Conservation of charge in secondary electron emission test stand

Shaoru Garner

University of Nevada, Las Vegas

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CONSERVATION OF CHARGE IN SECONDARY ELECTRON EMISSION

TEST STAND

by

Shaoru Garner

Bachelor of Engineering
University of Nevada, Las Vegas
2005

A thesis submitted in partial fulfillment
of the requirement for the

Master of Science Degree in Electrical Engineering
Department of Electrical and Computer Engineering
Howard R. Hughes College of Engineering

Graduate College
University of Nevada, Las Vegas
December 2007
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Master of Science in Electrical Engineering

Examination Committee Chair

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ABSTRACT

Conservation of Charge in Secondary Electron Emission Test Stand

by

Shaoru Garner

Dr. Robert A. Schill, Jr., Examination Committee Chair
Professor, Electrical and Computer Engineering
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This Thesis reports theoretical and experimental evaluations of the critical components of the UNLV secondary electron emissions test stand. These components include: 1) a source of electrons, an electron gun, 2) methods and instrumentation to obtain a direct measure of electron current supplied by the electron gun, and 3) a position sensitive particle detector that is capable of detecting single electrons and that provides the spatial and temporal distribution of secondary electrons. The overall objective of this project is to study the properties of secondary electron emission and the conservation of charge in the secondary electron emission test stand. Secondary electron emission (SEE) can potentially lead to beam instabilities, material degradation and r.f. breakdown. The past SEE studies have deduced secondary electron yield by invoking a conservation of charge without the need to experimentally account for all measurables. In the spatial distribution studies of SEE, one may not invoke conservation of charge without some knowledge leading to all loss effects. An electron gun in the SEE test stand at UNLV directs the primary electron beam through a beam drift tube piercing the
center of a particle position detector with controlling grid towards the sample under test. Secondary electrons emitted by the sample either drift freely or are drawn by a grid potential to the particle position detector. The particle position detector records the number of electrons and the locations of electron impact. Low primary beam currents are necessary in order to perform these measurements within the resolution of the detector. Because the detector surface is flat and finite in dimension, some loss to the chamber walls will result. Consequential SEE loss to the walls is not measurable in a noise environment even if the experimental apparatus (the SEE test stand) is isolated from the earth ground. A Faraday cup is used to monitor the primary beam current. The beam drift tube, grid, and sample currents are monitored and integrated to yield the number of charges collected by each component over time. Each component of the detector assembly, such as grid, microchannel plates and the data acquisition card will be studied in detail in order to achieve an absolute measurement of the secondary electron emission.
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To my family
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CHAPTER 1

INTRODUCTION

1.1 Thesis Objective

Secondary electron emission (SEE) can potentially lead to beam instabilities, material degradation and R.F. breakdown. The studies of secondary electron emission under electron bombardment play an essential role in vacuum electronic devices. When electrically charged particles with sufficient kinetic energy impinge on a solid surface, this surface emits electrons. The emitted electrons are called secondary electrons and the bombarding particles are called primary particles. Secondary electrons can be differentiated into three groups [1, 2], namely: I. elastically reflected primary electrons, II. inelastically backscattered primary electrons, and III. true secondary electrons. As the primary electron current impinges on a surface, the portion of electrons that reflect elastically are called reflected primary electrons, and the rest penetrate into the material. Those electrons that scatter from one or more atoms inside the material and reflect back out are denoted as the inelastically backscattered primary electrons. The rest of the electrons interact in a more complicated way with the material and yield the true secondary electrons. The secondary electron emission coefficient $\delta$ of a material is defined as the ratio of the secondary electron current emitted from the surface of the testing sample to the primary electron bombarding current. The secondary electron
emission yield is an important parameter of a material; the yield depends on many factors such as the primary beam energy, the incident angle and the coating and the condition of the surface under test. Conservation of charge is important in establishing the secondary electron yield and the spatial distribution of secondary electrons. Past SEE studies have deduced secondary electron yield by invoking a conservation of charge without the need to experimentally account for all measurables. The primary motivation of this thesis is to understand the function and the performance of each electronic component inside the vacuum chamber in order to establish a conservation of charge principle useful for the study of the spatial distribution of secondary electron emission.

1.2 Secondary Electron Emission

1.2.1 The Background

In the nineteenth century, Johann Hittorf and Sir William Crookes independently investigated the radiation produced by a cathode in a vacuum tube, demonstrating that an invisible "light" was produced which caused glass to fluoresce and cast shadows. In 1902 the phenomenon of secondary electron emission was discovered by Austin and Starke [3]. The use of secondary electron emission as a means for signal amplification was proposed by Slepian at 1922 [4]. The fundamental theory of secondary electron emission was developed by Jonker (1952), Lye and Dekker (1957) [5].

1.2.2 Electron Emission

Electron emission from solid was among the earliest phenomena to be observed scientifically. When the electrons penetrate the metal surface, the free electrons inside the metal respond to the non-equilibrium Coulombic forces being generated thereby resulting
in electron transport within or possibly from the supporting medium. External energy is required in order for the electrons to eject from the metal surface. The minimum amount of energy required for the electron to emit is defined as work function. There are four methods of emitting an electron from a metal surface: thermionic emission, field emission, secondary emission, and photoelectric emission. Thermionic emission is the flow of charged particles called thermions from a metal or a metal oxide surface, caused by thermal vibrational energy overcoming the electrostatic forces holding electrons to the surface [6]. Field emission is a form of quantum tunneling in which electrons pass through a barrier in the presence of a high electric field. This phenomenon is highly dependent on both the properties of the material and the shape of the particular cathode, so that higher aspect ratios produce higher field emission currents [7]. Photoelectric emission is a quantum electronic phenomenon; the energy is transferred from the light photons to the free electrons within the cathode. If the energy from photons is greater than the metal work function, then the electron will eject from the cathode surface. The emitted electrons are called photo electrons. The amount of photo electrons depends on the intensity of the light and the energy of the photons [8].

1.2.3 Energy Distribution of Secondary Electrons

After the primary electrons strike the metal sample, there are three groups of electrons produced; emitted secondary electrons and both elastically and inelastically reflected primary electrons. The general energy distribution of the primary electron energy is shown in Figure 1.1. Typically, the secondary electron has low energy as indicated by marker c, the reflected primary electron has energy that is close to the primary electron energy as indicated by marker ‘a’, and the backscattered primary electron, indicated by
marker ‘b’, has lost some energy from scattering inside the metal and as a consequence of surface emission. In general, the secondary electron has high yield of 60% at the primary electron energy of 300 eV according to Grobner [9].

1.2.4 Secondary Electron Measurement Techniques

There are many techniques of measuring secondary electron emission in the literature. The typical measurements make use of a Faraday cup to measure the primary electron beam, a detector (usually held at a positive potential with respect to the sample) to detect the secondary electron emission, and an electrometer to measure the sample-to-ground current. A comparison is made between the measured primary electron current to the sample-to-ground current. Some techniques used Faraday cups to measure the primary beam current and the secondary electron current by interposing a Faraday cup between electron gun and sample [10,11,12]. One Faraday cup is in the path of the primary beam to measure the primary beam current, $I_p$. The second is directed towards the sample to measure secondary electron current, $I_s$, as shown in Figure 1.2. The secondary electron emission coefficient $\delta$ can be written as $\delta = \frac{I_s}{I_p}$. Some techniques measure the current from a sample and from a secondary collector cage simultaneously while bombarding the sample by primary electrons [13,14,15]. The current measured from the collector cage is the secondary electron current, $I_s$, and the current measured from the sample is $I_{\text{sample}}$, therefore, $\delta$ can be written as $\delta = \frac{I_s}{I_s + I_{\text{sample}}}$. Some of the measurements of secondary electrons were conducted in the presence of a potential difference [16,17]. If a positive voltage applied to the sample is large enough it will force all of the emitted electrons to return to the sample. A negative voltage applied to the sample will repel the emitted electrons, so the current measured from the sample is the net current $I_{\text{net}}$, which is

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the difference between the secondary emitted current \( I_{sc} \) and the incident primary beam current \( I_p \). Therefore, the secondary electron emission coefficient \( \delta \) can be written as \( \frac{(I_{net} + I_p)}{I_p} \).

1.3 Uniqueness of the Research

The literature search revealed no evidence of a technique that measures all components accountable for the secondary electron emission from a single pulse allowing for spatial distribution studies. Consequently, spatial distribution studies require multiple pulses from either the same surface or an equivalent surface having the same surface properties. This is important since studies (including Scanning Electron Microscopy studies) have shown that metal surfaces undergo surface conditioning as the electron dose changes. The assumption that each electron beam pulse "sees" the same surface characteristics may be inaccurate.

An electron gun in the SEE test stand directs the primary electron beam through a beam drift tube piercing the center of a particle position detector with controlling grid towards the sample under test. Secondary electrons emitted by the sample either drift freely or are drawn by a grid potential to the particle position detector. The particle position detector records the number of electrons and the locations of electron impact. Low primary beam currents are necessary in order to perform these measurements within the resolution of the detector. Because the detector surface is flat and finite in dimension, some loss to the chamber walls will result. Consequential SEE loss to the walls is not measurable in a noise environment even if the experimental apparatus (the SEE test stand) is isolated from the earth ground. The uniqueness of this research project is to understand
the principle operations of each component inside the vacuum chamber in order to perform absolute measurement of the secondary electron emission. The data from the previous SEE test stand will be used, the typical value for primary beam energy is 1 keV and primary beam current measured from Faraday cup is 2.2 nA. Sample, grid, tube and Faraday cup current will be measured. The percentage of secondary electrons that are lost to grid and MCP will be calculated. The experimental results from the previous SEE test stand will be incorporated and compared with the experimental and calculated data develop from this research project.

An attempt will be made to develop a means to measure the properties of the low current primary electron beam in a nondestructive manner (i.e., does not destroy or alter the primary beam characteristics). Theory tends to indicate that the diagnostic, which we coined as the Faraday tube, offers a means in determining various beam characteristics by monitoring the induced wall currents in the tube. In practice, noise tends to limit its utility. Even so, special shielding may enhance its utility in future works. Therefore, this device is discussed at length due to its detection potential.

It is hypothesized that the state of the sample may influence the initial condition of the secondary electron emission momentum trajectory. In an earlier work, the backscattered electrons from cryogenic niobium targets seemed to exhibit an angle of reflection with property similar to an electromagnetic Snell’s law. If the target is heated, it is anticipated that the initial momentum trajectory will approach a more random nature. Therefore, MAGIC simulations have been conducted for proposed future experiment using micro wave to heat the sample for secondary electron emission experiments.
1.4 Organization of the Thesis

This thesis is organized into five chapters. Chapter 2 deals with the function and the characteristics of each component on an individual basis. The Faraday tube will be introduced. Chapter 3 discusses the use of Magic code to simulate microwave heating the sample and cooling the system by the modeling the mechanical components in electrical forms. The experimental setup with results is provided in Chapter 4. Chapter 5 concludes the thesis by offering some recommendations for future work.
Figure 1.1 The general shape of the energy distribution of secondary electrons [18].

Figure 1.2 Measurement apparatus. With the Faraday cups in the position shown, the ammeter is measuring the secondary current $I_s$. [11]
CHAPTER 2


2.1 Introduction

Prior to this study, the EK-5-M5 from Staib Instruments Inc. was chosen to study secondary electron emission. It has an electron energy range from about 100eV to 5000eV which covers the primary electron energy range for most secondary electron emission experiments of interest at this time. Due to the presence of the large potentials and potential gradients associated with the particle position detector, a drift tube inserted into the tip of the electron gun was essential in preserving the focus of the primary electron beam as it drifts through the detector and grid geometries towards the sample under test. In order to establish the secondary electron yields as a function of space over the detector surface and/or invoke conservation of charge, it is important to characterize the primary electron beam generated by the gun with beam drift tube impinging on the sample under test. Very low beam currents cannot be reliably measured by the electronics operating the electron beam gun. Non-intrusive techniques are required in order to establish the number of electrons impinging on the target surface. Visual beam fluorescent studies, Faraday cup with electrometer studies, and Faraday cup connected directly to an oscilloscope with 1MΩ input impedance measurements suggest the same
conclusions. The latter technique allowed for direct monitoring of the time profile of the signal relative to the pulse stimulus driving the electron gun in beam blanking mode.

2.2 Studies of the Electron Gun

2.2.1 Principle of Operation

The components of the electron gun include the cathode, the anode, and the optical system. The electron source power supply controls the electron gun. Figure 2.1 shows the front panel of the electron power supply. The cathode is a standard hairpin type W filament. The filament dial on the power supply controls the filament temperature by driving a current in the range of 1.5 A to 1.7 A through the filament. The electrons are created via thermionic emission when the filament is heated. The grid controls the magnitude of positive potential applied to the lens to extract the electrons from the filament. The electrons emitted from the filament are then sharply focused into the "cross-over" located near the anode, refer to Figure 2.2. The size of the cross-over ranges from 15 μm to 20 μm depends on the total current emitted by the filament, which is the emission current.

The optimal performance of the electron gun is obtained when the beam is well centered through the optical column. Figure 2.3 shows the alignment of the optical system. The first focusing element, the condenser alignment plates A1, designated by the focusing orientations X1, Y1, is located near the anode. The anode electrodes accelerate the electrons which allow the maximum current through the optical system. The second focusing element, the objective alignment plates A2, is a set of steering plates located in front of the objective lens. It is used to optimize the beam current at lower spatial
resolution and to optimize the minimum spot size at high spatial resolution. The third element is the stigmator alignment plates, S. It is used to obtain the smallest spot for a given beam current. Under normal operations, the deflection plates, X1, X2, Y1 and Y2 are set to 5.0 on the dial settings (division) on the electron source power supply. The condenser is set to 0.0 division and the objective is set to 7.0 division. The gun control unit is connected to the electron source power supply and can be used to scan the electron beam by adjusting the X and Y knobs [19].

2.2.2 Primary Beam Energy and Current

The energy and the emission current of the primary electron beam are displayed on the front panel of the electron source power supply. The beam current near the sample is much lower and is measured by the Faraday cup. Table 2.1 shows the primary beam current versus the energy measured by the Staib Instrument Inc. factory and by the electromagnetic lab at UNLV. Table 2.2 shows the primary beam current with the drift tube attached at the end of the electron gun versus energy measured by the electromagnetic lab. The purpose of the drift tube is to shield the electric field from the detector, so the primary beam can pass through the detector without being disturbed.

2.2.3 Limitation of the Electron Gun

The electron gun has an energy range from 100 eV to 5000 eV. The filament can support up to 2.0 A, but to prevent filament burn out, the maximum filament current should be under 1.8 A. The filament current is kept at 1.7 A under normal operations. It is also recommended to reduce the heating current to 1.4 A during pauses longer than 20 minutes. The emission current is limited to 200 µA, the beam voltage will drop if one exceeds the maximum emission current.
2.3 The Faraday Tube and the Initial Test Setup to Measure the Electron Beam Current

A Faraday tube is a non-intrusive sensor used to measure the charge particle beam current without significantly affecting the beam characteristics. The terminology, Faraday Tube, is coined by us. The Faraday tube is like a Faraday cup except that the tube allows the beam to enter and leave the tube without loss of charge and only a small loss of energy assuming that the beam does not collide with the tube wall. The tube end inserted into the gun is insulated from the gun walls with either a few turns of Teflon tape or a Vespel dielectric insulator coating. The other end of the tube was coated with a Vespel dielectric insulating the tube from the detector housing. A bared copper wire was wrapped around the metal portion of the tube twice with the end tightly twisted guaranteeing that the loop made good mechanical and electrical contact. The remaining end of the wire was attached to an electrical feedthrough. The atmospheric pressure side of the feedthrough was shielded with an aluminum cup and attached to a coaxial wire. The opposite end of the coaxial wire was attached to an internal amplifier in the electrometer with amplifier output connected to an oscilloscope. To minimize undesired capacitive coupling on the atmospheric side of the vacuum chamber, the unshielded insulated wire pairs were twisted about each other and then wrapped in properly grounded aluminum foil. Internal to the vacuum chamber, capacitive coupling effects were minimized by twisting insulated transformer wire around the wire attached to the Faraday tube from the tube to the electrical feedthrough. These undesired coupling effects are sometimes denoted as microphonics effects. The ends of the transformer wire were bared and attached to a ground surface (the chamber wall and the electron gun wall). As charge enters the electrically isolated tube, ideally charge of opposite sign is
induced on the tube wall being drawn from ground via the electrometer. The electrometer measures the induced current.

It is important that the Faraday cup aperture is properly aligned with the beam to capture and trap the primary electrons and all associated secondary electrons generated in the cup cavity. If the beam impinges on the outer metallic casing of the Faraday cup, current fluctuations are observed due to possible gain of primary electrons and loss and possible recapture of generated secondary electrons.

