation distance and - from Gauss’s Law - there will be a constant electric field $E$.

\[ E = 4 \pi \sigma \]  
\[ (2.1) \]

Where $\sigma$ is the surface charge density and is equal to:

\[ \pm \sigma = \pm n_o e \]  
\[ (2.2) \]

Where $n_o$ is the ion charge density (assuming each ion only has one charge state), and $e$ is the charge on an electron. We can now consider the voltage potential created between the two materials. From integrating the electric field, we can say that the potential between the two insulators is equal to:

\[ V = E d \]  
\[ (2.3) \]

Where $E$ is the electric field and $d$ is the separation distance between the two surfaces. These equations assume that all surfaces are planar. Furthermore, from Eq. 2.1 we can say:

\[ V = E d \]  
\[ (2.4) \]

\[ = 4 \pi \sigma d \]  
\[ (2.5) \]

\[ = 4 \pi n_o e d \]  
\[ (2.6) \]

It is known that with a minimum electric field strength any insulator can be forced to conduct electricity. This is known as dielectric breakdown, and for dry air is approximately $30,000 \text{ V/cm} \ (\text{or} \ 3 \times 10^6 \text{ V/m})$ [8]. Dielectric breakdown is known to decrease with increasing
values of humidity. Using this information, and Eq. 2.6 we can approximate the ion charge density in dry air.

\[
\begin{align*}
    n_o &= \frac{\sigma}{e} \quad \text{(2.7)} \\
    &= \frac{E}{4 \pi e} \quad \text{(2.8)} \\
    &= 1.49 \times 10^{24} m^{-2} \quad \text{(2.9)}
\end{align*}
\]

This is an interesting value to calculate, as Camara et al have experimentally determined that the average surface charge density is approximately \(n_o \approx 10^{14} m^{-2}\) [3] in other peeling tape systems. There is a dramatic difference of several orders of magnitude between these two values.

Assuming that discharge occurs at a maximum distance of 1mm (This will be verified later in Chapter 5), the highest-energy photons can be determined through Eq. 2.12.

\[
\begin{align*}
    \hbar \omega_{\text{max}} &= e \cdot V \quad \text{(2.10)} \\
    &= 4 \pi \cdot n_o \cdot e^2 \cdot d \quad \text{(2.11)} \\
    &= 2995 eV \quad \text{(2.12)}
\end{align*}
\]

This equation gives photons with values of just a few keV for \(n_o = 10^{24}\). For \(n_o = 10^{14}\), the highest photon energies would be on the order of \(10^{-7} eV\). However, the experimentally determined photon energies have been found to be several orders of magnitude higher than the values calculated [3], sometimes even as high as 100keV. The discrepancy between the experimentally determined energies and surface densities - and their calculated values - suggests that there exists an electric field enhancement between the two surfaces.

It should be noted that the above equations assume that the two surfaces are relatively
parallel to one another. Lazic et al suggest that this ideal case is not entirely true [21], and identify a means by which these even higher photon energies might be possible. Lazic posits that microscale local imperfections in the surface of the insulator material facilitate surface diffusion of the ions, causing charge to "pile-up" at local asperities and create localized regions of very high electric field. There have been many studies concerning the movement of charge on the surface of insulators but unfortunately, the theory behind these diffusion mechanisms is not very well-understood such as it is for metals or semiconductors [14]. The presence and utilization of the micro-asperities in triboluminescence assumes that there exists a certain degree of surface diffusion of the charged particles. Figure 2.5 illustrates the resulting electric field enhancement from the diffusion of surface charge.

2.2.1 Light Generation and Particle Mean Free Path

This discussion of dielectric breakdown in the environmental gas eventually lends itself to the consideration of light production via the ionization of gas molecules (also referred to as triboluminescence). When a high enough electric field is generated through charge separation, the
surrounding air can reach dielectric breakdown and the charge can recombine [18]. For this process to occur, the gas will begin to ionize and a conduction channel through the inherently insulative air is formed. The subsequent acceleration of electrons and ions results in excited states of gas ions that de-excite, emitting photons. The spectrum of the photon emission is entirely dependent on the environmental gas. As an example, triboluminescence in dry air (or $N_2$) emits a spectrum of photons that is identical to the atomic spectrum of Nitrogen [29].

There are several conflicting theories on the details behind the mechanisms of the breakdown and ionization process. These mechanisms are pressure and geometry dependent, but can be grouped into Townsend and Paschen Processes. Townsend discharge is an avalanche process occurring when the gas is ionized [7]. Under a very strong electric field, ions that are accelerated through the conduction channel hit other molecules in the gas, knocking their ions free and creating even more charge carriers. These carriers accelerate under the electric field and then collide with more molecules, providing even more carriers and multiplying the number of charge carriers by a factor of two for each collision.

A second possible description is that the gas ionization occurs through what is known as a Paschen process [17]. Also known as corona discharge, a Paschen process occurs when a plasma develops from an electrode of high potential via field emission. The plasma begins by spreading from the region of high potential - representing the gas that has been ionized - and allowing a channel of conduction. The presence of the plasma expands the effective electrode size and shape, reducing the electric field that is allowed to build between two surfaces. As a result, the ionization may not extend past the plasma, and charge recombination may occur in the surrounding gas instead. For both processes, there is a pressure dependence which is the result of the mean free path of the accelerated charged particles in the environmental gas.

In kinetic theory the mean free path of a particle - in our case an ion or electron - is the average distance the ion or electron would travel before colliding with another particle in a gas. The mean free path takes into account the effective cross-section by which a molecule may collide with another molecule based on their diameter. Considering the density of
molecules in the space, we can find the mean free path by dividing the path length by the number of collisions.

\[
\text{Mean Free Path (m)} = \frac{\text{Distance Traveled}}{\text{Interaction Volume} \times \text{Mols per Volume}} \tag{2.13}
\]

\[
= \frac{v \times t}{\pi \times r^2 \times v \times t \times n_v} \tag{2.14}
\]

\[
= \frac{1}{\pi \times r^2 \times n_v} \tag{2.15}
\]

Where \( r \) is the radius of the interaction cross-section (equal to the diameter of the gas molecule) and \( n_v \) is the number of molecules per unit volume.

The above equation assumes that all of the molecules in the volume are traveling at a rest velocity of zero, which is not correct. The velocity distribution of the gas molecules is required. Thus, we should express our mean free path in terms of an average relative velocity, where the average relative velocity can be expressed as:

\[
\overline{V_{rel}} = \sqrt{2} \times \overline{V} \tag{2.16}
\]

changing the effective interactive volume so that:

\[
\text{MFP} = \frac{v \times t}{\pi \times r^2 \times \sqrt{2} \times v \times t \times n_v} \tag{2.17}
\]

\[
= \frac{1}{\sqrt{2} \times \pi \times r^2 \times n_v} \tag{2.18}
\]

Using Bohl’s Ideal Gas Law to find an expression for the number of molecules in a volume \((n_v)\), we can now express the mean free path as:

\[
\text{MFP} = \frac{R \times T}{\sqrt{2} \times \pi \times r^2 \times N_A \times P} \tag{2.19}
\]
Table 2.2: Example values for mean free path and ion drift velocity. MathCAD calculations and assumed values can be found in Appendix A.

<table>
<thead>
<tr>
<th>Gas Element</th>
<th>Mean Free Path at 760 torr</th>
<th>Mean Free Path at 5 mtorr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen ($N_2$)</td>
<td>99.85 nm</td>
<td>0.015 m</td>
</tr>
<tr>
<td>Neon</td>
<td>1.55 um</td>
<td>0.236 m</td>
</tr>
<tr>
<td>Argon</td>
<td>1.78 um</td>
<td>0.271 m</td>
</tr>
</tbody>
</table>

Where $R$ is the universal gas constant, $T$ is the temperature of the gas, $N_A$ is Avogadro’s number and $P$ is the pressure. In our laboratory setting, we will hold several of these values constant when monitoring the light being generated. The temperature will be held at approximately 293K, and pressure will be varied from atmospheric pressure (760 torr) to approximately 5 mtorr. This gives the following values for mean free path of ions in select environmental gases in Table 2.2.

At atmospheric pressure (760 torr) and relatively low vacuums, it can be seen that the mean free path of an ion is on the order of micron. This provides justification to the theory that the mechanisms of triboluminescence; particularly, to ionization and Townsend discharge. When a mean free path is much smaller than the total distance of surface separation, numerous particle collisions occur in the environmental gas. These collisions are high enough in number to result in an avalanche process and promote a Townsend discharge. At higher vacuums when the mean free path is longer than the separation distance of the electrodes, the electrons or ions travel from one electrode to the other, accelerating at high velocity. The collision at the end of this acceleration results in the generation of x-rays.

2.2.2 X-ray Generation

As mentioned before, charge separation and the consequent charge recombination in a vacuum environment can produce X-rays. Under vacuum, the mean free path of a charged particle accelerated via charge separation between two insulators is many magnitudes higher than the distance at atmospheric pressure (as shown in Table 2.2). The increased distance before scattering allows the charged particle to accelerate for a longer period of time, increasing the particle’s
kinetic energy.

The energy of an accelerated particle can be given as:

\[ KE = \frac{1}{2} m v^2 \] (2.20)

Given a certain electric field, a charged particle will experience a force equal to the charge multiplied by the field. This force will deliver an acceleration dependent on the mass of the particle (whether it be an ion or electron). An ion has a mass that can be several orders of magnitude higher than an electron. Thus, the energies attained by an accelerated ion can be considered to be negligible when compared to the energies attained by the lower mass electrons in the same magnitude electric field.

In the context of two separating surfaces, a mean free path that is longer than the separation distance allows an ion or electron to be accelerated to a great speed until it collides with the insulating surface. The collision generates what is known as Bremsstrahlung Radiation, or stopping radiation. More specifically, the electromagnetic radiation is produced by the deceleration of a charged particle when deflected by another charged particle such as an atomic nucleus. The accelerated particles that cause the emission of Bremsstrahlung radiation are more likely to be electrons because of their higher energies (due to lower mass).

Since energy is conserved, the energy lost from the charged particle is converted into a photon. As the kinetic energy of an ion or electron increases with increasing mean free path, we should expect the energy of emitted photons to increase (to the limit of the distance traveled during acceleration) as environmental pressure decreases. The relationship between the cutoff wavelength and pressure is illustrated in Figure 2.7. The emitted spectrum of Bremsstrahlung should be relatively continuous until this cutoff frequency/wavelength. This is due to the fact that the "stopping" mechanisms present will not decelerate a charged particle the same way each time, giving different emission energies. The process behind Bremsstrahlung radiation is illustrated in Figure 2.6.