The following technique was used to align the electron beam with the beam drift tube and the Faraday cup. First the tube is aligned with the gun and the detector axes prior to pumping the system down in pressure. This alignment is made by inserting a straight metal rod through the tube and into the electron gun until it just fits into one of the aperture openings in the gun by a set of deflector plates. Further, visual observations were made to check for coincident axes. Once the electron beam and tube axes are nearly identical, the system is pumped down. With the electron beam on, the Faraday cup is moved along the X and Y directions with the gun deflection elements set for the beam to be in its ideal central position. A phosphorescence annular glass disk, with the ability to discharge the collected charge to ground, centrally located about the aperture opening of the Faraday cup, is used to give visual feedback on the presence and location of the beam relative to the cup opening. As the aperture opening of the cup is moved nearer to the beam axis, visual feedback is lost and electrical feedback from the electrometer connected to the cup is monitored. When the beam passes directly into the cup, the current reading reaches a maximum. A definite characteristic is observed when the beam is adjusted in the plus and minus x and y directions away from the optimal position. It is
this characteristic that is sought to guarantee that the beam is passing through the center of the tube and impinging in the cup. If the beam can not be located with the cup, the deflection plates (in sequential order the scanning plates, objective alignment plates, and the condenser plates are adjusted from their near optimal factory positions) are used to adjust the beam position. If no signal can be found, the machine is vented and the tube is physically readjusted in the gun and detector. The procedure of aligning the beam to the Faraday cup hole is to eyeball the beam to the center line of the Y-axis of the Faraday cup (Y dial of manipulator arm). While the Y position is fixed, one can move the X dial of the manipulator arm and monitor the current. (Refer to Table 2.3 and Figure 2.4). Once the Faraday cup is roughly aligned to capture the beam, the beam deflection plates are readjusted such that a maximum beam current is detected. This fine tuning with the deflection plates allows for optimal positioning of the electron beam in the gun - drift tube – detector – grid assembly. To find the optimal position of the beam, the X1, X2, Y1 and Y2 plates are adjusted one at a time. Table 2.4 and Figure 2.5 show the tube current versus the adjustment of the X1 dial while the others are fixed at the default position (5.0). The X1 dial at 5.56 shows the least amount of tube current. Table 2.5 and Figure 2.6 show the tube current versus the adjustment of the Y1 dial while the X1 dial is fixed at the position 5.56 and X2 and Y2 are fixed at position 5.0. The tube current shows a minimum when Y1 dial is about 5.6. The same procedure is followed for finding the position of the X2 dial, when the X1, Y1 and Y2 dials are fixed at the positions 5.56 and 5.6 and 5.0 respectively (refer to Table 2.6 and Figure 2.7). The last dial Y2 is adjusted with X1; Y1 and X2 at the positions where the least amount of the tube current is
measured from previous tests (refer to Table 2.7 and Figure 2.8). The same procedure is followed when the detector is energized. The experimental setup is shown as Figure 2.9.

2.4 Physical Description of the Signal Signatures from the Faraday Tube

The signal signatures from a Faraday tube connected to an ammeter is explored. The configuration is shown in Figure 2.10. A quasi static theory is employed to study the nature of the induced and collected currents resulting from the interaction of an external beam with the tube. A quasi static theory is reasonable since the beam is moving much slower than the speed of light and the overall tube dimension is small compared to the distance a wave would travel on the same time scale. Our attention is focused around beam energies below 1 keV. For a conservative estimate, consider a 1 keV electron beam. Electron beam energies well below 0.5 MeV are usually considered as nonrelativistic and hence classical Newtonian theory holds. Therefore, the average electron beam speed is \( v = \sqrt{\frac{2E}{m_e}} \). In free space, an electromagnetic wave propagates at the speed of light.

For the same time, the ratio of the change in the distance traveled by an electron to the distance traveled by the wave is \( \sqrt{\frac{2E}{c^2 m_e}} \). For a 1 keV electron, this ratio is 0.0625. The inside radius and length of the tube are 1 mm and 4 cm respectively. For a wave to propagate the radial distance of the tube, the electron will have moved a 2.5 mm distance. The ratio of this distance moved to the radius of the tube is 0.063. Of course, the same ratio holds when comparing the ratio of the distance moved by the charge to the distance the wave must propagate along the entire length of the tube. Since this is much smaller than 1, one may assume that the entire tube will feel the presence of the charge almost
simultaneously. The relaxation time of copper is on the order of 1.5x10^{-19} seconds. This is much faster than the time it takes the wave to propagate from the electron radially outward to the tube wall (3.33 ps). Consequently, one may also assume simultaneity of charge drawn to the tube wall within the timeframe of the experiment.

Assuming a quasi-static approximation, Gauss’ Law may be written as

$$\oint \mathbf{D}(t) \cdot d\mathbf{s} = q_{\text{em}}(t) \quad (2.1)$$

As a beam charge enters the cylindrical tube, the number of flux lines terminating on the tube wall increases. The amount of charge drawn to the surface of the wall is proportional to the number of electric flux lines terminated on the tube wall to the number of flux lines generated by the beam charge times the beam charge. Since the length of the tube is much larger than the tube’s diameter, near the central region of the tube, the number of charges drawn to the surface of the tube equals to the amount of beam charge in that region. Since the tube is electrically connected to ground, the charge drawn to the surface of the tube is pulled from ground. By conservation of charge, there is a one-to-one correspondence between the beam charge and the charge drawn from ground. Define the surface S to enclose the volume V of the tube bounded by, but excluding, the inside surface of the tube wall and the planar surface on the tube ends. Analytically, the rate of increase of charge $q_B$ entering the interior tube volume V through surface S generates an increase in flux that in turn draws charge $q_A$ of opposite sign from ground by way of the ammeter giving rise to $-i_F(t)$, is expressed as,

$$\frac{dq_B(t)}{dt} = \frac{d}{dt} \oint \mathbf{D}(t) \cdot d\mathbf{s} \geq -\frac{dq_A(t)}{dt} = -i_F(t) \quad (2.2)$$
The inequality results because the flux passing through the tube ends are not captured by the tube walls. Consequently, the charge drawn to the surface of the tube wall is based on the fraction of the beam charge flux captured by the tube wall times the beam charge times minus one. Since the tube length is much larger than the tube diameter and the beam diameter, nearly all of the beam charge flux lines will terminate on the tube walls as the charge passes through the middle region of the tube. Since the Gaussian surface does not contain the surface of the cylinder but does contain the region near the surface, the charge passing to the surface of the cylinder by way of the ammeter does not enter the volume V enclosed by the Gaussian surface S. From the definition of current and the continuity equation, the rate of increase of charge contained in volume V enclosed by surface S is equal to the net current flow into the volume normal through S bounding the volume,

$$\frac{dq_B}{dt} = -\iiint_S \vec{J}_B \cdot d\vec{S} = -\iiint_V (\vec{\nabla} \cdot \vec{J}_B) dV = \iiint_V \frac{\partial \rho_B}{\partial t} dV$$  \hspace{1cm} (2.3)

Three different cases will be examined based on this theory.

**Case I. No loss to walls**

Assume that the beam charge enters and leaves the Faraday tube without colliding with the tube walls. Figure 2.11 anticipates the time history of the measured current relative to the position of a beam charge inducing the tube current. As the charge approaches the tube from the outside near position one, some of the beam charge flux lines terminate on the interior and exterior tube walls. The Coulomb attraction is weak due to far proximity of the charge from the tube; consequently a weak tube current (possibly in the noise) is expected. As the beam charge approaches position two and
enters the tube, the majority of the flux lines begin to terminate on the interior of the tube and the Coulomb attraction its peaked yielding a maximum or near maximum electron tube current flowing through the ammeter to ground or equivalently, an effective positive charge flowing from ground to the tube. Refer to Figure 2.10. As the beam charge approaches and passes through region three, the number of flux lines terminating on the tube wall does not change hence the charge drawn from ground and therefore the measurable tube current is zero. As the beam exits the tube (position four), the flux lines begin to "detach" from the tube walls and the beam charge attraction force weakens. Coulomb repulsion among the excess charges begins to dominate in the Faraday tube walls forcing the excess surface charge in the tube to seek ground through the ammeter. Figure 2.12 shows the magnitude of the electron charge (or the equivalent effective positive charge) passing through the tube versus time, where $\tau$ is roughly the transient time, which is the time required for a single charge to pass through the tube without being lost to the walls of the tube.

Case II. Complete loss to walls of the Faraday tube

Assume that a long, uniform, continuous, charged particle beam pulse exists and is completely collected by the wall of the tube. No portion of the beam exits the tube; refer to Figure 2.13. Position one shows that the current is gradually rising due to the Coulombic force of the approaching beam increasing in strength as measured on the tube wall. As the back end of the beam pulse approaches the tube, the overall Coulomb strength begins to decrease in the opposite manner as the forefront of the beam approached the tube. Position two shows that the turn off condition of the pulse is symmetric to the turn on condition. The time integrated tube current is illustrated in Fig.
2.13. The continuous collection of charge is apparent in the figure with a maximum charge equaling to the total beam charge reached at the end of the beam pulse duration.

*Case III. Partial loss*

Consider the case of partial loss of the beam to the tube wall, refer to Figure 2.14. Position one shows that the charges are filling the tube. Position two shows the steady partial loss of current to the tube wall combined with the remainder of the beam drifting out of the Faraday tube. Position three shows the tail end of that portion of the beam exiting the tube. Note that \( q_A(t>T_0) = q_{collect} \) (charge collected by the tube wall).

2.5 Simple Theory for Faraday Cup and Faraday Tube

To measure the current passing through the electrically isolated Faraday tube, a polyethylene coated copper wire was bared at the ends and attached one end to the un-insulated part of the Faraday tube and other end to a vacuum chamber feedthrough. Because acoustic vibration is evident in our system due to the cryogenic pumps in the system, Faraday coupled currents become significant at these induced current levels. To minimize this coupling, a second wire (insulated) was twisted around the original signal wire and grounded at both ends. The atmospheric side of the feedthrough was connected to a Keithley electrometer. The electrometer was connected to a Tektronix TDS 680D digital oscilloscope with an input impedance of 1 MΩ. The Faraday tube was isolated from the gun with a few turns of Teflon tape in the first design and a thick vespe coating in the second design. The tape was carefully wrapped around the outside of the tube. When positioned in the gun holder, the tape provided electrical isolation from the gun without being exposed to the beam. Other modifications have been made in the system.
experimental setup but this does not alter the theory behind the Faraday tube and cup. The setup of the Faraday cup and Faraday tube is shown in Figure 2.15, and the setup of the Faraday tube and Keithley electrometer is shown in Figure 2.16.

2.5.1 Faraday Cup

The Faraday cup is connected to an oscilloscope with an internal input impedance of R. Neglect the capacitive effects in the circuit observed in Fig. 2.15 and the losses due to the lines connecting the cup to the oscilloscope. For a beam current of positive charge, \( i_B(t) \), the scope voltage \( v_o(t) \) is

\[
v_0(t) = i_B(t)R
\]

(2.4)

Let \( T \) be the duration of a single pulse. The total positive charge \( q_{BT} \) collected by the cup due to the charged particle beam in one pulse duration is

\[
q_{BT} = \int_0^T i_B(t)\,dt = \int_0^T \frac{v_0(t)}{R}\,dt
\]

(2.5)

2.5.2 Faraday Tube

Gauss's electric law and the continuity equation can be used to determine the number of charges entering and leaving the beam drift tube based on the current response on the wire attached between the Faraday tube and the external circuitry. Assume that the beam charges are not lost to the tube wall. From Gauss's electric law with the neglect of end effects, the net change in the number of electrons entering the beam drift tube to that leaving equals the number of charges of opposite sign (induced charges) drawn to the surface of the beam drift tube. It is this current, \( i_F(t) \), that is to be measured. The Keithley electrometer can be modeled as an inverting amplifier. The orientation of the current \( i_F \) is chosen to be flowing toward the ammeter, and since the positive charge is drawn toward
the tube, hence $i_F$ is negative as shown in Figures 2.10, 2.13 and 2.16. To isolate the tube from the gun, Teflon tape was wrapped around the tube three times. The thickness of the Teflon tape is 0.076 mm, so the tube is separated from the gun by 228 microns. The capacitance between the ground and the modeled source is 4.95 pF, as shown in the following equation

$$C = \frac{2\pi \varepsilon_0 L}{\ln \frac{b}{a}}$$  \hspace{1cm} (2.6)

where 'a' = 1.5 mm is the outside radius of the Faraday tube, 'b' = 1.728 mm is the distance from the center of the tube to the outermost layer of the Teflon tape, $L = 6$ mm is the length of the insulated part of the tube that is inserted into the electron gun, and $\varepsilon_r = 2.1$ is the relative permittivity of the Teflon. For the tube that is isolated from the gun with Vespel, the capacitance decreases to 0.808 pF where 'a' = 1.5 mm is the outside radius of the tube, 'b' = 6.5 mm is the distance from the center of the tube to the gun, $L$ remains the same as in the previous case; $\varepsilon_r = 3.55$ is the relative permittivity of Vespel.

The capacitance between the electron gun and the Faraday tube is small enough that when associated with the low resistance (1Ω) of the Keithley electrometer, the short time constant will allow most of the bandwidth of the induced current to pass through the Kethley. Therefore, the capacitance is neglected in the AC analysis while blocking all DC signatures. Applying simple circuit concepts for the source voltage orientation shown (refer to Figure 2.17); the amplifier output voltage is related to the input voltage as

$$v_0(t) = -\frac{R_f}{R_i}v_i(t) = -Av_i(t)$$  \hspace{1cm} (2.7)
where $A > 0$ is the inverting amplifier gain. Since the input impedance of the amplifier is nearly infinite and the inverting and noninverting terminals are virtually shorted and hence connected to ground, the input voltage is directly related to the Faraday tube current as

$$v_i = i_F R_i \quad (2.8)$$

Consequently, the measurable amplified output voltage is related to the tube current by

$$i_F(t) = -\frac{v_0(t)}{AR_i} \quad (2.9)$$

Note that $i_0 \neq i_F$, $i_F$ is the rate of charge accumulation on the Faraday tube wall. When $i_F$ is negative as shown in Figure 2.16, the tube is accumulating positive induced charge in the walls of the tube and hence negative electron beam charge in the free space interior of the tube. This is the beam charge enclosed inside the tube as suggested by Gauss’s Law, Eq. 2.1 where surface $S$ enclosing the volume $V$ of the tube is bounded by, but excludes, the inside surface of the tube wall and the planar surface on the tube ends. End effects of the Faraday tube will be neglected such that as the beam charge enters the tube, all of its flux lines terminate on the walls of the tube. This is a reasonable approximation since the nearest metallic surfaces available to the charge's fields is the tube walls. From the continuity equation, the rate of change of electron beam charge accumulation inside of the Faraday tube is directly related to the electron current density as give by (Refer to Figure 2.18.)

$$\frac{\partial q_{Be}(t)}{\partial t} + \int_{Stop} J_{Be}(z = 0, t) ds - \int_{Sbottom} J_{Be}(z = -z_0, t) ds = 0 \quad (2.10)$$
As the accumulation of beam electrons inside the tube increases, electrons on the wall of the tube are repelled leaving the tube wall to be more positively charged. Consequently, there is a one-to-one correlation between the beam electrons and the positive charges on the tube wall such that \( q_{Be}(t) = -q_F(t) \) where \( q_{Be}(t) < 0 \). Therefore,

\[
\frac{\partial q_{Be}(t)}{\partial t} = -\frac{\partial q_F(t)}{\partial t}
\]  

(2.11)

where the minus sign implies opposite charged species. In Figure 2.18, the current leaving the Faraday tube to ground by way of an electrometer was arbitrarily chosen. Being consistent with the physics of the problem, namely that the electrons are repelled to ground through the ammeter as the rate of beam electrons accumulate in the Faraday tube, Eq. 2.11 may be written as

\[
\frac{\partial q_{Be}(t)}{\partial t} = i_F(t)
\]  

(2.12)

For clarity, the rate of increase in beam electrons is positive in the negative sense since \( q_{Be} < 0 \) which stipulates that the Faraday tube current \( i_F(t) \), with orientation defined in Fig. 2.16, is negative as the number of beam electrons increase in the Faraday tube. Consistent with Fig. 2.18, the definition of current in terms of current density, and Eq. (2.12), Eq. (2.10) may be recast in terms of the electron beam currents and the induced current effects due to charge accumulation as

\[
i_{Be}(z = 0, t) = i_{Be}(z = -z_o, t) - i_F(t)
\]  

(2.13)

For an electron beam energy \( \mathcal{E}_{Be} \) and a Faraday tube length \( L \), the time of flight \( \tau \) of a single electron through the beam tube is

23
\[ \tau = \frac{L}{v} = \frac{L}{\sqrt{\frac{2E_{Be}}{m_e}}} \]  

(2.14)

where \( m_e \) is the mass of an electron. Knowing the beam energy, assuming that the beam electrons are not lost to the wall of the Faraday tube, the electrons entering the tube at \( t \) exit the tube at \( t + \tau \). Therefore,

\[ i_{Be}(z = -z_0, t) = i_{Be}(z = 0, t - \tau) \]  

(2.15)

\[ i_{Be}(z = 0, t) = i_{Be}(z = -z_0, t) - i_F(t) = i_{Be}(z = 0, t - \tau) - i_F(t) \]  

(2.16)

Since the number of charge entering the tube equals the number of charge leaving the tube delayed in time, one can deduce the charge leaving the beam tube based on the induced current, \( i_F(t) \). Consequently, the charge leaving the Faraday tube, \( q_{Be}(z=-z_0, t) \) of length \( L \) distributed over time is

\[ q_{Be}(z = -z_0, t) = \int_t^{t+\tau} i_{Be}(z = -z_0, t) dt = \int_t^{t+\tau} i_{Be}(z = 0, t - \tau) dt = \int_0^t i_{Be}(z = 0, t) dt \]  

(2.17)

The total charge over an electron beam pulse of time duration \( T \) is

\[ q_{Be}(z = -z_0, \Delta t = T) = \int_t^{t+\tau} i_{Be}(z = -z_0, t) dt \]  

(2.18)

The average charge over time duration \( T \) is

\[ q_{Be,ave}(z = -z_0) = \frac{1}{T} \int_t^{t+\tau} q_{Be}(z = -z_0, t) dt \]  

(2.19)

Because \( i_F(t) \) is the only measurable, Eq. (2.16) needs to be solved by an iterative approach keeping track of its time history. If one can assume time to be small on the order of \( \tau \), calculus principles may be applied. From Eq. (2.16), one may write
\[
\lim_{\Delta t \to \tau} \frac{i_{Be}(z=0,t) - i_{Be}(z=0,t-\tau)}{\Delta t} = \frac{di_{Be}(z=0,t)}{dt} = -\lim_{\Delta t \to \tau} \frac{i_F(t)}{\Delta t} = -\frac{i_F(t)}{\tau} \tag{2.20}
\]

Consequently,
\[
i_{Be}(z=0,t) = -\int_{\tau}^{T+\tau} \frac{i_F(t)}{\tau} \, dt = -\frac{1}{\tau} \int_{0}^{\tau} v_{s}(t) \, dt \tag{2.21}
\]

where \(i_B(z=L,t) = i_B(z=0,t-\tau)\) and Eq. 2.22 provides the total charge over an electron beam pulse of time duration \(T\). Equation 2.21 is not meaningful for time resolutions less than the time of flight through the beam tube.

\[
|q_{Be}(z_0)| = \int_{0}^{\tau} i_{Be}(z_0,t) \, dt \tag{2.22}
\]

Now consider the contribution of electron beam charges lost to the wall of the Faraday tube. In this case, one must include the surface current density contribution passing normal to the cylindrical surface of the tube. As a result, the measured Faraday tube current is
\[
i_F(t) = \frac{\partial q_{Be}}{\partial t} - \int_{cylFT} J_{se}(r=R,t) \, ds \tag{2.23}
\]

where \(R\) is the radius of the Faraday tube. For clarity, the first term on the right hand side of Eq. 2.23 is negative as the number of electrons accumulate in the Faraday tube and the sign of the second term implies that the current generated by the electron beam (By definition, current is the direction of flow of positive charge or is in the negative direction of flow of negative charge.) is in the opposite direction of the current orientation as defined in Fig. 2.16. This means that \(i_F(t)\) accounts for the loss of charge to walls as well as the accumulation of charge in tube. Therefore, the measurable, \(i_F(t)\) yields a different
time history response as compared to the case when beam electrons are not lost to the wall of the Faraday tube. Thus, Eqs. 2.13 and 2.23 are general.

To obtain a ball park estimate of the measured voltage, \( v_0(t) \), consider the case when the electron beam charges are not lost to the Faraday tube wall. The beam drift tube is roughly 4 cm (~1.5") long. The time of flight for a 1 keV electron beam passing through the beam drift tube is \( \tau = 2.13 \) ns. Assume a step beam current temporal profile of \( i_{B_e}(z=0,t) = i_{B_0} u(t) \) where \( u(t) \) is the unit step function and \( i_{B_0} = 0.1 \) nA as shown in Figure 2.19. Based on Eqs 2.13, 2.16 and 2.20 (within the validity of \( \Delta t \rightarrow \tau \)), the induced current is a constant within the time period \( 0 < t < 2.13 \) ns and zero outside of this range. The typical input resistance and voltage gain are respectively 2 M\( \Omega \) and 200 (conservative numbers). Consequently with the aid of Eq. 2.9, the output voltage is a rectangular 2.13 ns pulse with an amplitude of +0.04 volts. Although not considered here (Note the gain at low frequency may be as high as 200,000 for a 741 op amp.), the amplifier bandwidth will play a significant role in the signal measurement. Based on these crude estimates, it appears that a measurable signal may be obtained from the Faraday tube sensor if the currents are not too low and other loading effects including noise prior to the amplifier stage are not too significant. The number of electrons that will be in the tube at any one time for this beam current profile for \( t > \tau \) is given by

\[
N_{FT} = \frac{i_{B_0} \tau}{e} = \frac{i_{B_0}}{e} \frac{L}{\sqrt{2\epsilon_{Be}}} = \left(\frac{2}{m_e}\right)
\]

For a 0.1 nA beam current and a transit time of 2.13 ns, the number of electrons inside the tube at any one time once a steady state condition is reached is about 1.3 electrons. If
these electrons are spaced evenly apart in a single line, then the mean time between target impacts, $\tau_c$, is

$$
\tau_c = \frac{\tau}{N_{FT}}
$$

or numerically, roughly $\tau_c = 1.6$ ns. This number is important when considering the particle detector's ability to detect, to resolve, and to record individual of charges.

### 2.6 Use Magnetic Field to Divert the Electron Beam

To monitor the primary beam current, a C shaped ferromagnetic core coil (refer to Figure 2.20) fitted to the beam drift tube was designed to divert the primary beam to the beam drift tube wall for measurement with minimal SEE loss from the tube. Assuming successive shots are similar, the total number of incident charge can be deduced based on a statistical averaging. Once the beam current (beam charge per pulse) has been recorded, the coil current is then changed to partially null the earth's magnetic field allowing the beam to pass through the tube to the target.

#### 2.6.1 Estimate the Magnetic Field and Magnetomotive Force Required to Divert the Primary Beam

Current passing through wire tightly wound around the poloidal cross section of magnetic material in the shape of a toroid with an air gap slit, generates a large magnetomotive force (mmf) across the air gap as suggested by both Ampere's circuital law and Gauss's magnetic law. For simple magnetic circuits, Ampere's and Gauss's laws may be recast in terms of a lumped magnetic circuit with electrical circuit analogies such as Kirchhoff's law

$$
\text{mmf} = \Phi R = NI
$$
where $\Phi$ is the magnetic flux representative of current $a$ through variable, $R$ is the reluctance analogous to the electrical resistance, and the magneto motive force (NI) is analogous to the voltage, an across variable. The reluctance is given by

$$R = \frac{l}{\mu S}$$  \hspace{1cm} (2.27)

where $l$ is the mean length along which the magnetic flux flows along and $S$ is the cross-sectional area of the magnetic core in which the magnetic flux passes normal through. The magnetic property of the core is given by $\mu$ the permeability. With $J$ representing the beam current density, the $J \times B$ force diverts the primary beam passing through the Faraday tube to collide with the tube wall. Assume the electron beam is initially located on the tube axis, then the distance between the electron's original position to the tube wall is the radius of the tube (refer to Figure 2.21). The centripetal acceleration of the beam electrons is

$$a = \frac{v^2}{R_t}$$  \hspace{1cm} (2.28)

where $R_t$ is the radius of the drift tube and $v$ is the velocity of the electron. The electron beam is to be directed to collide normal to the surface of the beam tube wall. The center of mass of the distribution of secondary electrons can be deflected into the tube wall.

Next we determine the strength of the external magnetic field necessary to redirect these electrons to the wall. Assuming the initial velocity of an electron is along the tube axis (Choose the tube axis to be along the $+y$ axis.) and the magnetic field the electron experiences is uniform and perpendicular to this axis (e.g., in the $+z$ direction), the magnetic force law relative to the guiding center of the electron is
\[ F_\varphi = -qvB = evB = ma = m \frac{v^2}{R_i} \quad (2.29) \]

Therefore, the magnetic field required to divert the beam to collide normal to the surface of the wall is

\[ B = \frac{\sqrt{2mE}}{eR_i} \quad (2.30) \]

where \( E = 0.5mv^2 \) is the energy of the electron. Figure 2.22 shows an iron toroidal core of high permeability and average length \( l_i \) with an air gap of length \( l_g \). The concentrated winding with a current flowing through it serves as the source of the mmf. Because of the high permeability of the core, the magnetic flux within the coil is confined to the core's interior. From boundary conditions, the normal part of the magnetic flux density penetrates into the air gap region implying \( \phi_i = \phi_g \). Assuming that the magnetic flux density is uniform throughout the cross section of the core and the core's cross sectional area is uniform, then \( \phi = BA \) throughout the core where \( A \) is the cross sectional area of the toroid. If fringing in the air gap is negligible, the flux in the gap is confined to the same cross section as in iron. Consequently \( A_i = A_g \) yielding \( B_i = B_g \) from Gauss's magnetic law. Because the flux seen by the core is equal to the flux seen by the gap, the loading effect of the core and gap are in series. Kirchhoff's law for the series magnetic circuit is

\[ \text{mmf} = \phi(R_{\text{core}} + R_{\text{gap}}) = \frac{B}{\mu_o} \left( \frac{l_i}{\mu_i} + l_g \right) \quad (2.31) \]

where the relative permeability of the ferromagnetic core \( \mu_r = \mu_i \) is figuratively characterized by the magnetic properties of the material provided by the hysteresis curve shown in Figure 23. That is, \( B_i = \mu_0 H_i \). The magnetic field required for a 1 keV of
electron beam energy to be diverted from its original trajectory on the tube axis and collide normal to the tube wall for a tube radius $R_t = 0.1$ mm is

$$B = \frac{\sqrt{2mE}}{eR_t} = 0.107 Tesla$$

(2.32)

From the hysteresis curve for cast iron (Figure 2.23), when the magnetic flux density ($B_i$) is $0.107 T$, the magnetic field intensity ($H_i$) inside the core is $200$ A/m. Therefore, for the geometry of the toroidal solenoid provided in Figure 2.24, the magnetomotive force required to generate this magnetic field given by

$$mmf = \phi(R_{core} + R_{gap}) = \left( H_i l_i + \frac{l_i B_i}{\mu_o} \right) = NI$$

(2.33)

is $453$ A. Here, $l_i$ and $l_i$ are respectively $152$ mm and $5$ mm. To capture the secondary electrons emitted from the tube, the radius of the toroidal cross section about the minor axis, $R_p$, was chosen to be $31$ times larger than the tube radius $R_t$. [Note, the major axis of rotation of the torus is a straight line. The direction of rotation about the major axis is called the toroidal direction; $\phi$ direction. The minor axis of rotation is a circle of radius $R_{Tor}$ with axis coincident with the major axis. Although it does not appear to be conventional, the radius of the minor axis is defined as the toroidal radius, $R_{Tor}$. (In Fig. 2.24, $R_{Tor} = 2.5$ cm.) In a particular toroidal half plane ($\phi$ equal constant plane), the axis of a circle of radius $R_p$ is coincident with the tangent to the minor axis. (In Fig. 2.24, $R_p = 0.3175$ cm.) The direction of rotation of the radius $R_p$ of this circle about the minor axis to form this circle is denoted as the poloidal direction; let this angular direction be denoted as $\psi$. The torus is formed by two rotational transforms; one in which a constant radius $R_p$ is rotated about the minor axis generating a circle in a $\phi$ equal to constant plane and the second in which the circle is rotated about the major axis along the minor axis.
The terminology "poloidal" is commonly used in plasma physics to help describe the toroidal geometry of a plasma. The toroidal solenoid dimensions given in Figure 2.24 were chosen based on space accessibility and mounting in the experimental setup as well as on the physics of the problem.

2.6.2 Construction of the Electromagnet

The outside diameter of the drift tube is 4 mm; hence the length of the gap of the magnetic coil should be at least 4 mm. Since the second term on the right hand side of Equation 2.31 is the dominate term and minimal mmf is desired, the gap of the coil was chosen to be 5 mm. Twenty-two gauge transformer wire was chosen in the design because of its higher current capacity (0.92 A) and its ductile property. Although the 22 gauge wire can handle 0.92 amps of current, it is safer to perform the experiments with half of the current rating, that is, 0.45 amps. Therefore, the number of turns of the coil is

\[
N = \frac{453A}{0.45A} = 1007 \text{ turns} \tag{2.34}
\]

The resistance of the coil was measured to be 2.3 Ω. Resistive heating of the coil needs to be considered since the coil is closely wound and resistive coating has a temperature threshold. The temperature characteristics of the coil was experimentally studied at a current level exceeding the capacity of the wire (1.57 A) over an 11 minute interval. The temperature rose linearly with time as shown in Table 2.8. With the aid of a graphic software package, (KaleidaGraph), the slope of the curve was determined. The slope characterizes the temperature rise per second and is equal to 0.0515 °F/s as shown in Figure 2.25.

The ability for the coil to reach the designed magnetic field was examined. An adjustable current limited DC voltage power supply was used to drive the coil. Noting
the electrical resistance of the coil assembly, the power supply was set to an appropriate voltage limited by a very low current. The current was slowly increased and the magnetic field was measured using a Hall-effect probe that was centrally located in between the poles of the toroidal solenoid. Recorded data may be found in Table 2.9 and Figure 2.26. At about 0.5 amp, a 1.07 kG magnetic field was generated. A good correlation between experiment and design exists.

2.6.3 The Challenge in Controlling the Toroidal Solenoid's Gap Field

Because the toroidal core has nonlinear magnetic properties with hysteresis, controlling the solenoid field within some degree of repeatability proved challenging. The magnetized coil should be able to divert the primary beam as well as decrease the field between the poles to levels not exceeding the magnitude of the earth's magnetic field when desired. The latter process will allow the beam to pass to the sample under test with minimal loss of electrons to the tube wall. Repeatability is necessary since there is no access for magnetic field probes to monitor the B field inside the vacuum chamber. A simple, dependable, two step process was developed with a minimal error range. Of the various techniques attempted, one technique offered a reasonable degree of repeatability. Only this technique will be presented.

2.6.3.1 Use of a DC Power Supply to Control the Pole Fields with Some Degree of Repeatability

A circuit schematic of the controlling system to adjust the solenoid field to the desired maximum field of about 1 kG and to a minimum field between plus and minus the earth's magnetic field is shown in Figure. 2.27. These open feedback resistor networks control the current supplied to the toroidal solenoid for a constant source voltage. The resistor
values were chosen based on experimental measurements of the magnetic field using a Gauss meter. In Figures 2.27 and 2.28, Network A drives the coil such that the 1 kG magnetic field is realized between the solenoid poles. As the double pole double throw switch is activated, Network B causes the operating point of the solenoid to shift in such a manner as to nearly nullify the field between the poles to $0 \pm 0.5 \, G$ where the 0.5 G field error is equivalent to the earth's magnetic field. Because of the hysteresis effects of the solenoid core, the toroidal solenoid proved sensitive to small changes in coil current relative to the minimum current resolution of the power supply (~0.1 A). Consequently, a sensitive tuning network is required. As a result, Network B had to be designed based on the following criterion: The source voltage $V_s$ and source current $I_s$ are fixed at one operating point as depicted by Network A. As the state of the double throw double pole switch is changed with the same source voltage preserved at the second operating point, the minimum pole fields are attained. To realize this effect taking into account the sensitive nature of the nonlinear properties of the core, Network B consisted of a variable resistor combination that has a narrow current swing for a large swing in resistance assuming the load resistance, $R_C$ (resistance of coil), is fixed. To prevent drift in the resistor values as a consequence of thermal loading, the resistors were chosen such that they operate well within their power rating. For simplicity all fixed resistors in the Network B were chosen with the same value, $R$, and, in one leg of the parallel combination, a variable resistor (potentiometer), $R_a$, is chosen to control the minimum field properties between the solenoid poles. All resistors chosen were to be commercially available, minimum power ratings were desirable (due to space constraints), and all resistors in Network B are to have the same power rating.
Small changes in current result in a significant change in the operating point of the toroidal solenoid. As a result, Network A (as shown in Fig. 2.27) was designed with a 50 \( \Omega \) resistor in parallel with a 3 k\( \Omega \) resistor. This network, in series with the 2.3 \( \Omega \) solenoid, is attached to the voltage source, \( V_s \). To gain the resolution required to achieve nearly repeatable pole fields, a multimeter with sub milli-Ampere resolution monitors the current of the 3 k\( \Omega \) resistor. A measured 0.738 mA current through the 3 k\( \Omega \) (measured value is 3050 \( \Omega \)) resistor results in a 46 mA source current based on calculation. The 46 mA is calculated so the current required to demagnetize the coil can be monitored. The plot of the experiments shows that in between 46 and 47 mA, the magnetic field in between the poles of the toroidal solenoid is zero plus or minus the magnitude of the Earth’s magnetic field. (Refer to Figure 2.29) Because the currents passing through these resistive elements were significant, the resistor used had a power rating of 1W and were air cooled with a fan.