Like traditional X-ray generation tubes, the peeling tape system should also be able to
Figure 2.6: Bremsstrahlung Radiation. A charged particle is deflected in the presence of another charged particle. The change in energy is emitted as a photon due to energy conservation.
Figure 2.7: Spectrum of Bremsstrahlung Radiation. Spectrum is continuous until minimum wavelength is reached. Minimum wavelength of radiation is directly related to the gas pressure.

make use of Bremsstrahlung radiation to generate x-rays. Charge recombination events in a low-pressure environment accelerates ions and electrons, which then collide with the sheet of tape. When these accelerated ions and electrons collide with the tape, they begin to stop by interacting with nuclei in the tape. These interactions produce continuous radiation that includes x-rays.

2.2.3 RF Generation

Several researchers experimentally prove that triboluminescence also leads to the emission of electromagnetic radiation at radio frequencies [2, 3]. The mechanisms behind the emission of RF radiation are generally unexplained, but are thought to be related to the electrical discharge from charge separation and recombination. Other researchers suggest that the emission stems from the deceleration of free ions with Bremsstrahlung [19]. The work from Camera et al suggests that the radio emission temporally correlates with the light generated during triboluminescence and the stick-slip motion of the tape [3]. No research has been conducted as to the full spectrum of the emitted radiation, but Horvat and Lewis have analyzed the Terahertz
emission spectrum, and concluded the emission in that frequency regime to be fairly broadband and non-polarized [19].

Our conclusion is that this is a relatively unexplained area and that investigating the mechanisms behind the RF generation associated with triboluminescence is scientifically interesting. One possibility is that the mechanism by which RF radiation is produced can be explained by Larmor’s equation - a derivation of Maxwell’s Equations - which states that electromagnetic radiation is emitted when a charge is accelerated. Additionally, it will be interesting to discover whether the emission can be correlated with the physics of the light emission from the peeling of pressure sensitive tape.
References


Chapter 3

Literature Review and Applications

In this chapter, papers related to the generation of radiation by triboelectricity are reviewed.


3.0.4 Correlation between stick-slip action and triboelectric effects

Camara et al in 2008 used a peeling-tape system to investigate the radio, visible, and x-ray emission resulting from triboluminescence [3]. It was found that these emissions happen in short, spontaneous bursts that correlate to a centralized action event. These action events are thought to occur because of stick-slip friction, which are spontaneous failures of friction that
cause the tape to peel. The researchers created a tape-peeling apparatus that used an induction sensor and stainless steel leaf springs to measure the peeling force of the system. Using this setup, Camera et al. were able to correlate triboelectric emissions directly to the failure of friction during tape peeling. Figure 3.1 shows the relationship between force for peeling tape and the detection of X-rays and RF radiation.

![Figure 3.1: Correlation between X-rays, force and RF. The left axis shows the peeling tape force at 1 atm (green) and $10^{-3}$ torr (black). The right axis shows the x-ray signal in (blue) and the RF signal is the top trace (red). Graph from [3].](image)

The graph in Figure 3.1 shows that there is a clear correlation between the failure of friction (sudden decrease in force) and the emission of triboelectric radiation while in vacuum. The graph also shows that there is a noticeable increase in the amount of force needed to peel the tape under vacuum versus in atmosphere. This means that an increase in peeling force was necessary to overcome the extra electrostatic work done during charge separation.

Camera et al. also looked at a smaller timebase for the correlation between these emissions, and their graph can be seen in Figure 3.2. The response from the liquid scintillator (the x-rays) appear to come some time after the RF emission. This time difference makes sense if
we assume the RF radiation is being produced through Larmor mechanisms and the x-rays through Bremsstrahlung.

In a later paper, Camera et al took their previous experience to develop a miniature version of their tape peeling system [4]. They proved that the system and the triboelectric mechanisms could be scaled down to millimeter scales. In this experiment, the signal from a PMT was also correlated to the signals from an RF antenna and a liquid scintillator as seen in Figure 3.3. Strangely, the timing between the x-ray emission and light emission is off by several nanoseconds. Considering that both emissions should stem from Bremsstrahlung mechanisms, these mechanisms should be very closely matched in time. It is possible that the experiment’s measurement methods are at fault, as the PMT transit time and the cable delay times may have not been properly taken into account.

Camera et al did not investigate how the light emission correlated with the other triboelectric-based emissions with respect to pressure. The light spectra was analyzed from the peeling tape, but the results simply reaffirmed that the emissions are a result of a gas discharge [29]. An interesting study would be to look at the timescales for the light from the gas discharge as
3.0.5 Change of x-ray intensity with pressure

Constable et al investigated the dependence of the x-ray emission of a peeling tape system with the pressure of the environmental gas [6]. They present a model for the pressure dependence of the radiation that gives a strong indication of the physical origins of the emission. A Geiger-Muller counter is used to measure the x-ray photon counts at different instances of unwinding. The experiment finds that the environmental gas plays a role in providing free ions to the tape by the process of field emission. The number of charges present on the surface of the tape at any time is dependent on the concentration of free charge in the environmental gas that depends on the gas pressure. Through experimental observation, a theoretical model was derived for the relationship between x-ray photon count and air pressure. This model is illustrated in Figure 3.4. This model defines pressure thresholds for x-ray emission based on the production rate of uncompensated charge from unwinding of the tape, absorption of positive charges, and the rate of charge compensation in the tape.
ions from the gas, and the production of free electrons in the gas.

Figure 3.4: Pressure dependence of x-ray photon count based on experimental data (dashed line). The solid line is a quadratic fit model based on the how charge is generated and moved in the gas to the tape. Graph from [6].

The theory is that the acceleration of ions between the tape layers provides a means for free electron and hence $N_+$ ion (experiments are performed in nitrogen gas) generation through gas discharge mechanisms. This generation is offset by the absorption of the ions onto the tape for charge separation and recombination.

3.0.6 Presence of terahertz radiation

Horvat and Lewis investigated a terahertz radiation source based on a peeling tape system [19]. They investigated the time evolution of the terahertz radiation intensity through the use of a bolometer. It was found that non-polarized terahertz radiation was emitted when the tape was peeled at atmospheric pressure. This terahertz radiation was examined at different tape-uptake speeds as seen in Figure 3.5. The apparent oscillations in the signal at lower speeds
are said to be caused by ellipticity in the tape spool. This terahertz radiation was theorized to be attributed to the deceleration of free ions that had been excited through charge separation mechanisms. The lack of a polarization in the radiation is consistent with Bremsstrahlung.

![Figure 3.5: Time evolution of the terahertz signal at different tape-uptake speeds. Graph from [19].](image)

### 3.0.7 Angular dependence of x-ray emission

Constable et al also investigated the angular dependence of x-ray emission from a peeling tape system [6]. It was thought that the angular distribution could give important insight to the details of the Bremsstrahlung mechanisms of radiation. The angular dependence of the x-ray emission and the schematic defining the azimuthal angle can be seen in Figure 3.6. It was found that this emission had a 20 percent increase in intensity around the azimuthal angle that did not vary with pressure. This increase at the azimuthal angle can not be completely explained through ordinary Bremsstrahlung processes. Instead, Constable et al suggest that this x-ray emission may result from polarizational Bremsstrahlung, or the time-dependent change of atomic polarization that occurs when charged particles move nearby atoms or molecules.
3.0.8 Different means of achieving triboluminescence - non-peeling-tape systems

A unique means of generating x-rays that did not make use of peeling tape was developed by Hird et al [17]. The device makes use of a high-speed solenoid to utilize triboelectric effects and separate charge between silicone and an epoxy. Like tape-peeling systems the device was shown to emit light and x-ray radiation. Perhaps the most interesting aspect of an emission source like this is that the x-ray flux appears to be linearly dependent on the cycle frequency of the solenoid. This relationship can be seen in Figure 3.7. The relationship suggests that the only parameter limiting the effective x-ray dose of the triboelectric device is the speed of the solenoid.

The appeal of a solenoid-based system is fact that there is no tape that can outgas and interfere with the system pressure. However, a solenoid-based system requires more extensive design to ensure a good, clean contact between the silicone solenoid hammer and epoxy. In contrast, a peeling tape system is simpler in its execution and design.
3.0.9 Presence of x-rays from k-line transition

Hird et al also investigated the effect that powdered metals in the epoxy could have on the x-ray spectrum. It was found that these powdered metals could be added to the epoxy without effecting the tribocharging behavior of the solenoid-based system. In fact, the presence of the metals seemed to promote the emission of x-rays that were not generated through Bremsstrahlung mechanisms. Like modern x-ray machines, this solenoid based design emitted x-rays that were generated from the electronic transitions between the "‘K’" shell level and the higher energy levels of the metallic atoms. Figure 3.8 shows the resulting x-ray spectrum when the epoxy was loaded with molybdenum and silver; the K\(_\alpha\)1 and K\(_\beta\)1 lines for both metals are clearly visible.

The visibility of these K-lines gives a clear indication as to the direction of the acceleration of charged particles from charge separation. Hird et al assert that this also demonstrates that the silicone must charge negatively with respect to the epoxy. However, this assumes that electrons are the only active particles in these tribocharging mechanisms, which is still debated by researchers.
Figure 3.8: X-ray emission spectra for solenoid-based triboelectric device with epoxy loaded with molybdenum (gray) and silver (tan). Graph from [17].
References


Chapter 4

Experimental Setup and Methodology

4.1 Tape Spindle Chamber

A triboluminescence system was designed. For simplicity, a pressure sensitive adhesive peeling system was selected. Only tape and a rotational motor would be needed to experience triboluminescence and other triboelectric effects. To generate x-rays through Bremsstrahlung mechanisms, the tape system was to be housed in a vacuum chamber.

Several design parameters were considered in the system's fabrication. This included overall size and shape, radiation shielding, vacuum capability, and convenience for the user.