To achieve the low field operating point, a parallel network (refer to Figures 2.28 and 2.30) was chosen to minimize the power dissipation rating and provide limited current range control for large change in the tuning resistance. Since the total current splits up among the individual branches, the power splits up as well. For a large change in resistance to yield a small change in current, the tuning resistor \( R_s \) lies in series with resistor \( R \) in one of the branches. The series combination allows for the current to be limited in \( R_s \) and allows for the source current to change value over a limited range. This very fine tuning in source current is needed to demagnetize the solenoids iron core and/or nullify the earth’s magnetic field between the poles of the coil. To determine the range of the source current and the power dissipation in each resistor, \( R_s \) may be solved as a
function of R. Denoting \( V_s / I_s = R_T \), where \( R_T = R_t + R_c \), and using Figure 2.30 \((R_t = R_2 = R_3 = R_4 = R)\), one can show

\[
\frac{V_s}{I_s} - R_c = R_T - R_c = \frac{R(R + R_a)}{4R + 3R_a} = R_t
\]  \( (2.35) \)

The range of \( R_a \) (variable potentiometer) is between 0 and infinity, yielding the range of \( R_t \) between \( R/4 \) and \( R/3 \). Note that \( R_T \) is fixed, but in practice, the tolerance in the resistance can cause enough change in current to limit the ability to minimize the pole fields. Also, only an approximate value of \( R_T \) is known. Therefore, \( R \) is determined based on the approximate value of \( R_T \) with \( R_a \) in some intermediate value. By tuning \( R_a \), the exact value of \( R_T \) may be achieved. From Figure 2.30, the power dissipated \( P_{dR} \) in each resistor (\( R \) or \( R_a \)) in the jth branch is

\[
P_{dR_1} = \frac{RR_t^2V_s^2}{(R + R_a)^2(R_t + R_c)^2}
\]  \( (2.36) \)

\[
P_{dR_a} = \frac{R_aR_t^2V_s^2}{(R + R_a)^2(R_t + R_c)^2}
\]  \( (2.37) \)

\[
P_{dR_2, dR_3, dR_4} = \frac{R_t^2V_s^2}{R(R_t + R_c)^2}
\]  \( (2.38) \)

Because the current will be largest in branches containing resistors \( R_2 \), \( R_3 \), and \( R_4 \), it is reasonable to constrain the dissipated powers in these branches and calculate \( R \). Let \( P_{dR_2} = P_0 \), then

\[
P_{dR_2} = \frac{R_t^2V_s^2}{R(R_t + R_c)^2} = \frac{R_t^2I_s^2}{R} = P_o
\]  \( (2.39) \)

35

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Because $V_s$, $I_s$, and $R_c$ are fixed, $R_t$ as given by Eq. 2.35 is therefore a constant. Consequently, from Eq. 2.39,

$$R = \frac{R_t^2 I_s^2}{P_o} = \left[ \frac{V_s}{I_s} - R_c \right]^2 \frac{I_s^2}{P_o}$$

(2.40)

From Eqs. 2.35 and 2.40

$$R_d = \frac{4RR_t - R^2}{R - 3R_t} = \frac{4\left[ \frac{V_s}{I_s} - R_c \right]^2 I_s^2 P_o - \left[ \frac{V_s}{I_s} - R_c \right]^3 I_s^4}{\left[ \frac{V_s}{I_s} - R_c \right]^2 I_s^2 P_o - 3P_o^2}$$

(2.41)

A source voltage operating point of $V_s$ is 31.6 V is required to energize the solenoid to achieve the desired maximum pole field when Network A is driving the solenoid. From various tests starting from this operating point, it was determined that a source current of 44 mA through the toroidal solenoid with a resistance of $R_c = 2.3\Omega$ was needed to minimize the fields between the solenoid poles. Therefore, $R_t$ is 718.18 \(\Omega\) and $R_t$ is 715.88 \(\Omega\). Assume $R_a = R$, then from Eq. 2.41, $R$ is equal to 2506 \(\Omega\). Consequently, $R$ is chosen to be 2500 \(\Omega\). To explore the power dissipation of the resistor elements and the source current control, $R_a$ is varied between 0 and 100 k\(\Omega\). From Table 2.10, the source current varies from 38.122 mA to 50.375 mA, the power dissipated in resistor one varies from 0.236 mW to 0.396 W. The power dissipated in resistors two through four vary from 0.3965 W to 0.3972 W and in resistor $R_a$ varies from 0 to 9.45 mW.

With the resistor network in place, a means to test the overall system in time sequence is established. To initialize the toroidal solenoid, the power supply is set at the operating voltage with the current limiting dial in a position to prevent current flow from the source. Network A is switched into the circuit. The current limiting dial is then slowly turned
increasing the current from zero until it will no longer increase. The B field is recorded.
The second step is to place the double pole switch in an intermediate position such that
the power supply is disconnected from the coil (this is the same as turning the power
supply off). The residual B field is recorded. The final step is to switch Network B into
the circuit with the voltage of the power supply at its original operating point. The
potentiometer is adjusted to reduce B field to less than the Earth's magnetic field, if
necessary. Then, the power supply is turn off and the residual B field is recorded. After
numerous tests taken in the same sequence, the value of \( R_a \) was found to minimize the
field between the poles within ±0.5 Gauss from 0. Figure 2.31 shows that 97% of the
demagnetized fields are within the Earth's magnetic field (0.5 Gauss).

2.6.4 Mounting and Testing in Vacuum

Due to space restrictions inside the vacuum chamber about the drift tube, the toroidal
solenoid is attached to the electron gun tube using 14 gauge wire and a couple of hose
clamps as shown in Figure 2.20. The solenoid is mounted at diagonally as shown in the
figure. Because of symmetry for an ideal system, this orientation has no effect on the
fields the beam electron experiences.

The electromagnet is mounted on the electron gun with the gap fitted to the Faraday
tube. The primary beam is diverted and collides with the tube wall when the
electromagnet is energized. The primary beam current collected from the tube is in
between 14 to 15 nA as shown in Figure 2.32. When the electromagnet is demagnetized,
the primary beam passes through the tube and is captured by the Faraday cup. Figure 2.33
shows the primary beam current collected from the Faraday cup is between 13.5 to 14.5
nA. Figures 2.32 and 2.33 show the primary beam current collected from Faraday cup and Faraday tube have similar results.

Although a high level of success was achieved using this type of detector method, either the fringing field of the electromagnetic or an external DC magnetic field used to help adjust the gun parameters without changing focusing electrode voltages seemed to have saturated the mu material encasing the gun. It is hypothesized that either this saturation effect or possibly end effects (such as mu material terminating in a non-mu flange material) resulted in strong enough magnetic field penetration into the gun cavity to magnetize the gun electrodes beyond repair. Further, small magnetic flux resulting from fringing effects even when the solenoid coil is unenergized can have undesired effects on the electron beam trajectory that may not be controlled a priori due to the nonlinearity of the solenoid core. As a result, an alternative means of detecting the beam current was developed.

2.7 Modification of the Faraday Tube

Although the technique of using the electromagnet to divert the primary beam current shows agreeable results, the magnetic field has caused problems in the electron gun. In order to monitor the primary beam current without using a Faraday cup or an external diverting magnetic field, the Faraday tube was modified by the Staib Instrument Inc. as shown in Figure 2.34. The modified tube has a metal surface that is pressed on the top of the tube and the exterior of the tube end is covered with Vespel insulation that electrically isolates the tube from the electron gun and mechanically supports the tube in the gun's exit aperture. The primary beam is swept across the metal surface of the tube by adjusting
the scanning plates of the electron gun. The current measured from the tube is NOT the true primary beam current from the electron gun. Backscattered and secondary electrons may be emitted by the metal plate. Consequently, this detector is calibrated with Faraday cup measurements and Faraday (now just an ordinary beam drift tube) tube losses. In effect, the beam current measured by the cup assuming no cup losses is the current of interest that will actually reach the sample. Assuming that the tube detector will not be degraded by electron dose, this calibration procedure should be adequate for indirectly determining the primary beam current. Figure 2.35 shows the difference between the primary beam currents measured from the tube and cup.

When the detector is activated in the absence of an electron beam, a significant fluctuating beam drift tube (Faraday tube) current exists. The current appears to be constantly charging and discharging the Faraday tube yielding a noise level that exceeds the signal being detected. One possible cause of this fluctuation is dielectric breakdown. The Vespel dielectric insulating the beam drift tube (Faraday tube) from the high voltage anode detector has a dielectric strength of 560 V/mil (equivalent to 22 MV/m). Neglecting edge effects, the electric field anywhere in the Vespel medium between the tube and anode electrodes is

\[ E_r = \frac{V}{r \ln(b/a)} \quad \text{(V/m)} \quad (2.42) \]

where \( V = 3000 \text{V} \) is the voltage applied to detector, \( r = a = 3 \text{ mm} \) is the outside radius of the beam drift tube (Faraday tube) wall, and \( b = 4 \text{ mm} \) is the inside radius of the anode conductor. Hence, the maximum electric field is 3.48 MV/m, which is about 84% smaller than the dielectric strength of Vespel. If edge effects are considered, it is anticipated that the dielectric breakdown might be the source of the "noise" current.
Although possible, the fluctuating nature of the discharge with no measurable current draw from the voltage source tends to indicate that breakdown might not be the mechanism for the current detected especially since the voltage source can potentially supply steady currents orders of magnitude larger than the currents measured on the tube.

Because the measured Faraday tube dark current (electron beam off) is not constant, it cannot be subtracted from the signal current to yield the induced and direct electron beam currents resulting from the electron beam source. Up to this point, Vespel has been treated as a perfect dielectric. Although the dielectric is a very good insulator, it does have a finite resistivity allowing for a leakage current to be present. The resistivity of Vespel is about \( \rho = 1 \times 10^{14} \ \Omega\cdot\text{cm} \). It is well known that the resistance for a coaxial resistor is given by

\[
R = \frac{\ln(b/a)}{2\pi \sigma L} = \frac{\rho \ln(b/a)}{2\pi L} \tag{2.43}
\]

where \( L \) is the length of the resistor, \( \sigma \) and \( \rho \) are respectively the conductivity and resistivity of the dielectric, and 'a' and 'b' are respectively the outside radius of the Faraday tube (beam drift tube) and the inside radius of the outer anode electrode. For \( a = 3 \ \text{mm} \), \( b = 4 \ \text{mm} \), \( L = 17 \ \text{mm} \), the resistance of the coaxial resistor is about \( R = 2.69 \ \Omega \). Figure 2.36 displays a special test electrode simulating the anode of the detector connected in series to a 10 M\( \Omega \) resistor. At ambient temperature and pressure, various voltages between 100 and 1750 V were applied between the Faraday tube with insulator inserted in the anode and the connecting 10 M\( \Omega \) resistor. The voltage across the 10 M\( \Omega \) resistor is measured. Results listed in Table 2.11 and pictured in Figure 2.37 indicate based on a voltage divider that the Vespel resistance is on the order of 1 T\( \Omega \). Further, the
voltage tends to fluctuate more as the source voltage is increased. This is also observed in the vacuum experiments with the Faraday tube inserted in the anode. In a vacuum environment experiment, when the anode is roughly 1 kV a fluctuating Faraday tube current of about 1 nA is measured. Similar currents are measured at this value in the atmospheric tests using the modeled anode with attached resistor. As a result, it appears that the Vespel leakage current is a significant source of "noise" that needs to be minimized if the Faraday tube is to achieve the goal of measuring the characteristics of the electron beam.

To minimize the detection of this leakage current, a metallic shield is to be used to divert this current to ground. This new design is coined as a shielded Faraday tube. From the inside out, the shielded Faraday tube is to consist of a metal tube with wire lead for connecting to an external measuring device. The tube with wire is to be fitted into a thin wall dielectric insulator tube that has a metal film on the outside. The metal film will be attached to a wire lead connected to ground. This assembly is then inserted into the thick wall Vespel jacket to provide high voltage electrical insulation from the anode as shown in Figure 2.38.

2.8 Particle Position Detector Studies

2.8.1 Introduction

Secondary electron emission studies require accountability of primary and secondary electrons generated from the time the primary electron leaves the electron gun to impact the target material, through the time interval of the collision cascade internal to the target, the detector, or other external bodies. The detector assembly used for secondary electron
emission measurements consists of a microchannel plate (Figures. 2.39 and 2.40) to
enhance the electron signal backed with a hexagonal delay-line anode (Hexanode, HEX
40/o) to capture and transport the signals to be processed. The hexanode shown in Figure
2.41 is the detector consisting of three sets of delay line wire arrays each located at a
different level crossing the detection space of interest forming a hexagonal pattern. The
detector records spatial locations of the electron signal. The MCP consists of an array of
glass tubes that will generate many secondary electrons when struck by an incident
charged particle (e.g., electron, ion) or photon (e.g., x-ray) as shown in Figure 2.39. The
electron cloud emerging from the MCP impinges on the tri-level delay line arrays
generating signals that propagate in opposite directions along each set of arrays. Timing
studies of these signals determines the spatial location of the incident electron (electron
cloud) sometimes referred to as a hit. For processing the signals, the DLATR8 front-end
electronics containing signal de-coupling circuits, amplifiers and discriminators and
TDC8-PCI a standalone PC-based TDC (Time-to-Digital Converter) module were used.
The entire detector system is manufactured by RoentDek Handels GmbH.

2.8.2 Principle of Operation

When the primary electrons hit the target, secondary electrons are generated. Based
on collision kinematics at the target, a portion of the total number of secondary electrons
generated is directed towards the detector. A controlling grid is used to control the
electric field profile in the region between the sample under test and the grid which is just
below the detector. The detector is composed of a microchannel plate (MCP) for signal
amplification and a transmission line grid for detection and positioning of the collected
signal event. A fraction of the electrons traveling towards detector will be collected by the grid; the remaining will strike the MCP.

The MCP enhancers are frequently used in the radiation of beam imaging and atomic collision processes. The most common configuration is to use two MCPs that are v-stacked in the chevron shape. This configuration not only will produce the optimal gain ($10^8$), but also reduce ion feedback [20]. Figure 2.40 shows the mechanism of secondary electron production of a single channel of the MCP. The initial electron strikes the MCP channel wall and frees several electrons. These electrons will be accelerated along the channel until they strike the channel wall, which in turn produce more electrons. Eventually this cascade process yields a cloud of electrons which emerge from the rear of the plate. This electron cloud collides with a three tier transmission line wire grid on the detector's anode and generates a set of signals to be recorded and processes. Since the position of individual electrons are to be recorded, the MCP is to generate an electron cloud representing the incident electron such that the signal created on the delay lines are well above the noise level, so to be detected.

The delay line (transmission line grid) anode is a hexagon shape detector which consists of three sets of two bare wires wrapped side-by-side but not touching around the supporting anode plate insulated with ceramic rods as shown in Figure 2.41. Each set composes a detection layer oriented at a different 60° angle relative to the remaining layers. There are 6 terminals at the corners of the detector, the signals in each corner are combined as a twisted pair and attached to an electrical feedthrough. The two wires in each layer are transmission lines, one for signal detection and one for reference.
An eight channel time to digital converter computer board (TDC8) converts time analog signal to a digital signal. Once a channel is activated, this board records a relative time stamp. The TDC8 has a 500 ps per channel resolution and the maximum count rate is about 30K events per second. An event is defined as the data set that is transferred from the TDC8 to the computer after each trigger. Each event may contain up to a maximum of 16 hits.

2.8.3 Performance Characteristics

2.8.3.1 Time Acquisition

The TDC8PCI2 is based on the LeCroy MTD133B chips. It has a 16 bit counter implying 65,536 time increments. The internal chip frequency is 250 MHz (chip clock period of $T_{cc} = 4$ ns) with eight delay stages. Therefore, the time resolution of the chip is $T_c = T_{cc}/8 = 500$ ps. An event occurs when the 16 bit counter reaches its maximum count. At this time, all of the registers in the chip are transferred to the computer. Therefore, the duration of a single event is $T_c * 65500 = 32.8 \mu s$. Each of the 8 channels has 16 registers for relative time stamp storage. When a particular channel is activated, a relative time stamp is recorded in a register associated with the channel. Each time the channel is activated, the information stored in the registers is placed in the next register in a stack and the first register receives the new information. As the stack fills up, information will be lost in a sequential time order. Consequently, only 16 bytes of information, 16 relative time stamps, in a 32 $\mu$s window when the TDC8PCI2 is active are transferred to the computer for final processing. Software programming can decrease the number of counts accepted during each 32 $\mu$s window. For illustration purposes below, it is assumed that the full 16 byte signal per channel will be processed.
2.8.3.2 Position Acquisition

The location of the detected electron depends on a coordinated time of flight analysis of the signals activated on the three tier delay line grid. The electron cloud generated by the MCP strikes the delay line grid generating two electromagnetic pulses which travel in opposite direction along the transmission line. When a signal reaches one end of the delay line, the signal is conditioned and activates one channel in the TDC8 resulting in a relative recorded time stamp being stored in a register associated with the channel. As the second signal reaches the remaining end of the delay line, again a signal conditioning process results and then a different TDC8 channel is activated resulting in a relative time stamp being stored in a register associated with that channel. There are three sets of wires in a hexagon pattern covering the detection area. By recording the relative time of arrival and knowing the wire length and that the signal propagates nearly at the speed of light, one can determine the position of the electron over in the detection plane. The detector has a third delay-line layer. The first benefit of having three sets of wire is to filter out the signal that is not generated by the electrons but by the noise signal that is large enough to trigger the sensor at the end of each wire. For each sets of wires, the position of the event will be recorded in the XY coordinate system. If the XY locations are not the same for at least two sets of wires then the signal will not be counted as a hit. The second benefit is that the third wire can help increase the multi-hit resolution by resolving the ambiguity for simultaneous hits in different locations. Position and time can be reconstructed from the signals on the three layers as long as the particles do not arrive at nearly the same position and same time [21]. The third benefit is that it served as a redundant source of
information for the case where signals are lost due to non-contiguous winding schemes, such as anode with central holes.