4.1.1 Chamber Design Considerations

Basics of Design

A roll of scotch tape has 1 inch in diameter with an outer diameter of about 2 inches. Two shafts would be needed to hold the tape spindle, and these two shafts determined the total diameter of the chamber. To provide motive force to the tape shafts, magnetic coupling between the outside of the chamber and inside of the chamber was used. The height of the magnetic coupler, shaft
coupler, and tape spindle determined the overall height of the chamber. 6061-T6 Aluminum pipe was chosen for the chamber wall for its machinability and low cost. A 6061-T6 aluminum plate was chosen for the chamber bottom and was used to provide a connection to the vacuum pump, while an acrylic pane was used for the top of the chamber. This acrylic pane allowed the interior of the chamber to be visible during operation. The overall dimensions of the chamber can be seen in Figure 4.1.

![Figure 4.1: Diagrams showing the overall size of chamber and how tape peeling system fits in chamber.](image)

**Mechanical Stresses**

To understand the stresses that would be applied when the chamber was under vacuum, the maximum deflection of the chamber materials was analyzed. The mechanical properties for each material were found through the government generated Military Standarization Handbook 694A and research studies [22,24]. The deflection values can be found in Table 4.1 and were calculated...
Table 4.1: Chamber specifications and corresponding plate deflection. All MathCAD calculations used to generate this table can be found in Appendix A.

<table>
<thead>
<tr>
<th>Top Acrylic Plate</th>
<th>Bottom Aluminum Plate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>Length</td>
</tr>
<tr>
<td>Width</td>
<td>Width</td>
</tr>
<tr>
<td>$\alpha$ for $b/a=1$</td>
<td>$\alpha$ for $b/a=1$</td>
</tr>
<tr>
<td>Pressure</td>
<td>Pressure</td>
</tr>
<tr>
<td>Equivalent Force</td>
<td>Equivalent Force</td>
</tr>
<tr>
<td>Plate Thickness</td>
<td>Plate Thickness</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>Elastic Modulus</td>
</tr>
<tr>
<td>Max Deflection</td>
<td>Max Deflection</td>
</tr>
<tr>
<td>5 inches</td>
<td>5 inches</td>
</tr>
<tr>
<td>5 inches</td>
<td>5 inches</td>
</tr>
<tr>
<td>0.1267</td>
<td>0.1267</td>
</tr>
<tr>
<td>14.7 psi</td>
<td>14.7 psi</td>
</tr>
<tr>
<td>288.63 lbf</td>
<td>288.63 lbf</td>
</tr>
<tr>
<td>0.472 inches</td>
<td>0.125 inches</td>
</tr>
<tr>
<td>464120 psi</td>
<td>10*10^6 psi</td>
</tr>
<tr>
<td>0.047 inches</td>
<td>0.019 inches</td>
</tr>
</tbody>
</table>

from Eq. 4.1.

$$\Delta = \frac{\alpha \cdot F \cdot b^2}{E \cdot t^3} \quad (4.1)$$

Where $\alpha$ is a constant based on the aspect ratio of the plate, $F$ is the applied force, $b$ is the short dimension width, $E$ is Young’s Modulus of the material, and $t$ is the plate thickness.

The maximum calculated deflection values of the aluminum plate and acrylic plate were calculated to be 0.019 inches and 0.047 inches, respectively. Both of these deflection values corresponded to a deflection of approximately 1/10 the thickness of the corresponding material, and were considered acceptable.

**Radiation Safety**

As our vacuum system will be generating x-rays, it is important to verify that our system will be safe to operate in the lab and around other people. X-rays are ionizing radiation and are capable of penetrating objects and living tissues. The half value layer (or HVL) is the most commonly used quantity to describe the penetrating ability of a photon of a certain energy through a material of a certain composition. HVL corresponds to the thickness of a material penetrated by approximately half of the incident radiation and is expressed in units of distance. As an example, let’s say we have 200 photons of 5 keV incident upon a material. If those 5 keV photons have an HVL of 2 cm in the material, then only 100 photons will statistically
make it 2 cm, 50 photons will make it to 4 cm, and 25 photons will make it 6 cm through the material [27].

Using attenuation data from Chantler, we can plot the HVL values for different photon energies in aluminum [5]. The data plot can be seen in Figure 4.2 and the raw data can be found in Excel spreadsheets in Appendix-A.

From past experiments, it is known that the vast majority of x-ray photons emitted in a peeling tape system are of energies between 10 and 30 keV within vacuum pressures of $\approx 10^{-3}$ torr [3]. According to Figure 4.2, radiation consisting of photons of 30 keV energy are diminished in intensity - considering an aluminum thickness of approximately 0.635 cm - by about 85 percent. Radiation consisting of photons of 20 keV is reduced in intensity by about 99.7 percent by the aluminum walls of the chamber. Although the exact emission rate from a typical peeling tape x-ray system is unknown, this reduction in intensity should be considered high enough to minimize the received does of penetrating radiation. Furthermore, an additional aluminum cylinder can be added to block additional radiation.

Since any x-ray measurements will need to be done outside the chamber, the x-ray penetration of the acrylic window should also be considered. According to Figure 4.2, radiation consisting of photons of 30 keV and 20 keV will be reduced by approximately 50 and 35 percent, respectively. Again, this data has been sourced from Chantler [5], and can be found in its raw form in Appendix-A. Although this is a reduction in x-ray intensity, the relatively low density of the acrylic glass should allow for a fair amount of x-rays to reach any detector placed near the chamber window. Where measurements are not being made, an additional aluminum cylinder of 1.5 cm thickness can be added to block 99.9 percent of radiation under 30 keV.

**Motor for Spindle Rotation**

The torque of the motor needs to be greater than the frictional force of the tape (force is dependent on width of tape spindle), but also be capable of reeling the tape at an uptake speed up to 30 cm s$^{-1}$. The 30 cm s$^{-1}$ value was considered necessary from [19].
To better determine motor requirements, an experiment was conducted in order to find the frictional force of the tape. A reel of scotch tape was suspended from a table with a metal rod was attached to the end of the tape as seen in Figure 4.3. Measured weights were added to the metal rod until the tape began to spin. The total mass on the end of the tape was recorded when the tape first began to slip and was increased until the tape began to spin freely. The mass of the tape was neglected. Considering the increasing width of the tape spool, torque requirements were calculated and are shown in Table 4.2 and in more detail in Appendix-A.

In atmosphere, a tabletop lathe with digital speed control was used to determine if the uptake speeds were adequate by examining the amount of light that was generated as a function of speed. It was found that the perceived light output correlated well with the rotational speed of the lathe.

The torque calculations in Table 4.2 suggested that more than 5 N*cm (or 0.05 N*m) of torque, and up to 30 cm s$^{-1}$ of uptake speed were required. The Phidgets 3252 12 volt brushed DC motor meets these requirements with a 10x design margin. The 3252 is a planetary gearbox.
motor (3.7:1 ratio) that can provide approximately 0.14 N\(\cdot\)m at up to 654 rpm and a tape uptake speed of greater than 600 cm/s. Motor control was provided by a Phidgets 1065 MotorControl board, and allowed control of direction, velocity and acceleration of the DC motor on a computer via USB.

**Magnetic Coupling**

Operating an electric motor in vacuum is a design challenge. Outgassing, sparking, and temperature management are all well known problems to operating a motor in a vacuum environment. Keeping the motor outside the chamber and using magnetic coupling was the chosen approach
Table 4.2: Recordings of mass required for tape to slip/move and corresponding torque calculations.

| Mass/force where tape slip was noticed | 0.085 kg | 0.836 N |
| Mass/force where tape moved consistently | 0.201 kg | 0.972 N |
| Tape spool thickness min/max | 1.27 cm | 2.54 cm |
| Torque at tape slip min/max | 1.06 N*cm | 2.13 N*cm |
| Torque at tape movement min/max | 2.505 N*cm | 5.009 N*cm |

to avoid these problems and successfully couple rotary motion into the sealed vacuum chamber.

Ferrofluidic rotary feedthroughs use a series of liquid o-rings consisting of trapped ferrofluid to provide a vacuum seal around a single coupled shaft. These feedthroughs have the advantage of being able to handle very high vacuums, high rotational speeds, and axial and radial loads while providing a non-contaminating seal with low maintenance. These feedthroughs come at a preventively high price point - often approaching several thousand dollars.

Figure 4.4: Diagram of magnetic couplers. Motion is coupled across an air gap. Adapted from manufacturer data sheet.

A more affordable approach to rotary motion coupling is through magnetic disk couplers. Magnetic disk couplers use a ring of high-powered magnets to transfer torque from one disk to another through an air gap. The couplers considered can be seen in Figure 4.4. These couplers have the advantage of allowing a completely sealed feedthrough of motion without breaking through a vacuum gap and without contact or wear. However, a magnetically coupled system
introduces and must withstand a number of external loads on the rotational shafts that can make overall design difficult. If the disk couplers are misaligned for example, radial loads can begin to act on support bearings. Additionally, the magnetic attraction between the two disks induces an axial load on the two rotational shafts. These loads place more stress on the system as a whole, and need to be countered with the use of additional bearings to prevent friction and wear. On the other hand, the low cost of this coupling method, less than 100 USD for a set of two, makes magnetic disk coupling an attractive alternative to the ferrofluidic feedthrough.

Magnetic disk couplers were chosen as the means of rotary motion feedthrough. The pair chosen were the S50DCM-20H06 from Stock Drive Products. The couplers have a 0.375” Bore size, and can couple a nominal torque of 6 In-lb (67.8 N*cm) at an air gap of 0.188”
. These couplers are approximately 2” in diameter and project 0.25” from the magnetic base. These couplers house nickel-plated rare earth magnets and are encased in a 416 stainless steel hub.

**Motion**

Efficient coupling is achieved by ensuring the disk couplers are as close as possible to one another without being in contact with the vacuum barrier. Additionally, good angular and translational alignment are required for good coupling. The manufacturer specifies a maximum angular misalignment of 3 degrees and a maximum parallel offset of 0.25 inches.

The magnetic attraction from the disk couplers causes a strong axial (also known as thrust) force to be loaded on both the motor driveshaft and tape uptake shaft. According to its manufacturer, the 3252 motor can handle thrust loads up to 35 N. No load bearing equipment was used in conjunction with the shaft connecting the motor to the disk coupler. The axial loads on the shaft/vacuum side were accounted for with a simple shaft mount and a low-friction ball-bearing. This shaft mount was designed with an adjustable height to allow for control of the separation between the disk couplers,

Radial loads on the motor were expected to be less than the motor gearbox’s maximum overhung load specification of 50N. However, it was still necessary to account for radial loads
on the tape shaft that could arise from an imbalance in the components attached to the shaft or any angular misalignment. Two thrust ball-bearings were placed at the top and bottom of the shaft to reduce friction and mounted to stable aluminum plates to prevent radial movement of the shaft.