2.8.3.3 Temporal Resolution

Temporal resolution of the detector is the time duration between clock counts. For the TDC8PC12, the clock interval is 500ps. That is, if two electrons hit the detector within 500ps, they cannot be distinguished. This is called the pulse-pair resolution. Every time a cloud of electrons collide with the detector's delay line and generate a hit, counter propagating 20 ns signals are generated on each of the three delays. Once the signal is detected by the electronics, an 80ns processing dead time results on that channel. If another hit reaches the delay end of a channel during this 80 ns dead time, it is not recorded. This is called the multi-hit dead time.

An event dead time also exists. This results at the end of a 32 μs duration as a result of the 16 bit counter when information in all of the registers are transferred to the computer. The dead time of the LeCroy chip depends on the amount of data which has to be transferred, it can be expressed as

\[
\text{Dead Time} = 1.8 \, \mu s + (\text{No.\# channels}) \times (\text{No.\# signals/channel}) \times (100 \, \text{ns/signal}) \quad (2.44a)
\]
or

\[
\text{Max. Dead Time} = 1.8 \, \mu s + (6 \, \text{channels}) \times (16 \, \text{signals/channel}) \times (100 \, \text{ns/signal}) \quad (2.44b)
\]

All incoming signals are lost during this time. The maximum dead time interval is 11.4 μs. Based on a private communication, Hexanode with hole (HEX 40/o) works best if the time intervals between hits is at least 80 ns [22].
2.8.3.4 Spatial Resolution

Spatial resolution is how close the two electrons can hit the detector and still be distinguished. The detector has a single particle resolution of 250μm, which means as long as two particles are at least 250μm apart; the detector will be able to distinguish them as individual hits.

2.8.3.5 Data Acquisition

The readout of the MCP and delay-line anode signals requires amplifying and timing (discrimination) circuits. The constant-fraction discrimination (CFD) is incorporated in the DLA-TR8 circuit to produce digital signals for a time measuring device such as time to digital converter (TDC). The 25 ns dead time is caused by the CFD, so if 2 signals are closer than 25 ns then only one digital output signal will be recorded as shown in Figure 2.42. Because each register may record only sixteen relative time stamps, the first time stamp that is entered into the register is the first time stamp that is removed from the register when more than sixteen hits occurs within an event. Refer to Figure 2.43, during the first event, channels 1 through 3 experience 17 hits and channel 4 experiences only 16 hits. The 11.4 μs is calculated from the dead time of the LeCroy chip [23]. [Refer to Eq. (2.41.2b)] This scenario may result based on, for example, hits that take 80 ns to progress to the opposite end of the anode delay line at about the time the LeCroy chip reaches its maximum count. Table 2.12 shows how the data is transferred to the computer. Notice the ordering of the data. Because of the LILO sequence, the timestamp of hit No. 1 in channel 4 is associated to hit no. 2 in channels 1-3. It would seem that the entire block of data for event one is now in error. This wrong ordering can be resolved in some cases by using the time sums. The time sum of two signals is about 110 ns [24].
Further, during the 11.4 µs event dead time, data is lost. Depending where hits occur on
the anode during the 80 ns time duration, the second event could be in error as well. This
assumes that hits occur over the full area of the detector. Figure 2.44 is similar to Fig.
2.43 but now the event delay time occurs after the first 17 hits are felt by all channels.
Table 2.13 shows how the data is transferred to the computer.

2.8.4 The Loss of Electrons Due to the Grid and MCP

Secondary electrons emitted from the sample have to pass the grid and MCP before
they can reach the detector. Some of the electrons will be blocked by either the grid or the
MCP and hence not be detected by the particle position detector. To find the secondary
electron emission, one has to find the percentage loss of the electrons due to the grid and
to the MCP.

2.8.4.1 Electrons Loss Due to Mesh Grid

The grid is located in front of the MCP and it is used to create a field free region or a
controlled field region between the grid and the testing sample. To determine absolute
dimensions from relative measurements, the active length of the detector is related to the
graphical scales of the image plot. Consequently, when the image is magnified, an
absolute measurement may be made. The active diameter of the detector is 45 mm. The
graphical image scale contains 8 plot units along this length. Therefore, each plot unit is
5.625 mm. The image of the electrons being detected by the detector is shown in Figure
2.45(a). The white spaces between the electrons are the effective shadow of the grid
wires. The effective wires are depicted as the red lines as shown in Figure 2.45(b). The
width of the white space shadow is about 0.102 unit, so the effective wire diameter (D_{effw})
is 0.574 (0.102 unit × 5.625 mm/unit) mm. The measured wire diameter (D_w) is 0.36 mm

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at 1 strand per millimeter. Refer to Figure 2.46, L (= 1 mm) is the center to center distance between two wires. Let $A_G$ represents the area of grid, then $A_G = L^2$. $A_H$ is the area not block by the grid, so $A_H = (L-D_w)^2$. $A_{GB} = A_G - A_H$ is the area block by the grid wire. The percentage of the grid loss can be expressed as

$$\% \text{Loss} = \frac{A_{GB}}{A_G} \times 100\% = \left[ 1 - \frac{(L - D_w)^2}{L^2} \right] \times 100\% \quad (2.45a)$$

Based experimental measurements as suggested in Figures 2.45a and b, the wire diameter in Eq. 2.45a is replaced by the effective wire diameter, $D_{effw}$, yielding

$$\% \text{Loss} = \frac{A_{GBeff}}{A_G} \times 100\% = \left[ 1 - \frac{(L - D_{effw})^2}{L^2} \right] \times 100\% \quad (2.45b)$$

The percentage grid loss is 82%. In using the effective wire diameter, the effective grid loss is only valid for experimental setups with the same or nearly the same initial parameters. Therefore, this grid loss is valid with the grid potential is 100 V and the distance between the grid and target is 2.54 cm. It should also be dependent on the scattered electron emission energies. Since these energies can range over a broad spectrum of energies from near zero to the primary beam energy, the percent grid loss is associated to the average energy of the SEE and to the primary beam energy. Some dependence on the initial trajectory is anticipated but due to the partial random nature of the emission it is not assumed important at this time.

### 2.8.4.2 Electrons Loss Due to MCP

MCP consists of an array of glass tubes; each tube has a diameter of 25μm. The center to center distance between two glass tubes is 32μm. The MCP can be divided to
many squares and each of them contains a tube as shown in Figure 2.47. So the percentage loss can be shown as

\[
\text{%Loss = } \left[ 1 - \frac{\text{Area of Tube}}{\text{Area of Square}} \right] \times 100\% \tag{2.46}
\]

where Area of Tube represent the cross sectional area of the glass tube with radius of 12.5 \(\mu m\), and Area of Square is the area of the square that contains one glass tube, and the sides of the square are 32 \(\mu m\). Using Eq. 2.46, the percentage loss due to MCP is 52%.

2.8.5 The Issue of High Grid Current while the Detector is On

The current measured from mesh grid is significantly higher (in between nano-Amp to micro-Amp range) in the negative sense when the detector is on. That is, the grid is capturing electrons and directing them to ground through the ammeter. [The positive or input terminal of the ammeter is connected to the grid and the negative or output terminal is connected to ground.] To deal with this issue, the metal screws, bolts and washer that connect the grid to the ceramic ring of the MCPs are replaced with high vacuum compatible ceramic screws, bolts and washers. The purpose of using the ceramic hardwares is to prevent the electrical conduction between the MCPs and the grid. But the replacement of the hardware did not resolve the high current issue, so the resistance of the ceramic is examined.

Table 2.14 shows the voltage applied to the ceramic test setup (refer to Figure 2.48) and the current measured from the electrometer. From this test, it is observed that the resistance of the ceramic is in the Tera-Ohm range. Therefore, the current measured from the grid is not from the leakage current generated from the ceramic hardware. At this time, it is suspected that the source of this grid current may be a result of intense fields near the ends of the cut wires drawing charge from the MCP possible due to a breakdown effect.
2.8.6 The Effort to Interpret the List Mode File Data

A large portion of the secondary electrons that are emitted from the sample will be blocked by the grid and MCP. The remaining electrons that enter the multi channel plates will in turn generate the electron clouds that will be detected by the delay line anode. These signals detected by the delay line anode will be processed by the TDC8PC12. A MatLab code was written to determine every possible configuration for the distribution of counts to fit into the acceptance input and dead time windows based on the dead time calculation shown in Eq. 2.44. The data processed by TDC8PC12 is stored in a List Mode File (Imf) and then convert to a text file in order to be read by the MatLab code. From the counts in each 32 μs time frame, one can statistically estimating the number of counts missed in the dead time region. This provides a means to determine the number of hits seen by the three layer delay line anode. Figure 2.49 shows how the MatLab code can fit the data into the 32 μs time block. By translating the initial time of the acceptance window backwards in time from the acceptance of the first time stamp data point just below the resolution of the electronics (time increments of 1 ns used), one should expect to find at least one case in which all of the data will lie in the data acceptance windows that the electronics accepts data and no data in the computed dead time windows. One of these combinations should have fit the Imf file when the beam is on. But, upon testing the Imf data, this did not turn out to be the case.

After consulting with Dr. Czasch at the RoentDek, he indicated that the Imf data file is not very accurate. Although Microsoft Windows will read in the data at a rate of 12 bytes per microsecond, the computer's CPU is task managing a number of tasks and does not continuously monitor the data streaming into the system from the TDC8PCI2 card.
Once the CPU is ready to process data according to the software code, it reads the saved data from a buffer file at a fast rate assigning computer time stamps as the data is processed. This second time stamp is not the one provided by the TDC8PCI2 but by the acquisition software (CoboldPC). Consequently, the new assigned time stamps are neither accurate nor meaningful. The dead time of the system also depends on the speed of the computer. If the computer is not fast enough then it can not read all the data from the TDC card as fast as the data comes in. If Windows can accept 12 bytes every microsecond, then in 32 μs it will only be able to read 384 bytes of data. Hence, this transforms to 384 bytes divided by 6 channels yielding 64 relative time stamps. In early experiments, the data acquisition code (ecf file) was configured to record only one signal per event. So the actual number of signals in each 32 μs time frame was one. Since it is not possible to examine the data on a microsecond level, then at best on a macroscopic level it will be determined if the detector is saturated at one hit per 32 μs over the pulse duration of the electron beam. Specific on/off patterns in the data is sought to represent the on and off time of the beam since the beam pulse duration and repetition rate are know.
Figure 2.1 Front panel of the electron source power supply [19]

Figure 2.2 Schematic of optical system [19]
Figure 2.3 Optical alignment systems [19]
Figure 2.4 Beam current versus the X-axis of the manipulator
Figure 2.5 Tube current vs X1 deflection plate while X2, Y1 and Y2 are at the default dial settings of 5.0
Figure 2.6 Tube current vs Y1 deflection plate, X1 dial is at 5.6 and X2, Y2 are at 5.0
Figure 2.7 Tube current vs X2 deflection plate, X1 is at 5.6, Y1 is at 5.56 and Y2 is at 5.0 dial settings.
Figure 2.8 Tube current vs Y2 deflection plate, X1 is at 5.56, Y1 is at 5.6 and X2 is at 5.0 dial settings.
Figure 2.9 The experimental setup [25]
Figure 2.10. The Faraday tube and the Gaussian surface. Note, the orientation of the Faraday tube current $i_F$ is defined in the circuit. If negative charge moves in the direction of the defined current or if an equivalent effective positive charge moves in the opposite direction of the defined current, the defined current $i_F$ is a negative value.
Figure 2.11 The position of the charge passes through the tube in terms of the current versus time. The numbers correspond to the positions of the beam electron as it passes through the Faraday tube.

Figure 2.12 Magnitude of the negative charge passes through the tube versus time
Figure 2.13 The position of charge in terms of current and charge versus time.

Figure 2.14 The beam is partially loss to the tube wall.
Figure 2.15 The setup of Faraday cup and Faraday tube

Figure 2.16 The setup of Faraday tube and the Keithley electrometer

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Figure 2.17 Schematic of the amplifier in the Keithley Electrometer.

Figure 2.18 The relation of $i_B$ and $i_F$.
Figure 2.19 The temporal profile of the beam current ($i_{Be}$), the induced current ($i_F$) and the measured voltage ($V_0$).
Figure 2.20 C shaped ferromagnetic core coil.

Figure 2.21 Primary electron beam is diverted by the magnetic field to collide with the drift tube wall in a circular motion.
Figure 2.22 The magnetic circuit and its electrical equivalent of an electromagnet

Figure 2.23 The hysteresis curve of cast iron.
Figure 2.24 The dimension of the electromagnet

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Figure 2.25 The red curve shows the temperature of the coil rise with the increasing of time, and the blue line is the curve fit of the red curve in order to find the slope.
Figure 2.26 Current versus the magnetic field at fixed voltage
Figure 2.27 Network A (left) energize the coil to achieve 1 kG magnetic field between the solenoid poles. Network B (right) demagnetize the coil such that the field between the poles is within the earth’s magnetic field (0.5 G).

Figure 2.28 In order to fine tune the power supply to get the current desired (46 mA), a parallel resistor network (as shown in Figure 2.27) is added. Network A (left) energize the coil to achieve 1 kG magnetic field between the solenoid poles. Network B (right) demagnetize the coil such that the field between the poles is within the earth’s magnetic field (0.5 G).
Figure 2.29 The magnetic field between the poles of the toroidal solenoid is in the plus and minus range of the Earth's magnetic field when the current passes through the coil is at the 46 to 47 mA range.
Figure 2.30 The parallel resistor network
Figure 2.31 Numerous tests were performed while using the resistor network to demagnetize the electromagnet. 97% of the tests show that the demagnetized electromagnet has less than Earth's magnetic field. The abscissa and ordinate represent the electromagnet's residual magnetic field and counts of tests respectively.
Figure 2.32 Primary beam current collected from the Faraday tube when the electromagnet is magnetized. The abscissa and ordinate represent the tube current and counts of tests respectively.
Figure 2.33 Primary beam current collected from the Faraday cup when the electromagnet is demagnetized. The abscissa and ordinate represent the Faraday cup current and counts of tests respectively.
Figure 2.34 Top view (right) and side view (left) of the Faraday tube.

Figure 2.35 Primary beam currents measured from the Faraday tube (green line) and from the Faraday cup (red line).
Figure 2.36 The drift tube is in series with a 10 MΩ resistor, the voltage applied to the system and the voltage across the 10 MΩ resistor is measured.

Figure 2.37 The resistance of Vespel varies with the applied source voltage.
Figure 2.38 Redesign the tube by adding a shield around it.

Figure 2.39 Schematic of the micro-channel plate (MCP) [26]
Figure 2.40 Schematic of production of secondary electrons in a single channel [26]

Figure 2.41 Top view of the hexanode delay line detector [27]
Figure 2.42 Single event. Two hits occurring at the same point in space within the 25 ns dead time duration of the first hit.

Figure 2.43 Multiple events. Consequences of hits recorded when the chip goes in processing mode (dead time).
Figure 2.44 Timing diagram for multiple events.

Figure 2.45 (a) The image of the electrons being detected; (b) the white spaces between the electrons are the wires (red lines) from the grid that block the electrons.
Figure 2.46 The diameter of the measured wire and the effective wire of the grid at 1 strand/mm.

Figure 2.47 Divide the surface of MCP to numerous square, each square contains a glass tube. The radius of the tube and the side of the square are shown.
Figure 2.48 The setup of the ceramic hardware (a) and the measurement is taken while the setup is shielded (b).
Figure 2.49 Letter "D" represents the dead time between each 32 μs time block. Note that the width of D changes according to the number of counts in the previous 32 μs time block. The graph on the top has a data fall in the dead time (red dot); the Matlab code is able to change the starting point in order to include the red dot inside the 32 μs time block. But if there is another data that fall in the dead time (green dot) and the code cannot move the block any more, then the code stops. The code has tested to be able to move forward and backward in order to fit all the data.
Table 2.1 Primary beam current versus the beam energy measured by the factory and the EM lab

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Filament (A)</th>
<th>Grid/div</th>
<th>Emission (µA)</th>
<th>Beam Current (nA)</th>
<th>X1/div</th>
<th>Y1/div</th>
<th>X2/div</th>
<th>Y2/div</th>
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<td>Factory</td>
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<td>0.01 (pA)</td>
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Table 2.2 Primary beam current with the drift tube attached versus the beam energy measured by the factory and EM lab

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<th>Energy (keV)</th>
<th>Filament (A)</th>
<th>Grid/div</th>
<th>Emission (uA)</th>
<th>Beam Current (nA)</th>
<th>X1/div</th>
<th>Y1/div</th>
<th>X2/div</th>
<th>Y2/div</th>
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Table 2.3 Beam current versus the position of X axis

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### Table 2.4 The tube current vs the dial setting of deflection plate X1

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<th>X1 Dial setting</th>
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### Table 2.5 The tube current vs the dial setting of deflection plate Y1

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### Table 2.6 The tube current vs the dial setting of deflection plate X2

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Table 2.7 The tube current versus the dial setting of deflection plate Y2

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Table 2.8 Temperature of the magnetic coil versus time

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Table 2.9 Magnetic field versus the apply current

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<th>Voltage (V)</th>
<th>B field (kilo Gauss)</th>
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Table 2.10 The dynamic range of source current and the power dissipation in each branch

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<th>$P_{da}$ (W)</th>
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Table 2.13 Information transferred to computer corresponding to Fig 2.41 timing diagram (* 13 zeros total, ** 14 zeros total).