For clarity, the rotational system design and the components chosen can be seen in Figure 4.5 and Table 4.3, respectively.

**Vacuum Considerations**

The pumping station used was a Pfeiffer-Balzers TSU 170 E turbomolecular drag pumping station was found in storage. This pumping station consists of a turbopump, a diaphragm pump for the exhaust of the turbo pump, and an electronic control unit. This pump is capable of pumping down to $10^{-11}$ torr, and has a flow rate up to 170 liters per second. The roughing pump has a flow rate of 3 cubic meters per hour.

The chamber itself was built of aluminum and acrylic. Leakage and outgassing from these materials were expected to be minimal and should not effect the ability of the system to pump down to a medium vacuum. However, the use of rubber gaskets to form seals limited the expected pressures, but were useful for their convenience and low-cost. Two 1/32” thick Viton rubber sheet were chosen to seal the system because Viton is chemically resistant to oils and greases, highly impermeable to air, and a regular material choice for vacuum system gaskets. The gaskets were sealed with vacuum grease.

**4.1.2 Final Design Specifications**

**Chamber**

The final chamber design consisted of 4” tall by 5” OD pipe with a thickness of 0.25”. This pipe was topped with a 0.472” thick sheet of clear acrylic and bottomed by a 1/8” thick sheet of aluminum. Both sheets were 6” x 6” in size. Between these components sat cut pieces of 1/32” thick Viton rubber. The guts of the chamber consisted of stacks of aluminum sheets.
supported by 1” diameter aluminum posts. This stack served as a means to support and hold the rotational shafts, bearings, and other miscellaneous parts. For the sake of completeness a list of the miscellaneous components can be seen below in Table 4.3.

The core of the chamber was comprised of two varied thickness aluminum sheets supported by four 1” diameter, 1” tall aluminum posts (or sometimes 7/8” in height, see Figure 4.7). A long bolt and nut were used in the center of the core to secure the components together. Figure 4.7, Figure 4.8, and Figure 4.9 show schematics displaying some rough dimensions of the chamber core. Figure 4.6 shows an isometric view of the chamber core. It should be noted that additional mechanical standoffs were used to support the core near the magnetic disk coupler.

### Chamber Base/Support

The chamber base consisted of another 6” by 6” aluminum plate that was held up by four 5” tall and 1”OD aluminum posts connected to magnetic bases. These magnetic bases allowed the system to be securely anchored to an optical table. The aluminum plate was machined to hold the 3252 motor and allow a route through which a vacuum connection could be made to the chamber. Figure 4.10 and Figure 4.11 show the top and side views of the schematic, respectively.

The completed triboelectric system can be seen without the casing in Figure 4.12.

The total price of these components came to about 200 USD. The completed system can be seen in the picture in Figure 4.13.

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### Table 4.3: Components within the chamber core, their specifications and quantity

<table>
<thead>
<tr>
<th>Component</th>
<th>Specifications</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum Shafts</td>
<td>3/8” OD - 12” Length</td>
<td>2</td>
</tr>
<tr>
<td>Adjustable-Width Shaft Collar</td>
<td>7/8” OD - 3/8” Bore</td>
<td>1</td>
</tr>
<tr>
<td>Nylon Snap-in Thrust Bearing</td>
<td>Fits 7/16” - 3/8” Bore</td>
<td>4</td>
</tr>
<tr>
<td>Steel Thrust Ball Bearings</td>
<td>7/8” OD - For 7/16” Shaft</td>
<td>1</td>
</tr>
</tbody>
</table>
Vacuum System

The chamber was sealed with two 1/32” thick Viton rubber gaskets and was pumped down using a Pfeiffer TSU 071 E turbomolecular drag pumping station. All vacuum connections were made using VCR fittings except for a pipe-thread type connection into the chamber, and the vacuum pressure was monitored with a Granville-Phillips 275 Convection gauge. This vacuum gauge is capable of measuring vacuum pressure down to 1x10^{-3} torr, which fits well with the chamber purposes.

4.2 Experimental Methods

The goals of the experiment were to:

- Verify and detect x-ray emission.
- Analyze the time evolution of the triboluminescent light intensity at atmosphere and with respect to pressure.
- Verify the spectrum of emitted light in different environmental gases.
- Investigate the spectrum, polarization, and time evolution of the RF radiation.

4.2.1 Light Emission

Spectrum

Light measurements were first done using simple qualitative measurements. In atmosphere, light emitted when the tape was peeled was visible to the naked eye, thus simple observation is a strong tool for verifying the light emission capability of the system. Although other researchers had investigated and characterized the light emission from a triboluminescent peeling tape system [29], similar experiments were reformed to verify results. The spectrum and color of the emitted light is known to be derived from the electronic states of the gas surrounding the tape.
This relationship was verified by looking at the color and spectrum of the light with different surrounding gases. Additionally, the color/spectrum of the emitted light should be assessed at lower chamber pressures. At lower chamber pressures, Bremsstrahlung radiation should dominate the light generation process, and the emission should be characteristic of continuous white light.

An experiment was devised to measure the spectral content using either an Ocean Optics USB2000 spectrometer or a Spectral Products CM110 monochromator paired with an AD131 Silicon photodetector array. Both of these systems have high-sensitivity in the UV-VIS region. Experiments using either of these components were very similar in their design. The components needed to be connected to a computer to record any measurements, and the system needed to be optically set-up to detect light from the closed chamber. This was done using an optical fiber for the Ocean Optics Spectrometer and through free-space with the Spectral Products monochromator.

Spectral measurements were at atmospheric pressure (nitrogen gas), 10 torr of argon gas, and at low chamber pressures where Bremsstrahlung emission should dominate. Hence, the chamber needed to be closed for these measurements, and all optical components were to be housed outside the acrylic viewing window. It was thought that this separation from the peeling tape would not become a problem in taking measurements.

Only the 3000-4500 Angstrom spectrum region was considered. In this region, the differences between the different spectra measurements should be very dramatic, and allow proper verification of the electronic states of whichever gas is in the chamber. Figure 4.14 shows a simple diagram of the expected set-up.

**Intensity Versus Pressure**

An important and novel investigation would be into the impact of different chamber pressures on the time evolution of the light intensity peaks that correlate with the stick-slip action of the tape. As previously mentioned in Chapter 2, the exact mechanisms behind the light emission are
currently unclear to researchers. Research into how the intensity changes at different pressures should lead to new insights into charge recombination and gas ionization mechanisms present in triboelectric systems.

Measuring the change in light intensity required high-speed detection equipment. For light detection, a Hamamatsu R228 28mm head-on photomultiplier tube (PMT) was used. A photomultiplier tube provides high-sensitivity and fast response times compared to other detection schemes, making it suitable for a measurement like this. The R228 is an 11 dynode PMT with a Borosilicate window for high-gain/sensitivity between 3000-9000 Angstroms. The electron transit time and rise time for the PMT give the device an approximate time-resolution of 30 ns. The PMT was paired with Hamamatsu’s C1053/C1556 socket and detection electronics, and connected to the C3830 high-voltage power supply. The detection electronics were the limiting factor in determining the time-resolution of the system. The C1053 has a frequency bandwidth of 5 MHz, giving an effective resolution of 200 ns.

Measuring the signal from the photomultiplier tube’s electronics was done with the Tektronix TDS540B digitizing oscilloscope. This oscilloscope has a maximum sampling rate of 100 million samples per second which translates to a time-resolution of 10 ns; enough to fully sample the signal from the Hamamatsu PMT. The TDS540B is capable of triggering at certain signal events, which makes it a useful tool for tracking the light intensity shortly after an excitation event occurs from the stick-slip action of the tape.

Using this system to measure light intensity was found to be fairly easy; no imaging components were required because of the photomultiplier tube’s incredible sensitivity. A few precautions needed to be taken in order to prevent too much light from reaching the photomultiplier tube when running the experiment. The experiment was designed as such: the chamber was first pumped down and set-up for normal operation, with the PMT placed facing down (towards the peeling tape) on top of the acrylic slab with a rubber cutout surround in place to block all stray light from entering the chamber. A diagram of the proposed system can be found in Figure 4.15.
Intensity versus tape uptake speed

One other measurement was performed involving the light emission from the tape: looking at the light emission intensity versus the speed of the tape uptake. Similar measurements have already been performed by other researchers [29]. In this experiment, the R2228 photomultiplier tube was used in conjunction with the Tektronix TDS540B digitizing oscilloscope. This setup was functionally identical to the one used to measure the time-evolution of the light intensity at different pressures. The triboelectric system was run at varying tape speeds, and the maximum intensity triggered by the oscilloscope was recorded.

4.2.2 X-ray Emission

The physical observation of x-rays is a more difficult thing to do qualitatively as humans are unable to see x-rays. As an alternative, materials known as scintillators can be used in place of our eyes. Scintillators are generally inorganic materials that luminesce (emit visible light) when excited by high-energy ionizing radiation. For application in the triboluminescence system, scintillators can be used as a means to visually verify that x-rays are being emitted from the peeling of the pressure sensitive adhesive. Two types of scintillators were chosen as appropriate for the radiation emitted, the BC-404 and BC-408. Both of these scintillators are from the company Saint-Gobain, made from polyvinyltoulene, and reported to be capable of detecting x-ray radiation less than 100 keV.

These scintillators were thought to able to intercept x-ray radiation inside the chamber as well as just outside the chamber above the acrylic slab. When testing for emission, the scintillators were placed in both locations to verify that they were receiving radiation. If emission from the scintillator could not be directly perceived, the PMT could be used to detect the trace light from the scintillator.

Besides the scintillators, x-ray film - also known as a radiograph - could be used as a means to detect the emission of x-ray radiation. X-ray film also has the advantage of being able to see if the emission from the triboluminescence system is strong enough to actually be used for
medical imaging (an important objective). Film behaves like a sort of radiation integrator, so if x-ray radiation cannot be verified through the observation of a scintillator, film may still work.