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Table 2.14 The voltage applied to the ceramic screws, the current measured from the setup and the calculated resistance of ceramic.

<table>
<thead>
<tr>
<th>Voltage (V) (unshielded, pA)</th>
<th>Resistance (TΩ)</th>
<th>Current (shielded, pA)</th>
<th>Resistance (TΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000 2.60</td>
<td>385</td>
<td>5.10</td>
<td>196</td>
</tr>
<tr>
<td>1500 3.20</td>
<td>469</td>
<td>7.50</td>
<td>200</td>
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<tr>
<td>2000 3.60</td>
<td>556</td>
<td>9.20</td>
<td>217</td>
</tr>
<tr>
<td>2500 4.80</td>
<td>521</td>
<td>10.9</td>
<td>229</td>
</tr>
<tr>
<td>3000 6.00</td>
<td>500</td>
<td>12.8</td>
<td>234</td>
</tr>
<tr>
<td>3500 6.20</td>
<td>565</td>
<td>15.0</td>
<td>233</td>
</tr>
</tbody>
</table>
CHAPTER 3

THE SEE TEST STAND FOR TRANSIENT THERMAL STUDIES

3.1 Introduction

Heat removal in metal structures is often the limiting factor in high power, high frequency microwave tube devices. As higher critical heat flux cooling techniques are found, the operating power of the microwave device may be increased if other limiting factors are not of importance. Larger temperature gradients may be observed across the microwave tube wall assuming the heat source is constant. Larger output powers may be realized for brief periods in time at the expense of operating in a pulsed power and/or pulsed cooling mode. During these brief periods of time, temporary temperature fluctuations on the walls of the microwave tube will be realized. It is hypothesized that the temperature fluctuations and to a much lesser extent temperature gradients may influence secondary electron emission resulting from primary electrons colliding with the microwave wall. Low energy primary electrons that penetrate the microwave wall experience the collective effects of the electrons in the conduction band of the metal; plasmons. It is anticipated that the surface and bulk temperature of the metal wall influences the ability for plasmons to interact with the primary electron in the scattering process. Further, aging effects resulting from heat stress cycling of the metal cavity may alter the state of the cavity walls leading to changes in the secondary electron emission.
properties. It is also of interest to note that, high-energy primary electron beams behave differently than low energy beams when interacting with a material containing a crystalline lattice structure. Electron diffraction can be significant at the higher energies. Heating the material perturbs the crystalline structure resulting in a broadening of the diffracted electron beam. With a flat energy profile, low primary beam currents, and various external-heating techniques, changes in the scattering dynamics may be observed for each SEE mechanism. Energy deposition of low- and high-energy primary electron beams will differ. Low energy beams find relevance in multipacting studies from cavity walls, rf windows, and environmental barriers.

Based on the concept of the skin depth, microwave and laser sources will be used in future experimentation to impart temporary thermal gradients in a sample under test. Placing the opposite side of the sample next to a cooling reservoir allows for some degree of thermal gradient control in a vacuum environment. The future study of the secondary electron emission distribution from a typical target sample is planned to take place both in thermal transient and thermal steady state modes.

In this chapter, the electromagnetic and thermal properties of the proposed future work are studied. It is hypothesized that the state of the sample may influence the initial condition of the SEE momentum trajectory. In an early work, the backscattered electrons from cryogenic niobium targets seem to exhibit an angle of reflection with properties similar to an electromagnetic Snell's law. If the target is heated, it is anticipated that the initial momentum trajectory will approach a more random nature. The MAGIC software will be used to simulate the microwave heating process. Further, a thermal model is
developed to simulate the cooling process in order to determine the thermal time constants.

3.2 MAGIC

3.2.1 Introduction

MAGIC modeling software is used to simulate the propagation of microwaves guided into and out of a vacuum chamber via a rectangular waveguide towards and from a sample under test for surface heating without affecting the sensitive components housed internal to the chamber. The name "MAGIC" comes from MAGnetic Insulation Code, referring to the magnetically insulated diodes of Sandia's X-ray simulators. The original author of the MAGIC software is Dr. Bruce Goplen, who also directed its development for the first 20 years. Initially, the code provided guidance and intuitive insight for a variety of plasma physics problems as it was designed to solve physics and engineering problems. Since then its capabilities have matured and the code has sufficient capability to be used in the design and refinement of a wide variety of vacuum tube devices. In addition, other applications have become accessible as the material and process models have been extended [28].

3.2.2 The Approach of the Simulation

Operating in the $TE_{10}$ mode, a microwave source launches a high power microwave along a rectangular waveguide through a vacuum chamber viewport towards the sample as shown in Figure 3.2. The mode coupled surface wave will transport EM energy from the horn to the piece being heated. The incoming wave will have a decaying nature in the direction perpendicular to the planar surface. As the wave propagates over the sample
under test, it generates surface currents that heat up the sample as a result of power dissipation. To optimize the energy stored in the wave, the sample is enclosed in a metallic cavity with slit. The incoming wave in part passes into the cavity through the slit. The wave frequency is chosen to be the resonant frequency of the cavity with sample (refer to Figure 3.3). The rectangular waveguide can only propagate TE and TM modes (the TEM mode is not supported) since the waveguide consists of a single conductor. For the rectangular cavity, sample placement on either the broad wall or the narrow wall needs to be addressed for optimal heating. The power dissipated on the cavity walls may be expressed as [29]

\[
P_c = \frac{R_s}{2} \sum_{\text{walls}} |H_1|^2 \, ds
\]

\[
= \frac{R_s}{2} \left\{ 2 \int_{y=0}^{b} \int_{x=0}^{a} |H_1(z=0)|^2 \, dx \, dy + 2 \int_{z=0}^{b} \int_{y=0}^{d} |H_1(x=0)|^2 \, dy \, dz \right. \\
\left. + 2 \int_{z=0}^{d} \left( \int_{y=0}^{a} |H_1(y=0)|^2 + |H_2(y=0)|^2 \right) \, dx \, dz \right\} 
\]

\[
= \frac{R_s E_0^2 \varepsilon^2}{8 \eta^2} \left( \frac{l^2 ab}{d^2} + \frac{bd}{a^2} + \frac{l^2 a}{2d} + \frac{d}{2a} \right) 
\]

where \( R_s = \frac{\sqrt{\omega \mu_0}}{2\sigma} \) is the surface resistance of the metallic walls, \( H_1 \) is the tangential magnetic field at the surface of the walls, \( \eta = \sqrt{\mu/\varepsilon} \) is the intrinsic impedance of the material filling the waveguide, and \( l = 1 \) for \( \text{TE}_{101} \) mode. The first term of Eq. 3.1 represents the power dissipated from the front and the back walls, the second term represents the power dissipated from the left and right walls (narrow wall) and the last term represents the power dissipated from the top and bottom walls (broad wall).

The ratio of the power loss from the broad wall and the narrow wall is
Since \(d > a > b\), the ratio of the power loss from the broad wall and the narrow wall is greater than one. Therefore, the test sample should be placed on the broad wall since power dissipation on this wall is higher. Because the end walls of the cavity (one of which contains the slit) effectively shorts out the wave propagating along the axis of the waveguide, optimal heating (maximum power dissipation) of the sample occurs when the center of the sample is located about multiple odd integers of a quarter wavelength of the supported resonant wave from the end walls.

3.2.3 Heating Calculations

The size of the cavity examined is 6 cm \(\times\) 3 cm \(\times\) 10 cm (broad wall \(\times\) narrow wall \(\times\) length) which is close to standard S band waveguide dimensions (7.2 cm \(\times\) 3.4 cm with recommended single mode operating frequency range of 2.6 – 3.95 GHz). There are two types of perturbations, material perturbations and geometry perturbations. Changing the size of a cavity or inserting a tuning screw can be considered as a change in the shape of the cavity. Since the cavity contains a metallic sample under test, it is treated as the perturbation in geometry. Cavity geometry perturbations causes a shift in the resonant frequency form the ideal geometry as determined by [29]

\[
f = f_0 \left( 1 - \frac{2\Delta V}{V_0} \right)
\]  

(3.4)

where \(f_0\) is the resonant frequency of the cavity in the absence of the sample under test and \(f\) is the resonant frequency of the perturbed cavity. \(V_0 = a \times b \times d\) and \(\Delta V = l \times \pi \times r_0^2\), where \(l\) is the height of the cylindrical sample of radius \(r_0\) and \(a, b, d\) are the width of
the broad wall, height of the narrow wall and length of the rectangular cavity, respectively. The resonant frequency for the TE\textsubscript{101} mode in the rectangular cavity is

\[ f_{mn l} = \frac{c}{2\pi \sqrt{\varepsilon_r \mu_r}} \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \] \hspace{1cm} (3.5)

or numerically 2.91 GHz. The cutoff frequency of the rectangular waveguide for the TE\textsubscript{10} mode is 2.5 GHz. When the sample geometry is inserted in the cavity, a shift in resonant frequency is expected as dictated by Equation 3.4. Since there is a slit on the block, the orientation of the slit should be considered. The vertical slit (perpendicular to the broad wall) will be examined first, then the horizontal slit (parallel to broad wall). The simulation shows that when the slit is vertical, the power inside the cavity is small roughly 15 fW as shown in Figure 3.4. This is the result of the incoming wave having an evanescent nature in the direction perpendicular to the planar surface with slot as a consequence of the slot orientation. The surface currents on the wall are in the direction along the slot hence minimal capacitive couple results into the cavity structure. For the horizontal slit, the simulation shows the power inside the cavity is increasing (Figure 3.5) and it is slightly higher than the input power of the microwave (Figure 3.6) if the sample is located at the middle of the cavity. If the center of the sample is positioned one quarter of a wavelength from the end of the waveguide, the simulation shows the power inside the cavity is increasing and is higher than the previous position (Figure 3.7). From the above simulations, it is observed that when the input microwave is about 0.5 mW, the power dissipated by the sample inside the cavity is about 40 mW. The horizontal slit on the block capacitively couples the wave to the cavity. Even so, it is difficult to determine
the size of the slit that will be sufficient to cause optimal resonance inside the cavity. Therefore, a theoretical approach will be examined.

Electromagnetic energy may be coupled from one waveguide into another guide or into a cavity resonator by a small aperture located at a suitable position in the common wall. A rectangular cavity is formed by placing a transverse wall with a small centered circular aperture into a rectangular waveguide, a distance $d$ from the short-circuited end as shown in Figure 3.8. Mounted on a manipulator arm, the second waveguide internal to the vacuum chamber can be moved within the chamber. The bottom broad-wall of the cavity is not attached to the cavity proper but instead is mounted on the sample as shown in Figure 3.9. This wall has two purposes. First, it acts as a heat source to the sample establishing a temperature gradient within the sample for a period of time that is long enough to conduct secondary electron experiments with the waveguide removed. Second, it helps shape the field lines in the region between the sample test stand and the detector.

On a metallic wall, the normal magnetic field and the tangential electric field vanish, but a tangential magnetic field and a normal electric field may be present. For a small circular aperture in the wall, within the hole there will be a tangential electric field and a component of the magnetic field perpendicular to the wall. If a linear dimension $x$ of the hole satisfies the relation that $x \ll \lambda/2\pi$, then the fields in the neighborhood of the hole are closely approximated by the unperturbed fields $H_0$ and $E_0$ plus the fields from an electric dipole and a magnetic dipole within the hole. The strength of the electric dipole is proportional to $E_0$, and the dipole is directed normally to the wall. Similarly, the magnetic dipole is in the plane of the wall and of strength proportional to $H_0$. The constants of proportionality are the polarizabilities of the hole. The electric polarization $P$ is simply a
constant, since the dipole and the field are parallel. The directions of the magnetic dipole and the exciting magnetic field are not necessarily the same. Collin [30] shows the magnetic polarizability $\alpha_m$ can be calculated and the radius of the aperture is equal to

$$r = \left[ \frac{3\alpha_m}{4} \right]^{1/3} \tag{3.6}$$

For a resonant frequency of 2.91 GHz, the surface resistance of the metallic walls can be calculated as followed [2]

$$R_s = \sqrt{\frac{\omega \mu_0}{2\sigma}} \tag{3.7}$$

where $\omega = 2\pi f = 1.832 \times 10^{10}$ (rad/s), $\mu_0 = 4\pi \times 10^{-7}$ (H/m) and $\sigma$ for copper = $5.813 \times 10^7$ (S/m). Therefore, the resistance, $R_s$, is equal to $1.407 \times 10^2 \Omega$.

The quality factor, $Q$, is [2]

$$Q = \frac{(k\alpha d)^3 b \eta}{2\pi^2 R_s} \frac{1}{2l^2 a^3 b + 2bd^3 + l^2 a^3 d + ad^3} \tag{3.8}$$

where $k = \alpha_0 \sqrt{\mu_0 \varepsilon} = \frac{2\pi f \sqrt{\varepsilon_r}}{c} = 61.06 m^{-1}$, $\lambda = \frac{c}{f} = 1.03 \times 10^{-3} m$ and $\eta = \frac{\eta_0}{\sqrt{\varepsilon_r}} = 377$.

For $a = 6$ cm, $b = 3$ cm, and $d = 10$ cm, the quality factor is $1.30 \times 10^4$. With the aid of Eq. 3.6, the magnetic polarizability, $\alpha_m$, is determined from [30]

$$\alpha_m = \frac{k_{101}^2 abd}{\pi k_{101} \sqrt{8\beta_0 Q} d} \tag{3.9}$$

where $k_{101} = \sqrt{\left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{d}\right)^2}$. Again, for $a = 6$ cm, $b = 3$ cm and $d = 10$ cm, $\alpha_m = 6.121 \times 10^{-7}$. Therefore, the radius of the aperture is $r = \sqrt{\frac{3\alpha_m}{4}} = 7.71 \times 10^{-3} m = 0.771 cm$ is
obtained for the cavity without sample at the resonant frequency of 2.9 GHz. By slightly varying the aperture radius and location, MAGIC verified that the calculated radius, with slight perturbation in location, yielded the largest peak with longest duration of oscillation as shown in Figure 3.10.

For completeness, a rectangular pulse was also launched into the waveguide with cavity containing the end aperture coupling. The cylindrical 1 cm diameter shaped sample, placed in the center of the cavity, extended about 0.625 cm into the cavity above the lower cavity wall. Since the height of the narrow wall of the cavity is only 3 cm, a 20% change in distance of separation between the sample and top surface results. A spectral study identified at least three resonant frequencies above cutoff when the sample was placed inside the cavity. The capacitive and inductive effects of the sample shifted the resonant frequency from that for the empty cavity. Refer to Figure 3.11. A wave at each of these four frequencies was launched in separate runs and the resonant signature of the cavity was examined. The 6.5 GHz source frequency seemed to provide the largest resonant effect as shown in Figure 3.12.