The x-ray film used is dental film from Ergonom-X that is approximately 1”x2” in size and encased in small, hermetically sealed packets. Each film packet includes developing liquid for self-processing, making it ideal for do-it-yourself exposure systems. The film itself is classified as ”‘E-speed’”, meaning less dosage is needed for a full exposure when compared to alternative, slower speed films; again, useful for an x-ray system with an unknown - and more than likely minimal - dosage. The self-contained nature of the x-ray film limits placement to outside the chamber when the system is under vacuum. Experiments using the film placed the film in numerous locations above the acrylic in an attempt to better understand the angular dependence of the Bremsstrahlung radiation. Aluminum pieces with distinct shapes were placed in front of the film to verify the system’s ability to image.

A Geiger-Müller counter was used as a quantitative means to measure the x-ray flux from the triboluminescent system. The counter used was a Ludlums Model 3A with a 44-9 pancaketype radiation detector as seen in Figure 4.16. The Model 3A can measure radiation between 0-500K counts per minute (cpm) using four different sensitivity multipliers (x0.1,x1,x10,x100). From the manufacturer’s description, the 44-9 has a strong energy response in the 20-100 keV range. Experiments placed the 44-9 detector directly above the acrylic, and x-ray emission was monitored and recorded at the different sensitivity multipliers.

4.2.3 RF Emission

As previously discussed in Chapter 2 and Chapter 3, there has been little investigation as to the nature of and mechanisms behind the RF emission present from a triboelectric system. It would be of significance to initiate further research into the subject.
Spectrum

The spectrum of the emitted RF radiation is a very important characteristic that deserves a closer look. Depending on the mechanisms, the RF spectrum can give a lot of information as to what is happening to the charged particles during charge recombination. The RF spectrum can be measured both qualitatively and quantitatively using an AM radio and spectrum analyzer, respectively.

The AM radio may at first seem like a crude and unscientific means of investigating the RF spectrum, but the tool can actually give a lot of information. An AM radio acts like a very narrow bandpass filter, only accepting and amplifying any signals that fall within the frequency band in question. By listening to the radio's audio output as the center frequency of this filter is adjusted (this is done while the triboelectric system is operating, of course), RF radiation can be verified to be emitted in certain frequency regions.

The radio itself is a nondescript radio/alarm clock combination by Sony. The radio's antenna is external and is housed in a conveniently adjustable wire. All experiments with the AM radio situated the radio's antenna within a few centimeters of the tape's peeling point. Any noises or popping from the radio in the AM frequency bands (adjusted from 530 kHz to 1700 kHz) were noted. This analysis was repeated with the radio set to the pick up the FM RF emission just out of sheer curiosity.

Another more quantitative means of interpreting the spectrum of the RF emission is through the use of a spectrum analyzer. A spectrum analyzer is an electronic device that can measure the magnitude of an inputted signal versus frequency. The spectrum analyzer used was a Hewlett-Packard ESA-L1500A that has a detection range from 9 kHz to 1.5GHz. The spectrum analyzer's input port was connected to a monopole antenna created from a stripped coaxial cable. The exposed 'antenna' portion of the cable was 5 cm in length and was placed in a horizontal position just a few centimeters from the tape’s peeling point. In separate experiments the spectrum analyzer was configured to look at both a narrow and broad range of frequencies to assess bandwidth and spectrum.
Polarization

The polarization of the emitted RF radiation is also a worthwhile characteristic to investigate. Knowing if a polarization is present in the radiation can give a strong indication as to the nature of the mechanism behind the emission. Linear Polarization of the RF radiation can simply be checked through the use of a monopole antenna that has been oriented in a particular direction: to check for horizontal polarization in the electric field, the antenna would be mounted horizontally, for vertical polarization, the antenna would be mounted vertically. The monopole antenna was created from a stripped coaxial cable and has an exposed 'antenna' portion of the cable of 5 cm in length. The antenna’s signal was picked up by the Tektronix TDS540B digitizing oscilloscope. The antenna’s mounting configuration was changed between horizontal and vertical while keeping the antenna at a narrow distance from the tape peeling vertex and maintaining a constant tape pull speed. Comparing the signals between these two antenna configurations should give a clear indication to whether or not a polarization is present in the RF signal. Figure 4.17 illustrates how the antenna was configured in these polarization experiments.

Intensity Versus Pressure

Another novel investigation would be to look at the effect of pressure on the time evolution of the intensity signal resulting from the RF radiation. It is thought that this information will give a useful insight into the mostly unexplored mechanisms behind the RF emission associated with triboelectric systems. However, this experiment required that the emitted RF radiation can be successfully coupled to an antenna positioned outside the sealed chamber. This coupling was unsuccessful, thus a means of routing the antenna into the chamber needed to be explored. An electric feedthrough was created using a hollowed out set screw, positioned into the side of the chamber, and sealed with torr-seal.

Like the previously mentioned polarization experiment, monitoring the signal intensity versus pressure required the use of a monopole antenna and the Tektronix TDS540B digitizing
oscilloscope. The signal intensity was measured at triggered signal pulses (which correlate to mechanical stick-slip events) and pulse length and relative intensity of the RF radiation was recorded. These measurements were repeated at atmospheric pressure and below with the hope of finding a correlation between one these recorded parameters and decreasing pressure.
Figure 4.5: Diagram of rotational system illustrating use of magnetic couplers.
Figure 4.6: Isometric schematic view of chamber core.

Figure 4.7: Side schematic view of chamber core.
Figure 4.8: Top schematic view of chamber core.

Figure 4.9: Bottom schematic view of chamber core.
Figure 4.10: Top schematic view of chamber base.

Figure 4.11: Side schematic view of chamber base.
Figure 4.12: Side schematic view of system without outer chamber casing.

Figure 4.13: Actual fabricated system.
Figure 4.14: A simplified diagram of the spectrum measurement system using the Spectral Products CM110 monochromator and AD131 Silicon photodetector array.

Figure 4.15: A simplified diagram of the measurement system to investigate the time-evolution of the light intensity at different pressures.
Figure 4.16: The Ludlums Model 3A Geiger counter with attached 44-9 pancake-type radiation detector.

Figure 4.17: Experimental setup to investigate possible polarization of RF radiation with monopole antenna mounted (A) Horizontally, and (B) Vertically.
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Chapter 5

Experimental Results and Discussion

This chapter will present the results from the experiments outlined in Chapter 4. These results are organized by emission type, and include light, x-ray, and RF radiation resulting from triboelectric effects.

5.1 Light

The light emission from the triboluminescence system was measured using a photomultiplier tube and a high-speed oscilloscope. Figure 5.1 shows the PMT signal intensity measured over a period of 200 ms. The light emission appears to come in non-periodic bursts that may be chaotic in nature. These bursts are very quick, and at this digitizing rate, do not appear to have any sort of settling time. The light emission mechanism has been previously linked to the failure of stick-slip friction in the tape [3].

Figure 5.2 shows the PMT signal intensity at a smaller time scale of 6 µs. The graph shows the time-evolution of the signal. The light intensity appears to maximize within about 500 ns, and remains relatively constant for approximately a microsecond before decaying.

At a significantly lower chamber pressure, Bremsstrahlung processes begin to dominate visible light generation. Figure 5.3 shows the PMT signal intensity from the peeling tape system at a pressure of 40 mtorr on a 60 µs timescale.
Figure 5.1: PMT signal intensity on a time scale of 200 ms. Repeated pulses of various light intensity are measured by the PMT as the tape is peeled.

The time-evolution of the light intensity signal at 40 mtorr is notably different in shape and duration from the signals recorded at atmosphere (Figure 5.2). This extended signal duration suggests that different mechanisms of light emission appear at lower gas pressures. The mechanism is most likely Bremsstrahlung in nature, as the extended duration indicates a fluorescence emission from the tape. This fluorescence emission saturates the PMT. An interesting note is that the extended duration appears to occur after an initial pulse from the gas ionization. If we consider the energy that an accelerated particle would have to have to cause this x-ray emission, we can find the necessary velocity of the accelerated particle and by approximation, the distance this particle traveled between the separated tape layers. Assuming the highest photon energy of white light received is at a wavelength of 300 nm (the detection limit of the PMT), the highest photon energy is calculated to be:
Figure 5.2: Time evolution of PMT signal intensity at 760 torr on a time scale of 6 $\mu$s. Pulse illustrates light intensity from gas ionization.

\[
\text{Energy}_{max} = \hbar \omega \quad (5.1)
\]
\[
= \frac{\hbar c}{\lambda} \quad (5.2)
\]
\[
= 4.141 \text{eV} \quad (5.3)
\]

From Eq. 5.3 we can calculate the maximum velocity needed by a charged particle to generate this energy.

\[
\text{KE}_{max} = \frac{1}{2} m v^2 \quad (5.4)
\]
\[
v = \sqrt{\frac{2 \text{ Energy}_{max}}{m}} \quad (5.5)
\]
\[
= 1.206 \times 10^6 \text{m/s} \quad (5.6)
\]

Eq. 5.6 assumes that the charged particle mass is the mass of an electron. For a particle
of the mass of a nitrogen gas ion \( m \approx 2.33 \times 10^{-26} \text{ kg} \) a maximum velocity of 7541.58 m/s is needed.

Camara et al estimate the charged particle travel time to be approximately 1 ns [3]. Assuming the average electron velocity is half the maximum value for the emission of blue light through Bremsstrahlung, this gives a separation distance of approximately 600 µm. The calculated distance value assumes no influence from scattering events, however. A more realistic value might be approximated with slightly lower average charged particle velocities.

### 5.1.1 Intensity versus pressure

Figure 5.4 shows the evolution of PMT signal intensity at different gas pressures in the chamber. The pulse recorded at each pressure was near or at the maximum intensity of all pulses at each pressure. With decreasing pressure, it is apparent that pulse intensity also decreases. This can be explained by the lower amount of molecules present in the gas at lower environmental pressures. Less molecules in the gas mean less overall ionizing collisions at each separation event, and thus less light being emitted. Additionally, we can see that the pulse length decreases with decreasing pressure. This decreasing pulse length implies that the light emission mechanism...
operates via a sort of avalanche effect, and suggests that light is emitted via a Townsend discharge in these pressure regimes. For higher pressures it appears that the pulse intensity does not immediately decrease after reaching its peak. Instead, the intensity slowly decreases before eventually dropping off (note that at 760 torr and 100 torr, the output of the PMT is saturated at 12V for a brief period). This can be explained by the Townsend mechanisms. The accelerated charged particles repeatedly collide with gas molecules on their trip across the tape gap and produce more charged particles; higher pressures correspond to more ionizing collisions, a higher number of total charged particles, a longer total electron trip time, and a longer PMT signal pulse width.