A theoretical study is developed to determine the required output power of the source. Since the bottom plate of the cavity is to be heated by ohmic losses and this plate is much larger than the sample itself, standard wall loss expressions will be used to determine the power dissipated in the plate with sample by modeling these as just a plate in the absence of the sample. For the TE_{101} mode, the power dissipated in the lower cavity broad-wall, \( P_{LB} \), is given as

\[
P_{LB} = \frac{R_s |E_0|^2 \pi^2}{4 \eta \omega^2 \epsilon \mu} \left( \frac{a}{2d} + \frac{d}{2a} \right)
\]

while the power dissipated in all of the cavity walls, \( P_{LC} \), is
where respectively $R_s$ and $\eta$ are given by Equation 3.7 and an expression leading to Eq. 3.8. Aperture coupling theory through a transverse waveguide wall is applied neglecting the effect of the reflected wave generated internal to the cavity. Within this constraint, the theory is valid since the aperture diameter is smaller than a wavelength. The electric field amplitude for the TE$_{10}$ mode in the cavity, $E_0$, is related to the electric field amplitude, $E_{0w^+}$, for the TE$_{10}$ wave in the waveguide propagating towards the cavity with end aperture coupling given by

$$E_0 = \frac{j4\beta\alpha_m}{ab} E_{0w}^+$$  \hspace{1cm} (3.12)$$

When losses are negligible and the source and cavity resonate, the power grows linearly with time. Since the source frequency resonates with the natural response of the system or some harmonic thereof, Equation 3.12 is modified to allow for linear power growth consistent with resonant harmonic oscillator studies for the resonant circuit. Consequently, assuming resonance at the fundamental frequency $\omega_0$,

$$E_0 = \frac{j4\beta\alpha_m}{ab} E_{0w}^+ \left[\frac{\omega_0}{2\pi} t\right]^{-1/2}$$  \hspace{1cm} (3.13)$$

Equation 3.13 will provide unrealistic results since it does not account for attenuation of the wave as it propagates twice the length of the cavity. Phenomenological, this may be incorporated in the relation as follows. At $t=0$, the cavity input field is $E_0$. Let $T$ be the time it takes for the wave to propagate twice the length of the cavity while dissipating some of its energy in the walls of the guide as dictated from the wave equation by $\exp(-\alpha L)$ while $L = 2d$ is the round trip distance of the cavity and $\alpha = P_i / (2P_{10}) = 0.0023$
Np/m at 6.5 GHz, where $P_i$ and $P_{io}$ are the power loss per unit length and the incident power without loss for the TE$_{10}$ mode of a rectangular waveguide respectively] is the attenuation coefficient associated with the counter propagating waves in the cavity treated as a waveguide. Then, after $N$ round trip times,

$$E_m = E_o [1 + e^{-\alpha d} + e^{-2\alpha d} + \cdots + e^{-N\alpha d}]$$  \hspace{1cm} (3.14)

The bracketed finite series may be expressed in closed form. Let $NL = vt$, Equation 3.13 may be re-written as

$$E_o = \frac{j4\beta \lambda m}{ab} E_{ow}^* \left[ \frac{1 - e^{-\alpha v}}{1 - e^{-2\alpha d}} \right]$$  \hspace{1cm} (3.15)

where $v$ is the velocity of propagation of the wave (phase velocity). If the source is resonant with the cavity, then the source period is an integer value of the transit time. For Equations 3.12, 3.13, 3.15,

$$\beta^2 = \omega^2 \varepsilon \mu - \left( \frac{\pi}{a} \right)^2$$  \hspace{1cm} (3.16)

With some manipulation based on a power flow argument, the power supplied by a source may be directly related to the incident electric field of the TE$_{10}$ mode in a lossless rectangular waveguide yielding

$$P_{in0} = \frac{ab}{4\omega \mu} |E_{ow}^*|^2$$  \hspace{1cm} (3.17)

Combining Equations 3.11 and 3.15-3.17 yields an expression relating the power dissipation in the cavity walls to the incident power from the source assuming no loss in the waveguide

$$P_{LC} = \frac{8\beta \lambda m^2 R_0 \pi^2}{\omega \mu a^3 b^3} \left[ \frac{ab}{d^2} + \frac{bd}{a^2} + \frac{a}{2d} + \frac{d}{2a} \left[ 1 - e^{-\alpha v} \right] \left[ 1 - e^{-2\alpha d} \right] \right] P_{in0}$$  \hspace{1cm} (3.18)
For \( a_m = 6.12 \times 10^{-7} \) m\(^3\) (based on the resonant frequency of the cavity without sample; Equation 3.4), \( f = 6.5 \) GHz, and using Equations 3.7 \( (R_s = 1.407 \times 10^{-2} \Omega) \) and 3.16 \( (\beta = 31.41 \text{rad/m}) \) for copper, the ratio of the power dissipated in the lower broad-wall of the cavity to the power supplied by the source is

\[
\frac{P_{LC}}{P_{m10}} = 5.6 \times 10^{-7} \left[ \frac{1 - e^{-\alpha L}}{1 - e^{-2\alpha L}} \right]^2
\]

(3.19)

The ratio of the power dissipated in the broad-wall with sample (Equation 3.10) to the total power loss in the cavity (Equation 3.11) walls is

\[
\frac{P_{LB}}{P_{LC}} = \frac{1}{2} \left[ \frac{a + d}{2d} \right] \left[ \frac{a + 2d}{2a} \right]
\]

(3.20)

or numerically, \( P_{LB} / P_{LC} = 0.26 \).

Knowing the specific heat of the sample and relating the power dissipation in the wall of the cavity with sample to the heat energy imparted to the wall, the change in the temperature of the wall with time is

\[
\Delta T = \frac{\Delta Q}{mc} = \frac{P_{\text{diss}} t}{mc}
\]

(3.21)

where \( Q \) is the heat, \( m \) and \( c = c_p = 0.385 \) J/gK for copper at room temperature and 1 atm) are respectively the mass and the specific heat of the sample and adjoining cavity wall at constant pressure, \( P_{\text{diss}} = P_{LB} \) or \( P_{LC} \) is the power dissipated in the waveguide wall or walls, and \( \Delta T \) is the temperature difference. The mass density of copper is 8.92 g/cm\(^3\).

The volume of the sample is 0.625 cm\(^3\) and the volume of the lower cavity broad-wall plate is roughly 90 cm\(^3\) (solid rectangular plate with no holes) whereas the narrow wall, upper broad wall, and the end plate volumes are respectively 6 cm\(^3\), 12 cm\(^3\), and 3.6 cm\(^3\).
The ratio of temperature change in the cavity walls relative to the incident source power is
\[
\frac{\Delta T}{t} = \frac{1}{m_{T}c_{p}} \frac{8\beta \alpha_{w} R_{c} \pi^{2}}{a \rho \mu a^{3} b^{3}} \left[ \frac{ab}{d^{2}} + \frac{bd}{a^{2}} + \frac{a}{2d} \frac{1-e^{-a \omega t}}{1-e^{-2ad}} \right]^{2} P_{m10}
\]  
(3.22)

Because heating the lower cavity wall will result in heating all of the cavity walls, \(m_{T}\) represents the total mass of copper cavity walls. Consequently, \(m_{T} = 1.08\) kg. Numerically,
\[
\frac{\Delta T}{t} \approx 1.35 \times 10^{-5} \left[ 1 - e^{-2ad} \right]^{2} P_{m10}
\]  
(3.23)

For 100 °C change in temperature in a 1 minute period would require about 260 W within the constraints of this theory. Since cavity radiation losses coupled back to the waveguide have been neglected and waveguide wall losses have not been considered, an order of magnitude increase in power would appear reasonable. This should allow for the heating of other metals of interest to the high power microwave community. Consequently, a microwave source with output powers between 1 kW and 3 kW is required.

3.3 Thermal Model

3.3.1 Introduction

To determine the temperature transient characteristics of the sample, the thermal properties of the heat circuit are modeled in terms of electrical components. The thermal system inside the vacuum chamber is shown as Figure 3.13. Each of the material components has both electrical properties and thermal properties. Only the thermal properties: thermal resistance and thermal capacitance of the heat circuit are considered. Each material component can be modeled as a resistor in parallel with a capacitor and all
of the components are in series because they experience the same heat flow. The microwave is modeled as a pulsed thermal source and the heat source as a DC thermal source. The electrical equivalent model of the thermal system is shown in Figure 3.14. The electrical and thermal across parameters voltage, \( v \), and temperature, \( T \), are related while the associated through parameters current, \( i \), and heat flow rate, \( q \), are related. Based on linearity, a set of scaling parameters \( S \), \( r \), and \( c \) are defined

\[
S = \frac{v}{T}, \quad r = \frac{R}{R_i}, \quad c = \frac{C}{C_i}
\] (3.24)

The remaining scaling parameters

\[
t = \tau cr, \quad i = \frac{S}{r}q
\] (3.25)

follow allowing one to recover the thermal law and the electrical laws. Here, \( t \) represents time in the electrical circuit formulation while \( \tau \) is time for thermal formulations. In order to build an electrical circuit with typical components available, the following scaling factors were chosen: \( S = 0.01 \text{ (V/K)} \), \( r = 102.85 \text{ (\Omega W/K)} \), and \( c = 5.95 \times 10^{-9} \text{ (F°K/J)} \).

3.3.2 Cooling Calculations

Typically, high power microwave devices require cooling systems that generate a temperature gradient in the material structure. Since the system is in a UHV environment, thermal cooling by radiation losses closes the electrical circuit. The sample itself sits on an electrical insulator to prevent electrical contact with the bulk heating/cooling source. This allows for monitoring the electrons lost to the sample in secondary electron emission experiments. This barrier also acts as a thermal barrier. By varying the thermal capacitance and resistance of this medium, the transient time constant and the
temperature gradient in the sample may be controlled. The thermal resistance and capacitance are given by

\[ R_t = \frac{I}{KA} \]  
\[ C_t = c_pDV = c_p m \]

where \( R_t, I, K, \) and \( A \) are respectively the thermal resistance of the material (°K/W), thickness of the material (m), thermal conductivity of the material (W/m °K), and the cross sectional area that is perpendicular to the direction of heat flow (m³). In sequence, \( C_t, c_p, D, V, \) and \( m \) are the thermal capacitance (J/°C), heat capacity of the material at constant pressure (J kg⁻¹°C⁻¹ or J kg⁻¹ K⁻¹), mass density (kg/m³), volume (m³), and mass (kg). Typical thermal barriers studied are Teflon, Aluminum Nitride (AlN), and glass. Table 3.1 shows some of the thermal properties of the mechanical components, sample, thermal barrier and the cryostat. Table 3.2 provides the thermal and equivalent electrical component values realizing the thermal and electrical models of the sample with plate.

The waveguide and the sample will be heated by the microwave. Since the waveguide is much larger than the sample, the waveguide can be treated as a heat source after the microwave is turned off. Therefore, the waveguide is included in the electrical model. The bottom plate of the waveguide with hole for sample is shown in Figure 3.9, and the top view and the cross section of the waveguide is shown in Figure 3.15 and Figure 3.16, respectively. From Figure 3.15, the bottom plate of the waveguide is divided into seven parts; each part has a capacitor in parallel with a resistor. The thickness of the waveguide, \( h \) (Refer to Fig. 3.16), where it is in contact with the sample will determine the heat flow from the waveguide to the sample. Effectively, the output voltage is measured across the resistor that models the lower half of the sample just below the contact point between the
sample and the thermal load bearing plate. All graphical plots provide the expected voltage decay for an RC circuit. Results have been tabulated in Table 3.3. As expected, as the thermal resistance increases, the temperature gradient in the sample decreases and the thermal time constant increases. The thermal time listed is the thermal time constant, the time it takes for the system to cool to 36.8% of its initial value. Figure 3.17 shows the PSpice simulation of the electrical time constant of Teflon, aluminum nitride, and glass as thermal barriers. Teflon and glass provide enough time to move the heating system and conduct secondary electron experiments while the sample is in a transient posture. Although thermal gradients may not have a direct influence on secondary electron emission, it may have an influence on secondary effects on the sample which in turn may influence the emission process as a result of sample aging.
Figure 3.1 Microwave heating mechanisms illustrated.

Figure 3.2 Rectangular waveguide
Figure 3.3 The side view of the rectangular waveguide, a block with a horizontal slit (the blue geometry) was inserted inside the waveguide and the sample is the black geometry.

Figure 3.4 Power dissipated from the sample with vertical slit.
Figure 3.5 Power dissipated from the sample when it located at the center of the cavity and the slit is in the horizontal orientation

Figure 3.6 Power of the input microwave at the beginning of the waveguide
Figure 3.7 Power dissipated from the sample when it located at the position of $\lambda/4$ from the end of the waveguide and the slit is in the horizontal orientation.

Figure 3.8 End excited rectangular cavity with circular aperture.
Figure 3.9 Bottom plate of cavity is to be mounted one the sample separate from the cavity proper. The plate will be used as a heat source extending transient cooling times and helping to setup temperature gradients in the sample. The sample sits on an electrical insulator also used as a thermal barrier to adjust thermal temperature gradients and transient times in the sample.

Figure 3.10 The wave resonate inside the cavity with the peak power of 41.5 mW at resonant frequency 2.9 GHz, no sample was inside the cavity.

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Figure 3.11 Fast Fourier Transform of the response of a rectangular pulse launched internal in the waveguide as measured over the cavity cross section close to and parallel with the wall containing the aperture just inside the cavity.
FIELD POWER S.DA at PROBE5  Frequency = 5.3999 GHz

(a)

FIELD POWER S.DA at PROBE5  Frequency = 5.7999 GHz

(b)

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Figure 3.12 Power dissipated from the sample inside the cavity in four different frequencies: a. 5.4 GHz, b. 5.8 GHz, c. 6.5 GHz and d. 6.8 GHz.
Figure 3.13 Thermal system inside the vacuum chamber
Figure 3.14 Electrical circuit modeling all components in the thermal circuit
Figure 3.15 Top view of the waveguide and its electrical components
Figure 3.17 PSpice simulations show the time constant (time for the voltage to drop 36.8%) of a. Teflon, b. Aluminum Nitride and c. glass as thermal barrier. Axis labels: [Horizontal, Vertical] for: a. [Volt (mV); Time (ms)], b. [Volt (V); Time (μs)], and c. [Volt (mV); Time (ms)].
Table 3.1 Thermal properties of the mechanical components.

<table>
<thead>
<tr>
<th>Components</th>
<th>Material</th>
<th>Specific heat capacity (J/g°C)</th>
<th>Thermal conductivity (W/m°C)</th>
<th>Density (kg/m³)</th>
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</thead>
<tbody>
<tr>
<td>Sample</td>
<td>Copper</td>
<td>0.385</td>
<td>400</td>
<td>8920</td>
</tr>
<tr>
<td>Thermal Barrier</td>
<td>Glass</td>
<td>0.8372</td>
<td>0.67 (@100°C)</td>
<td>2579</td>
</tr>
<tr>
<td></td>
<td>Teflon</td>
<td>1.172</td>
<td>0.2</td>
<td>1000</td>
</tr>
<tr>
<td>Cryostat</td>
<td>Aluminum Nitride</td>
<td>0.74</td>
<td>180</td>
<td>3260</td>
</tr>
<tr>
<td></td>
<td>304L grade stainless steel</td>
<td>500 (J/kg°C) (@0–100°C)</td>
<td>16.3 (@100°C)</td>
<td>8030</td>
</tr>
</tbody>
</table>

Table 3.2 Properties and the dimensions of the thermal and electrical components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Waveguide 1 and 6</th>
<th>Waveguide 2, 3, 4, 5</th>
<th>Waveguide 7</th>
<th>Sample (top)</th>
<th>Sample (bottom)</th>
<th>Insulator 1</th>
<th>Insulator 2</th>
<th>Insulator 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>Cu</td>
<td>Cu</td>
<td>Cu</td>
<td>Cur</td>
<td>Cu</td>
<td>Teflon</td>
<td>AIN</td>
<td>Glass</td>
</tr>
<tr>
<td>Specific heat</td>
<td>385</td>
<td>385</td>
<td>385</td>
<td>385</td>
<td>385</td>
<td>1172</td>
<td>740</td>
<td>873.2</td>
</tr>
<tr>
<td>capacity (J/kg°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (W/m°C)</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>400</td>
<td>0.2</td>
<td>180</td>
<td>0.67</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>8920</td>
<td>8920</td>
<td>8920</td>
<td>8920</td>
<td>8920</td>
<td>1000</td>
<td>3260</td>
<td>2579</td>
</tr>
<tr>
<td>Radius (cm)</td>
<td>N/A</td>
<td>N/A</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>N/A</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>2.0</td>
<td>1.7</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>2.2</td>
</tr>
<tr>
<td>Width (cm)</td>
<td>6</td>
<td>6</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Thickness (cm)</td>
<td>1.5</td>
<td>1.5</td>
<td>0.02</td>
<td>0.2</td>
<td>0.425</td>
<td>0.0035</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Resistor value (Ω)</td>
<td>5.7</td>
<td>107</td>
<td>32.75</td>
<td>6.55</td>
<td>13.9</td>
<td>220</td>
<td>3.6</td>
<td>95.2</td>
</tr>
<tr>
<td>Capacitor value (nF)</td>
<td>370 μ</td>
<td>240 μ</td>
<td>0.18</td>
<td>10 μ</td>
<td>0.020</td>
<td>0.470</td>
<td>1.55</td>
<td></td>
</tr>
</tbody>
</table>

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Table 3.3 Thermal times and temperature gradients resulting from cooling with different electrical and thermal insulators between the sample and the bulk heating unit. These results were obtained from the case when the vertical height of the base plate in contact with the sample is 0.2 cm.

<table>
<thead>
<tr>
<th>Contact length</th>
<th>Simulation results</th>
<th>Teflon</th>
<th>Aluminum nitride</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 cm</td>
<td>Initial voltage</td>
<td>290.4 mV</td>
<td>3.0 V</td>
<td>583 mV</td>
</tr>
<tr>
<td></td>
<td>Voltage after one time constant</td>
<td>182.5 mV</td>
<td>1.9 V</td>
<td>368 mV</td>
</tr>
<tr>
<td></td>
<td>Temperature gradient (°K/m)</td>
<td>10.8</td>
<td>110</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>$\tau$</td>
<td>5.12 min</td>
<td>27.25 s</td>
<td>2.56 min</td>
</tr>
</tbody>
</table>
CHAPTER 4

EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Experimental Results

The main goal of this research effort is to establish a conservation of charge principle through absolute measurements. The following five charge measurements are examined: the primary beam electron, the electrons captured at the sample, electrons lost to the grid, electrons lost to the beam tube, and detector recorded electrons. In the sections that follow, rough calculations are used to estimate the percentage of secondary electrons that are directed to the detection region just before the grid. Also calculated is the percentage of those electrons passing through the grid and the percentage blocked by the microchannel plate (MCP) material. Data acquisition losses are also considered as a result of data conditioning, data transfer, data computation and data recording and storage. In early experiments, relative measurements where performed to compare SEE effects from different surface conditioned samples. Although useful when comparing to a standard, these measurements do not provide enough information to the study of the surface physics of the sample. Consequently, a careful study of each measurement and its difficulties are presented in this chapter with regards to establishing a conservation of charge principle.
4.1.1 The Experimental Complexities Addressed

Seemingly straightforward, a number of unexpected, and in some cases, unexplained complications have questioned measured results. Those complications are addressed here.