![Figure 5.4](image)

**Figure 5.4:** Time evolution of PMT signal intensity on a time scale of 60 \(\mu s\) at varying chamber pressures. Pulse length and pulse intensity were found to be proportional to the chamber pressure. The extra peak in the 300 mtorr signal (light blue) is thought to be due to another stick-slip event.

Visually speaking, the plasma appeared to increase in size with decreasing chamber pressure. This increase in plasma size comes as no surprise, and can be explained through the increase in mean free path of the accelerated electrons and ions. As the mean free path increases
inversely (and linearly) with chamber pressure, the average energy of any accelerated particle also increases and ionizing collisions will occur at greater distances of separation. As ionizing collisions will randomly scatter the accelerated particles, the particles may produce additional ionizing collisions in all directions, resulting in a plasma that should appear larger in size.

5.1.2 Maximum intensity versus speed

The light emission at different tape uptake speeds was investigated. As expected, the total photon emission intensities were dependent on the peeling speed. In Figure 5.5 we show the dependence on the peel speed of the total photon emission in the PMT detection region between 300 nm-900 nm. From the data, it can be seen that the light intensity rapidly increases up to 10 cm/s. At higher peeling speeds, the total light intensity begins to decrease. Zhenyi et al have found a similar intensity maximization at 10 cm/s, but their data does not show a dramatic drop in intensity at higher peeling speeds [29]. This decrease in intensity in our dataset could be attributed to the imperfect rotation of the tape spool at high speeds. Alternatively, from [29], the possible intensity drop at higher peeling may not be perceptible with their dataset’s logarithmic plot. It should be noted that the total flux of light did vary proportionally with tape peeling speed. More pulses of light corresponding to more discharge events were recorded for a given period of time by the PMT when the tape speed was increased.

The saturation of light pulse intensity suggests that the energies involved in discharge events change at different tape peeling speeds. A possible explanation is that at lower speeds the strength of the electrical discharges or the electric field established between the tape layers are diminished. The reduced strength of the electric field would also reduce the total energy that an accelerated particle could attain and then release for gas ionization processes. It is possible that at lower peeling speeds the discharge events occur at larger tape separation distances, but more investigation (possibly into the effect of tape speed on peak intensity of different gas ionization spectral peaks) would be needed before making such an assertion.
Figure 5.5: Maximum PMT signal intensity at different tape peeling speeds. Data shows that light intensity is maximized at an uptake speed between 10 and 15 cm/s. Green circles show data points from measurements, blue line is simple polynomial fit to show trend. The dip at the end of the blue line is an artifact of the fit.

5.1.3 Spectrum

Spectral data was collected using both the monochromator and spectrometer setup as described in Chapter 4. Unfortunately, no conclusion on the spectral properties of light emission can be made from the data collected. The monochromator data was very noisy. Ten total exposures were collected and averaged between 3000 Angstroms - 4500 Angstroms, but no conclusion could be made from the dataset. Data was collected from the spectrometer at different CCD integration times up to 30 seconds, but no spectral information could be inferred from the data.

Qualitative observations were performed of the light emitted in the chamber as an alternative means of analyzing color. At atmosphere, the light emitted from the tape-peeling system appeared to be deep blue in color as seen in Figure 5.6. When the chamber was pumped with Argon (to 10 torr), the light emitted from the tape-peeling system appeared to be a bright purple color as seen in Figure 5.7. These colors match with the colors expected from these ionized gases.

At lower chamber pressures (around 40 mtorr) Bremsstrahlung mechanisms appeared to
be the main source of light emission. The light emission in this pressure regime was visibly brighter than the emission from gas ionization and was white in color.

Other researchers have previously measured in detail the light emission spectra from the gas ionization and Bremsstrahlung processes [3, 29]. A qualitative verification of the spectrum is adequate for this research.

Figure 5.6: Picture showing the blue light emission from Nitrogen in the tape-peeling system chamber. Picture was taken when chamber was at a pressure of 760 torr.

5.2 X-rays

5.2.1 Detection

Light emission from the scintillators was not visible to the naked eye when the tape-peeling system was operated under vacuum. As a result, we chose to use the scintillators in conjunction with the PMT to detect the x-ray emission from the tape-peeling system. The system was pumped down to 15mtorr, and the light intensity pulses were monitored as the system slowly increased in pressure under vacuum. Figure 5.8 illustrates how these pulses changed in size and
shape as chamber pressure increased. From 15 mtorr to approximately 40 mtorr, the pulses seen took two forms. One form appeared to be narrow in width, and the other resembled the white light pulse from Figure 5.3. As pressure increased to around 40 mtorr, the narrower pulse disappeared. As pressure increased to above 100 mtorr, no light was detected by the PMT.

The evolution in pulse shape versus pressure gives information as to the nature of the emissions in the different pressure regimes. Considering the absence of signal at higher pressures, we can infer that light from gas ionization is not reaching the photo multiplier tube. Thus, any light reaching the PMT must result from Bremsstahlung radiation (whether this be light or x-ray excitation of the scintillator) and not from gas ionization. At lower chamber pressures to 40 mtorr, continuous light emission from Bremsstrahlung begins to appear. At even lower chamber pressures down to 15 mtorr, it is thought that low energy x-rays are emitted. These x-rays excite the scintillator and cause light to be emitted, and are picked up as short pulses by the PMT.

The specific energy response of the scintillators used are undefined by the manufacturer.
Figure 5.8: PMT response when used in conjunction with scintillation blocks for the detection of x-rays. Diagrams illustrate the change in pulse shape as pressure in the chamber increased.

The Ludlums Model 3A Geiger-Müller counter was used to quantify x-ray flux from the triboluminescence system. The system was first run on the highest sensitivity (0.1x), which gave a detection range from 0 to 660 cpm. In the first experiment, the chamber was pumped down to 1 mtorr, and the pancake detector was positioned directly over the peeling vertex. When the tape was peeled, the Geiger counter immediately responded, and the dial showed the maximum reading (at 0.1x sensitivity) of 660 cpm. This reading was held for approximately 5 seconds, and was held until the pressure in the chamber read approximately 10 mtorr. This increase in chamber pressure can be attributed to outgassing in the tape.

In the following Geiger counter experiment, the counter sensitivity was decreased to 1.0x. This setting gave a detection range from 0 to 6600 cpm. The chamber was once again pumped down to 1 mtorr, and the pancake detector was positioned above the peeling vertex. When the tape was peeled, the Geiger counter began to respond, and the dial read a value of approximately 2500 cpm. The value read from the Geiger counter was maximized when the chamber read 5 mtorr.
The energy response of the 44-9 detector is strongest between 20 keV and 100 keV. This strongly suggests that the system is in fact producing mid-energy x-rays.

5.2.2 Film Exposure

X-ray dental film was used to investigate the imaging capability of the triboluminescence system. In Figure 5.9, we see the film in a series of different development environments: no exposure, exposure with nothing in front of the film, and exposure with a drilled piece of aluminum in front of the film to block exposure to x-rays. This piece of aluminum is approximately 85 mm thick and has drilled holes of 5 mm diameter. From HVL calculations, this piece of aluminum should block 99.9 percent of all x-rays 20keV and below.

![Figure 5.9: X-ray film under different conditions of exposure. a) Film that has been developed without exposure to x-rays. b) Film that has been developed after complete exposure to x-rays. c) Film that has been developed after partial exposure to x-rays through 5 mm sized holes. Holes are marked in red on film image.](image)

The film appears translucent without any exposure to x-rays. When exposed to x-rays and properly developed, the film begins to become opaque in the regions exposed as seen in
Figure 5.9b. The swirls and imperfections in the dark areas of the film can be attributed to fluctuations in exposure to the developer and/or oxidation of the developer. Imaged exposure is apparent in Figure 5.9c, where the opaque circle on the bottom of the film is located in the same region as the drilled hole in the aluminum and is of roughly the same size. The opaque mass at the top of the film may be attributed to oxidation of the developer and not exposure due to x-rays.

Figure 5.10: An additional x-ray film exposure using an adjustable wrench. a) The adjustable wrench b) The film after exposure to x-rays c) The film superimposed onto the wrench.

An additional film exposure can be seen in Figure 5.10. In this exposure, an adjustable wrench was used to block the incident x-rays on the film. The wrench was opened to a width of approximately 1 cm, which corresponded with the width of the apparent exposed region on the film. The top of the film was freely exposed to x-rays and was not blocked by any portion of the wrench.

The x-ray film manufacturers have given guidelines for determining exposure time based on
the voltage and current levels of a conventional x-ray source. For a voltage of 70 kV and tube
current of 8 mA, a 0.2 second exposure is recommended for good exposure. Using the software
titled "Rad Pro Calculator" (freeware included as supplemental materials with [12]), the dose
rate of the described conventional x-ray source was approximated. Dental x-rays are typically
taken approximately 30 cm from the source, which gives a dose rate of 2567 R/hr (Roentgen per hour). For 0.2 seconds, this correlates to an exposure of 0.1426 R, or in SI units $3.679 \times 10^{-5}$ C/kg. We know that the tape-peeling triboluminescence system is capable of exposing the x-ray film, but it needs several seconds to do so (an exact exposure time is not known). Hence, the dose rate of the triboluminescence system should be an order of magnitude less than 2567 R/hr.

The intensity of the x-ray emission has been found to be sufficiently strong to make imaging with a peeling tape triboluminescence system a possibility. Further investigation into the resolution of the x-ray system could result in a greater understanding of the size of the x-ray emission region and thus the length of the gap between the separating faces of the tape.

5.3 RF

The RF radiation from the peeling tape system was measured with a monopole antenna and a high-speed oscilloscope. Figure 5.11 shows the antenna signal intensity measured over a period of 200 ms. Like the light emission, the RF radiation emission appears to come in spontaneous, non-periodic bursts that do not appear to have a settling time at this digitizing rate. The RF radiation emission mechanism has been previously linked to the failure of stick-slip friction in the tape [3]. This RF emission has been found to correlate in time with the light emission from the tape, and the correlation can be seen in Figure 5.12. From Figure 5.12, the correlation between light and RF emission is not always apparent, but is noticeable at the end of the total time sample. The RF pulses appear to occur more frequently than the light pulses. This suggests that the separation energies needed for light emission are higher than those needed for RF emission; this energy requirement may not be fulfilled at each discharge event.
Figure 5.11: Antenna signal intensity on a time scale of 200 ms. Repeated pulses of various RF intensity are measured by the PMT as the tape is peeled. The signal pulses did not appear to have a periodicity.

Figure 5.13 shows the antenna signal intensity on a 2 ms timescale (in blue). At a chamber pressure of 760 torr, the pulse length of the RF signal is approximately 1 ms. This pulse length is two orders of magnitude greater than the pulse length of the light intensity signal from the PMT. Additionally, it appears that the RF pulse has a settling time associated with it of approximately 700 $\mu$s. This longer duration suggests that the RF emission mechanisms are able to occur at greater separation distances and lower energies than the visible light emission of gas ionization. This statement suggests that the RF radiation is being emitted by the acceleration of charged particles and not through ionizing collisions, whereas the energy (or velocity) of these particles should not effect the overall flux of RF radiation. Changing the antenna length (sizing down from 5 cm) did not have any noticeable effect on the detected intensity of the RF signal.
5.3.1 Polarization

All of the previous experiments were performed with the antenna positioned horizontally in front of the tape peeling vertex. To assess the possible polarization and directionality of the RF radiation, experiments also arranged the antenna horizontally behind the peeling tape vertex, horizontally but reversed in direction, and vertically.

Figure 5.13 shows the time evolution of the signal pulse when the antenna was placed both in front of the tape peeling vertex and behind it (in both cases the antenna is pointed in the same direction). The time evolution of the pulse intensity did not change when the antenna was placed behind the tape peeling vertex and the magnitude of the intensity remained positive. The increase in magnitude of the signal from the antenna behind the tape peeling vertex can be attributed to the antenna’s closer distance to vertex. It can be asserted that the RF radiation emits from both sides of the peeling tape vertex. If the RF radiation is emitted through the acceleration of charged particles, then we can assert that the directionality of the emission...
should be similar to that of Larmor Radiation. The power pattern of the RF radiation should be
toroidal in shape centered around and perpendicular to the movement of the charged particles.
The total electromagnetic power radiated by an accelerated charged particle can be expressed
through Larmor’s Equation in Eq. 5.7.

\[ P = \frac{e^2 \times a^2}{6 \times \pi \times \epsilon_0 \times c^3} \]  

(5.7)

Where \( e \) is the charge on the particle, \( a \) is the acceleration, \( \epsilon_0 \) is the permittivity of free
space, and \( c \) is the speed of light. We can see that the power radiated is dependent on the
square of the acceleration, which gives a hint as to the nature of the particles involved in the
RF emission. Given a constant electric field, a constant force is exerted on a particle of a
specific charge. Thus, in a tape-peeling triboluminescence system, a particle’s acceleration is
determined solely by its mass. Electrons and ions are the two possible charged particles that
are being accelerated in the established electric field. Since the mass of an electron is several
orders of magnitude lower than that of an (nitrogen) ion, we can say that the dominant particle
contributing to the radiated electromagnetic power is the electron.

Figure 5.14 shows the RF signal intensity when the antenna was rotated to a vertical di-
rection. No signal was discerned from the noise. Figure 5.15 illustrates how the signal received
changes when the horizontally oriented antenna is reversed in direction.

From these polarization measurements we can conclude that the RF radiation has a distinct
horizontal polarization. The measurements also tell us that the RF radiation is emitted both
in front of and behind the tape peeling vertex. The electric field direction can be extracted
from the series of pictures in Figure 5.15. It can be stated the tape adhesive charges positively
with respect to the tape substrate because of the reverse in polarity of the antenna signal
when the antenna’s orientation is reversed. Consider that negatively charged electrons are the
active charged particle whose acceleration is dependent on the established electric field. The
accelerated electron will generate magnetic fields according to Maxwell’s equations as shown
in Figure 5.16. These magnetic fields induce localized differences in potential in the monopole
Figure 5.13: Time evolution of the antenna signal intensity on a time scale of 2 ms. The blue line shows the intensity versus time when the antenna was placed in front of the tape peeling vertex. The green line shows the intensity versus time when the antenna was placed behind the tape peeling vertex. The difference in magnitudes between the two plots can be attributed to different antenna distances from the tape.

... antenna which are picked up by the oscilloscope. Defining that the tape adhesive charges positively with respect to the tape substrate agrees with the conclusion given by Camara et al [3].

5.3.2 Spectrum

The spectrum of the was first inferred through the use of an AM radio. Measurements from the AM radio were qualitative in nature and were based on the audio output of the radio. The antenna length and type (loose coated wire approximately 3 feet in length) prevented polarization from being assessed, but the antenna was kept as horizontal as possible. Table 5.1 shows the notes from the experiment. When the tape was not being peeled, the AM radio maintained a white noise output. As soon as the tape began to be peeled, the audio output from the radio immediately changed; the output went silent except for a distinct popping sound.
Figure 5.14: Antenna signal intensity on a time scale of 200 ms when the antenna was oriented vertically.

Table 5.1: Description of audio heard at different set frequencies of an AM radio when tape was peeled.

<table>
<thead>
<tr>
<th>AM Frequency</th>
<th>Description of Response (Audio)</th>
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<tr>
<td>Control (no peeling)</td>
<td>General noise, no distinct sounds</td>
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<tr>
<td>530 kHz</td>
<td>‘Popping’ heard. No apparent periodicity to sounds.</td>
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<td>750 kHz</td>
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<td>1000 kHz</td>
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<table>
<thead>
<tr>
<th>FM Frequency</th>
<th>Description of Response (Audio)</th>
</tr>
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<tbody>
<tr>
<td>Control (no peeling)</td>
<td>General noise, no distinct sounds</td>
</tr>
<tr>
<td>All frequencies</td>
<td>General noise, no distinct sounds</td>
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</table>

The popping sound did not appear to have a distinct periodicity and continued to be heard no matter the frequency chosen by the user. When the radio was set to pick up FM radio transmissions, no distinct sounds could be heard when the tape was peeled.

The data in Table 5.1 leads us to believe that the RF radiation spectrum is fairly broadband. An interesting distinction, but more data is needed to come to a conclusion on the mechanisms behind the emission.

Quantitative RF spectral data was obtained through the use of a spectrum analyzer. However, this data was found to be inconclusive, and as such is not included in this paper.
Figure 5.15: Change in antenna signal intensity on a time scale of 200 ms when the antenna is configured in one of two different orientations. Signal detected in orientation 2 is inverted with respect to the signal from orientation 1.

Figure 5.16: Diagram illustrating how an electric field generated from the separation of charge affects the signal as seen by a monopole antenna.

One final analysis was conducted by using the oscilloscope to look at the beginning of the RF pulse on a nanosecond time scale. As seen in Figure 5.17, a distinct oscillation is apparent in the RF signal. This oscillation has a period of approximately 20 ns, which corresponds to a frequency of 50 MHz.

5.3.3 RF intensity versus pressure

The RF emission intensity was investigated at different chamber pressures using an electrical feedthrough. It was found that the RF pulses would decrease in intensity as the chamber pressure would decrease until completely disappearing at a chamber pressure between 350 and 400 torr. The duration of these RF pulses did not distinctly appear to change with decreasing chamber pressure.

The reason behind the RF emission disappearance at lower chamber pressures is currently
Figure 5.17: Antenna signal intensity on a time scale of 1 \( \mu s \). A distinct signal oscillation is seen that has a period of approximately 20 ns.

unexplained. This disappearance occurs at a relatively high chamber pressure, and hence it is improbable that this can be correlated to the linearly proportional increase of the mean free path to the pressure in the chamber. It is possible that there is some sort of connection between the generation of RF radiation and the number of ionizing collisions occurring after each discharge event.
References


Chapter 6

Future Considerations

In the hopes of stimulating future scientific research in x-ray generation through triboluminescence, we have devised a number of questions that can and should be approached in future research.

6.1 Non-tape-based triboluminescence system

We have established that the triboluminescence phenomenon is capable of producing x-rays that are of a high enough intensity to image dental film. This fact alone makes a tape-peeling system an interesting alternative to conventional x-ray generation machines. However, we have found that the tape-peeling system investigated in this research has a number of limitations that prevent it from becoming an attractive low-cost alternative to current x-ray generation systems.

First, we have identified that the tape-peeling system experiences significant out-gassing in vacuum. This makes maintaining an optimum system pressure difficult at $10^{-3}$ torr. One possible solution would be to replace the weak point of the vacuum system - the Viton sealing gaskets - with a more adequate (but more expensive) substitute such as o-rings. However, this outgassing means that a vacuum system would always need to be present in a tape-peeling triboluminescence system to remove excess gas molecules and hold the chamber at a constant
pressure, further limiting the practicality and increasing the total system cost.

Another limitation is that the tape-peeling system can only be operated for a limited amount of time before running out of tape to peel. This results in having to pump the chamber back to atmosphere, reset the tape spool, and re-seal and re-pump the chamber down to $10^{-3}$ torr. These steps take time and would prevent the system from being practical in a medical setting. What is needed is a means to recycle the tape feed. This could be accomplished through the use of another motor and pair of magnetic couplers. Such a step would not only increase the overall cost of a tape-peeling x-ray system, but would also increase the torque requirement of the tape-peeling motors and require additional motor control equipment.

The problems of out-gassing and resetting the tape limit the practicality of a tape-peeling x-ray generation system, so an alternative is presented. Figure 6.1 shows a diagram of the suggested system. It borrows a number of ideas from the tape-peeling system including a mechanical power source and magnetic coupling into a vacuum chamber. Rotational motion is coupled from a shaft to a rotating set of rare-earth magnets inside a fixed holder. These magnets cause another set of magnets mounted in a rotating drive to spin inside a vacuum chamber. The rotating drive shaft is secured with thrust bearings and is connected to a silicone cylinder resembling a set screw. As the driveshaft is rotated, the silicone lobes make contact with a layer of epoxy mounted on the inner wall of the vacuum chamber and then separate. This motion provides a means by which charge can be separated, an electric field can be established, and triboluminescence can occur.

6.2 Useful Measurements

6.2.1 X-ray spectrum with respect to pressure

Several researchers have investigated the x-ray emission from a triboluminescence system [3, 4, 17]. However, it is believed that further study into this spectrum - particularly on its dependence with pressure - can give researchers a better understanding of the separation distances involved
in a peeling tape system. The maximum (or statistical average) Bremsstrahlung energy can be related to the mean free path in order to extract this information. However, we would need a much better statistical understanding (or possibly a model) of Bremsstrahlung and mean free path in order to approximate this separation distance.

6.2.2 Absorbed Radiation Dose

In Chapter 5, a rough approximation of the system’s x-ray exposure was generated. This approximation was found using the film manufacturer’s recommended x-ray source voltages and currents for proper exposure and the Rad Pro Calculator software distributed with [12]. The dose rate was estimated to be an order of magnitude less than current x-ray generation tubes. It should be stressed that this is just an approximation, however. It would be useful to make a more accurate assessment of the exposure and dose of the system in order to metrically compare the ability of a tape-peeling triboluminescence system with modern x-ray generation
equipment (most x-ray systems are measured by their ability to expose). In medicine, absorbed
dose and absorbed equivalent dose are metrics typically used to describe the amount of radiation
absorbed by biological tissue. The SI unit for absorbed radiation dose is known as the Gray,
and is defined as one joule of ionizing radiation per kilogram of absorbing tissue. The average
radiation dose for an imaging x-ray is typically between 1 - 30 mGy.
References


Chapter 7

Conclusion

A peeling-tape based triboluminescence system was fabricated. Scotch tape was used as a means to mechanically separate charge and induce a strong electric field between two insulating layers of tape. The system was designed and constructed to handle a medium vacuum environment, couple rotary motion into a vacuum, and shield from ionizing radiation. The system was mechanically powered and cost approximately 200 USD. This system was built with the purpose of generating X-ray radiation and to develop an understanding of the mechanisms by which these X-rays and other triboelectric emissions are generated.

X-rays were proven to be generated by the triboluminescence system through the use of scintillators and a Geiger-Müller counter. It was found that the tape-peeling system was capable of delivering approximately 2500 counts per minute of X-ray photons at a chamber pressure of 5 mtorr. X-ray radiographs were used to assess the imaging capability of the system, and the intensity of the emitted X-rays was found to be strong enough to expose X-ray film.

The light emission from the triboluminescence system was investigated, and was found to occur in a series of pulses over time that correlate with stick-slip events. The spectrum of this emission was verified to correspond to chamber gas ionization processes. Blue light was seen when the tape was peeled in nitrogen at 760 torr and purple light was seen in argon at 10 torr. At chamber pressures around $10^{-2}$ torr, higher energy Bremsstrahlung radiation corresponding
to visible light began to appear. This light due to Bremsstrahlung was white in color. The intensity of the light was verified to correlate with tape peeling speed and, with increasing speed, a saturation and then slight decrease in intensity was seen. It is thought that this increasing intensity corresponds to discharge events occurring at decreasing separation distances. The light intensity was found to be maximized between 10 cm/s and 15 cm/s tape peeling speed. The time evolution of the light pulses was also investigated with respect to chamber pressure. It was discovered that the pressure in the chamber was proportional to the pulse duration and intensity of the emitted light, suggesting that the light is emitted via an avalanche mechanism such as Townsend discharge.

The RF emission from the triboluminescence system was also investigated and, like the light emission, was also found to occur in a series of pulses. These RF pulses were correlated with the light pulses in time. The time evolution of the RF pulses was investigated at atmosphere, and it was found that these pulses were maintained two orders of magnitude longer than the pulses of light. It was found that the RF radiation maintained a distinct horizontal polarization. From this information it was asserted that the tape adhesive charges positively with respect to the tape substrate, which agreed with results from other researchers. The RF spectrum was also investigated, and it was discovered that the RF emission was continuous.

The tape-peeling triboluminescence system has the disadvantage of having significant out-gassing during the peeling of scotch tape in vacuum. From an x-ray generation system standpoint, this is a significant problem. The out-gassing prevents the chamber from maintaining the pressures required to generate x-rays through Bremsstrahlung mechanisms. An alternative mechanically-powered triboluminescence system was suggested that made use of rotating silicone cylinder to make contact with and tribocharge the surface of an epoxy substrate.

Although the system was proven to be able to expose an x-ray radiograph, future triboluminescence experiments should investigate the absorbed radiation dose. Knowing the given dose will allow researchers to assess the usefulness and capability of a triboluminescence-based x-ray generation system. Furthermore, if the system is ever to be used in a medical environment -
where minimizing exposure is paramount - these parameters will greatly aid professionals and researchers alike in determining how best to utilize these systems.
References


Chapter 8

Appendix-A
8.1 MathCAD used for Calculations

8.1.1 Mean Free Path

Universal Gas Constant

\[ R = 8.3145 \text{ J mol}^{-1}\text{K}^{-1} \]

\[ P := 760 \text{torr} \quad P_{\text{vac}} := 5 \times 10^{-3} \text{torr} \]

\[ T := 293 \text{K} \]

Avogadro's Number

\[ N_A := 6.0221 \times 10^{23} \text{ mol}^{-1} \]

\[ r_1 := 3 \times 10^{-10} \text{m} \quad r_2 := 7.6 \times 10^{-11} \text{m} \quad r_3 := 71 \times 10^{-12} \text{m} \]

MFP of Nitrogen gas

\[ \text{MFP}_1 := \frac{RT}{\sqrt{2} \pi r_1^2 N_A P} = 9.985 \times 10^{-8} \text{m} \]

MFP in near vacuum of Nitrogen gas

\[ \text{MFP}_{12} := \frac{RT}{\sqrt{2} \pi r_1^2 N_A P_{\text{vac}}} = 0.015 \text{m} \]

MFP of Argon gas

\[ \text{MFP}_3 := \frac{RT}{\sqrt{2} \pi r_3^2 N_A P} = 1.783 \times 10^{-6} \text{m} \]

MFP in near vacuum of Argon gas

\[ \text{MFP}_{32} := \frac{RT}{\sqrt{2} \pi r_3^2 N_A P_{\text{vac}}} = 0.271 \text{m} \]

MFP of Neon gas

\[ \text{MFP}_2 := \frac{RT}{\sqrt{2} \pi r_2^2 N_A P} = 1.556 \times 10^{-6} \text{m} \]

MFP in near vacuum of Neon gas

\[ \text{MFP}_{22} := \frac{RT}{\sqrt{2} \pi r_2^2 N_A P_{\text{vac}}} = 0.236 \text{m} \]
8.1.2 Mechanical Deflection in System

Define a and b to give the ratio of largest to smallest length of plate
\[ a = 5 \text{ in}, \quad b = 5 \text{ in} \]
\[ \alpha = 0.1267 \text{ for } a/b = 1 \]

Pressure: 14.7 psi
Area: \[ \pi \left( \frac{b}{2} \right)^2 = 19.635 \text{ in}^2 \]

Force: Pressure Area = 288.634 lbf

**Variables**

**Thickness:**
\[ t_2 = 0.125 \text{ in}, \quad t_{acr} = 0.472 \text{ in} \]

**Elastic Modulus**

For 6061-T6 Aluminum
\[ Al_{elas} = 10 \times 10^6 \text{ psi} \]

For Acrylic
\[ Acr_{elas} = 464120 \text{ psi} \]

**Bottom Alum**
\[ \text{max}\Delta := -\alpha \cdot \text{force} \cdot \frac{b^2}{Al_{elas} \cdot t_2^3} = -0.047 \text{ in} \]

**Top Acrylic**
\[ \text{max}\Delta := -\alpha \cdot \text{force} \cdot \frac{b^2}{Acr_{elas} \cdot t_{acr}^3} = -0.019 \text{ in} \]
8.1.3 Motor Torque Requirements

Base holder mass:
\[ m_{\text{holder}} := 7.49 \text{gm} \]
\[ m_1 := 38.93 \text{gm} \]
\[ m_2 := 28.97 \text{gm} \]

Began to overcome tape friction at:
\[ 2m_1 \]
\[ m_{\text{slip}} := m_{\text{holder}} + 2m_1 = 0.085 \text{ kg} \]
\[ F_{\text{slip}} := m_{\text{slip}} \cdot 9.8 \frac{m}{s^2} = 0.836 \text{ N} \]

Began to move consistently at:
\[ 2m_1 + 4m_2 \]
\[ m_{\text{move}} := m_{\text{holder}} + 2m_1 + 4m_2 = 0.201 \text{ kg} \]
\[ F_{\text{move}} := m_{\text{move}} \cdot 9.8 \frac{m}{s^2} = 1.972 \text{ N} \]

\[ \text{width}_{\text{tapemin}} := 0.5 \text{in} = 1.27 \text{cm} \]
\[ \text{width}_{\text{tapemax}} := 1 \text{in} = 2.54 \text{cm} \]

Torque of motor:
\[ \text{Torque}_{\text{motor}} := 0.1402 \text{N-m} \]

Torque Requirements (slip):
\[ \text{Torque}_{\text{slipmin}} := \text{width}_{\text{tapemin}} F_{\text{slip}} = 1.062 \text{N-cm} \]
\[ \text{Torque}_{\text{slipmax}} := \text{width}_{\text{tapemax}} F_{\text{slip}} = 2.125 \text{N-cm} \]

Torque Requirements (consistent movement):
\[ \text{Torque}_{\text{movemin}} := \text{width}_{\text{tapemin}} F_{\text{move}} = 2.505 \text{N-cm} \]
\[ \text{Torque}_{\text{movemax}} := \text{width}_{\text{tapemax}} F_{\text{move}} = 5.009 \text{N-cm} \]

\[ 6\text{in-lbf} = 67.791 \text{N-cm} \]

Calculating maximum tape take-up speed
\[ \text{rpm}_{\text{motor}} := 654 \text{rpm} = 68.487 \frac{1}{s} \]
\[ \text{circumference}_{\text{tapemin}} := 2\pi \text{width}_{\text{tapemin}} = 7.98 \text{cm} \]
\[ \text{circumference}_{\text{tapemax}} := 2\pi \text{width}_{\text{tapemax}} = 15.959 \text{cm} \]
\[
\text{speed}_{\text{min}} = \text{rpm}_{\text{motor}} \times \text{circumference}_{\text{tap\_min}} = 546.5 \, \frac{1}{\text{s}} \, \text{cm}
\]

\[
\text{speed}_{\text{max}} = \text{rpm}_{\text{motor}} \times \text{circumference}_{\text{tap\_max}} = 1.093 \times 10^3 \, \frac{1}{\text{s}} \, \text{cm}
\]
## 8.2 Excel Spreadsheets

### 8.2.1 X-ray Attenuation in Aluminum

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8.2.2 X-ray Attenuation in Acrylic

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