As discussed in Chapter 2, when the detector is on a high grid current typically fluctuating between nano to micro appear. The temporal shape of the current draw was not constant but appeared to exhibit a charge/discharge like pattern. These currents occurred when the grid was separated from the MCP housing with either steel washers and screws or with ceramic washers and ceramic screws. The ceramic hardware have leakage resistance values on the order of $1 \times 10^{14} \, \Omega$. At most, because four sets of ceramic hardware connect the grid to the MCP housing, current surges on the order of 60 pA should be measured for a potential difference of 3.5 kV (typical anode voltage). It should be noted that the potential difference between the grid and the closest electrode is on the order of a 300 V. Based on the experimental chart provided in Chapter 2 (refer to Table 2.14), this would imply that the maximum current measured would be less than 20 pA. The wire connecting the grid to the outside instrumentation is not shielded. Therefore, to minimize microphonic effects, a second wire is twisted around the grid wire and attached to ground on both ends. If the grid is physically disconnected from the detector housing but located within a centimeter from the MCP, with all power and instrumentation wires nearly in the same position, the seemingly high grid current vanishes to picoampere noise level values. It is hypothesized that it is possible that dirt or dust particles on the MCP or the grid was generating electrons through field emission is a random fashion that no real pattern could be observed over the particle position.
detector surface as the consequence of a large signal-to-noise ratio but resulted in a measurable current draw in the grid.

In early experiments, the grid current was not monitored. Therefore, it is not clear if the effect existed at that time. Consequently, two approaches to examine grid capture or grid loss are examined. One is based on an effective capture area was developed as described in Section 2.8.4.1. The shadow area of the grid formed over the surface of the detector region, when one count is subtracted from each pixel area of the detector, is used as a measure of area in which electrons are lost. The second is based on the fact that the undesired grid current only exists when the detector is energized. If field emission is the cause, then one should be able to eliminate this effect by turning the detector off. It is hypothesized that field emission and leakage sources of current only add to the measured current and are neither apart of the experiment nor apart of the pictured results as a result of the detected image. Therefore, grid current studies are performed with the detector off and are assumed to be equivalent to the case when the detector is on when noise effects are eliminated. This does not provide a direct measurement of the current detected during a particular experiment but does allow for a quantitative absolute measurement that can be used when all external parameters (i.e., grid voltage, primary beam energy and current, angle of beam incidence onto the sample surface, and similar surface structure). Some variability will exists since the surface morphology and mono layer surface contaminants will be slightly different after each beam exposure. This variability is assumed small.

It is not completely understood at this time why the data recorded by the particle position detector appears to show no counts over the major portion of the detector area.
unlike early experiments and, in earlier experiments, why the number of counts are appear to be orders of magnitude smaller. Extensive tests were performed with the aid of the Roentdek manufacturer to identify the cause of these problems. Both software (e.g., CoboldPC software integration of data and timing studies) and hardware (e.g., voltage checks at the detector sensors, signal amplifier checks, data acquisition board checks, timing studies and personal computer Windows platform integration CPU checks) issues. Two separate issues are of concern. First, the location of recorded hits performed during experiments associated with this thesis do not agree with early experiments and second, data time stamps of early experiments neither correlate with anticipated manufacturer specifications of the data acquisition interface board (TDC8PCI2) nor agree with maximum total counts associated with the primary beam pulse duration. The CoboldPC software should be able to detect the number of electrons that "hit" the detector over time while the detector is activated assuming that appropriate dead time discussed in Chapter 2 are taken into consideration. In current experiments related to this thesis, data displayed on the graphic data file (dcf file) indicated that the number of electrons that are detected is insignificant compared to early experiments. After a rigid sequence of tests and retests extending over a six month period, it appears that either the delay line anode or the MCP has degraded. The electronics, power to the sensor, etc. seem to be operational. The anode is just an array of wires and no visible damage can be observed. Although this study is still in progress, all signs tend to indicate that the MCP may be damaged even though it can hold-off the bias voltage. One of two possibilities arise, either during its long storage life in a nitrogen atmosphere desiccator was not suitable in preventing material degradation or the MCP is flooded with too many electrons that saturation
occurs thereby overloading the amplifier reducing the electron acceleration voltage through the MCP. With reduced acceleration voltage, fewer electrons will be generated yielding a weak electron cloud signal whose signal strength is below a threshold strength that can be detected. The first possibility could simply be a consequence of the MCP tube pores being plugged preventing electrons from entering in the tube for amplification. Consequently, until this issue is resolved, one must rely on data secured in an earlier study [25].

The data related to early experiments were not analyzed in detail with absolute measurements in mind [25]. Based on a simple charge number calculation knowing the electron gun currents, electron pulse duration, plausible secondary electron yields and conservative loss assumptions at each stage of the experiment, the total number of charge recorded by the detector is orders of magnitude smaller than calculated. This observation motivated the detailed examination of each component in this experiment seeking to explicitly establish conservation of charge experimentally so to understand the gross differences in charge number. Unknown to investigators in earlier experiments, the data acquisition board (TDC8PCI2) was programmed to accept data for a single hit in a 32 μs window with an associated processing time (dead time) of 2.4 μs. Further, in earlier experiments, the time stamp for the data recorded was not accessible. Working with the RoentDek manufacturer through a series of systematic correspondences, time stamp studies and timing diagrams in Sections 2.8.3.5 and 2.8.6 resulted. Although the single shot primary electron pulse duration was 0.1 s, maximum timestamp data from six different files ranged from 0.5 s to 4 s (refer to Table 4.1). The TDC8PCI2 does not record timestamp. The timestamp recorded in the .imf file is produced by the data
acquisition software, CoboldPC. TDC8 is an eight channel peripheral component interconnect (PCI) card which has a resolution of 500 ps per clock count assigning a relative count number (two bytes or 16 bits) to the card's internal registers. (The card has 8 channels, 6 of them are the delay line anode channel, one of them is the MCP channel and one channel is unused), that is eight parallel ports to accept data, and each channel has the programmed capacity to store a single relative time stamp count or up to a maximum of 16 relative timestamp counts.) The (PCI) bus provides direct access to system memory for connected devices, but uses a bridge to connect to the frontside bus. The frontside bus is a physical connection that actually connects the processor to most of the other components in the computer, including main memory (RAM), hard drives and the PCI slots. The function of the PCI is therefore to also assign the IO address to store the data in buffers until the control processing unit (CPU) is available to allow the CoboldPC software to perform data processing. CoboldPC produces a timestamp based on the computer's clock during the time when the CPU is available. Consequently, the timestamp depends on a number of issues unrelated to the experiment including the presence of programs running in the background on the computer. Therefore, the timestamp of the TDC8PCI2 is meaningless. This further implies that the number of digits in the timestamp shown in the Imf file does not indicate the accuracy of the timestamp.

The following calculation shows that Windows XP is robust enough to read data from the TDC card when made available. Microsoft claims Windows XP has data acquisition rate of 98 mega bits (Mb) per second. Therefore, data obtained from the TDC board is read by the operating system at a rate of 98 mega bits per second data acquisition rate (98
bits per microsecond) and placed in a buffer until the CPU is free. Since the maximum clock count in the TDC board is $2^{16}$, this implies that the relative count recorded for each hit is 2 bytes (1 byte is 8 bits) long. This implies that the operating system can read about 6.1 hits per microsecond (98/16 pairs of bytes per microsecond or single hits per second).

Looking at the dead time of the LeCroy chip

$$\text{Dead Time} = 1.8 \mu s + (\text{No.}\# \, \text{channels}) \times (\text{No.}\# \, \text{signals}/\text{channel}) \times (100 \, \text{ns}/\text{signal}) \quad (4.1)$$

One hit recorded on each channel yields a dead time of 2.4 microseconds whereas 16 hits max on each channel yields a max dead time of 11.4 microseconds. The data is transferred from the TDC to the buffers by parallel ports; there is enough time to read one data point (at 12 bytes per microsecond or 6 hits per microsecond) to the TDC registers if one data point is stored in each register. Since Windows can read 6.1 hits per microsecond, then Windows can read 69.6 hits per 11.4 microseconds. It is observed that Windows is fast enough to process the data from the TDC card.

To further understand the data recorded by the TDC8PCI2, one has to investigate the Imf data file in detail. The first set of data (1401.Imf) that was chosen to be analyzed has the parameter of beam energy of 1 keV, beam current of 2.2 nA and the beam was incident at 30 degree. The scatter plot of the data (refer to Figure 4.1) shows that the data was not time stamped randomly but in groups. The duration of each group range from 4 ms to 8 ms and there is a 40 ms gap in between two groups of data set. Since CoboldPC is programmed to take only one count per 32 ps, so the dead time is 1.9 µs. Hence, the total time required to record one count is 33.9 µs. Figure 4.2 shows the number of electron counts in each time block that is taking data. The total run time of 1401.Imf is 569 ms, the sum of the gaps when no data is time stamped is about 480 ms, so the total
data acquisition time is 89 ms. It takes 33.9 μs to record one electron hit, so the maximum number of counts can be recorded in 33.9 μs is 2625 counts. This number is close to the number of counts show in the 1401.lmf, which is 2704 counts. If one compares the calculated number of counts with the counts show in the dcf file, then the difference of counts is even smaller. The dcf file is a graphic file generated while the CoboldPC is taking data, and the lmf file is generated simultaneously. Figure 4.3 shows the dcf file of the data that is being analyzed. The data acquisition code (cpp file) contains the algorithm that calculates the position of the electron hits. If the hit was too close to the hole in the detector or far out at the rim of the detector or if the impact on the detector has very low energy (such as noise), then the code will not show the hits on the dcf file. The lmf file contains all of the electron hits but it cannot distinguish which hit does not make sense.

The 40 ms gap in between groups of data is not a unique phenomenon; a rather constant time exists between surges of data time stamps throughout a data set. Further, looking at about six past data sets, data time stamp extremes in each data set ranged from 0.5 seconds to 4 seconds for a single 0.1 s pulsed beam (refer to Table 4.1). The processing time is CPU dependent and depends on the number of programs running in the background. For the most part, data time stamp intervals ranged between 8 to 10 milliseconds in duration. It is not clear if all of the data in the buffers are processed when the CPU is available or if only a small portion is processed. Among the data files that are being investigated, the time duration between burst of data (time duration when no data is time stamped) processing is between 40 to 60 milliseconds. In one case, as long a 2 seconds was reported and in a handful of cases about 90 milliseconds were observed. When the total number of hits were counted, 3 of the 7 data sets evaluated had counts
well exceeding the total possible number of counts that can occur in a 0.1 second pulse assuming a one count maximum every 34.4 microseconds window with a LeCroy dead time of 2.4 microseconds (maximum number of hits = 2910). These observations therefore suggest that the timestamp associated with the data is not a reliable parameter that may be used in the study of the data secured at this time. A future focus will be to amend this difficulty.

Because of the unexpected complexities associated with the experimental measurements discussed above, the conservation of charge analysis will be based on past experimental data as found in the thesis by Anoop George. Using the same conditions as reported in these experiments, electron charge count will be either experimentally measured with the detector in an off state or deduced by means of calculation associated with some characteristic of the element in the secondary electron emission assembly. As a result, both target and grid current measurements are conducted and evaluated in light of the primary beam current. The primary beam current is also measured at the output of the detector with a carefully positioned Faraday cup. Losses as a result of MCP are calculated based on geometry. Detector recording processes are evaluated with no relevance given to the timestamp associated with the data. Because early experiments (multi-pulsed experiments are not considered) were performed with a single 0.1 s electron beam pulse, all data recorded will be assumed to be a consequence of this pulse duration. As shown in the earlier study [25], the number of dark counts is insignificant over this time duration.

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4.1.2. Analysis of Past Secondary Electron Emission Data

In order to establish conservation of charge experimentally, one can either count the numbers of charges in a period of time or demonstrate conservation of current. Each of the three delay lines composing the anode of the detector has two pairs of output wires that transport the signal signature of the electron hit on the delay line to a set of electronics and a TDC8PC12 to be process. Since knowledge of the time of flight of the electron or its associated magnetic field signature is not measured, secondary electron beam current signatures can not be measured. The detector can only measure the presence and location of charge and not its final energy or momentum. As a result, one is forced to count the charge over a specified period of time to establish conservation of charge. Although important, time delays associated with the count are not critical in establishing conservation of charge since the time duration to record the signals is long (order of seconds) compared to the duration of the primary beam pulse. Further, time delays associated with the internal cascade collision within the target leading to an emitted secondary is fast relative to time scales of the recording instrumentation. Consequently, average current measurements from the primary electron beam, target, and grid are used to determine the current over anode detector wire array. This current is averaged over time assuming a constant time profile for all current measurements.

To compare the experimental results with the previous SEE test at UNLV, the beam and grid characteristics are adjusted to be nearly equivalent to the initial conditions of earlier experiments. The beam energy is set at 1 keV and the primary beam current measured from the Faraday cup is limited to 2.2 nA by adjusting the filament current or emission current from the electron power supply. The detected secondary electron
emission depends on the material properties associated with a Secondary Electron Yield (SEY). The figure of merit, SEY, is defined as the ratio of the current emitted from the target (secondary electron emission) to the current incident to the surface of the medium (primary beam current). This yield will change based on the target's surface characteristics. Typically, one is interested in finding the SEY. Here, the yield is guessed at based on the experimental properties of the ideal target material at appropriate primary beam energies found in literature. Based on this guess, one should be within an order of magnitude in matching numbers of charge. The current incident on the target is the primary beam current minus all losses associated to the beam prior to collision with the target. Consequently, the secondary electron emission current at the target can be expressed as

\[ I_{\text{SEE}_{\text{target}}} = \text{SEY} \times (I_{\text{pb}} - I_{\text{loss}_{\text{PB}}}) \]  \hspace{1cm} (4.2)

where \( I_{\text{pb}} \) is the primary beam current measured from Faraday cup, and the typical SEY for the 1 keV electron energy on an ideal niobium target is one (refer to Figure 4.4). \( I_{\text{Loss}_{\text{PB}}} \) is the loss of primary beam, which can be expressed as

\[ I_{\text{Loss}_{\text{PB}}} = I_{\text{PBG}} + I_{\text{PBT}} + I_{\text{PBW}} \]  \hspace{1cm} (4.3)

where \( I_{\text{PBG}}, I_{\text{PBT}} \) and \( I_{\text{PBW}} \) are the primary beam loss to grid, tube and chamber wall respectively. By conservation of current at the target,

\[ (I_{\text{PB}} - I_{\text{loss}_{\text{PB}}}) = I_{\text{Sample}} + I_{\text{SEE}_{\text{target}}} = I_{\text{Sample}} + \text{SEY} (I_{\text{PB}} - I_{\text{loss}_{\text{PB}}} ) \]  \hspace{1cm} (4.4)

where \( I_{\text{Sample}} \) is the sample current. Therefore, the sample current can be determined as

\[ I_{\text{Sample}} = (I_{\text{PB}} - I_{\text{loss}_{\text{PB}}}) (1 - \text{SEY}) = I_{\text{SEE}_{\text{target}}} \left( \frac{1 - \text{SEY}}{\text{SEY}} \right) \]  \hspace{1cm} (4.5)
At the front surface of the grid relative to the direction of motion of the secondary electrons, the secondary electron emission is

\[ I_{\text{SEEgrid}} = SEY \times (I_{PB} - I_{\text{lossPB}}) - I_{\text{LossSEE}} \]  \hspace{1cm} (4.6)

where \( I_{\text{LossSEE}} \) represents the loss of current prior to reaching the grid surface. Because the detector has a hole in its center to support an electron beam drift tube to allow for the primary beam to pass from the gun to the sample through the detector, loss results when secondary electrons are directed toward the center of the detector. Therefore, the secondary electron emission loss, \( I_{\text{LossSEE}} \), prior to the grid is divided into two terms: one due to loss at the drift tube (\( I_{\text{lossT}} \)), and one due to loss at the chamber wall (\( I_{\text{lossW}} \)) and components not related to the experimental setup. Therefore,

\[ I_{\text{LossSEE}} = I_{\text{lossT}} + I_{\text{lossW}} \]  \hspace{1cm} (4.7)

Because the number of collision cascades suffered by the electron as it enters the target is large, one may assume that the trajectory of the emitted electron is random. Therefore, the emitted electron is assumed to have equal probability in being emitted over a hemispherical surface above the target with normal perpendicular to the surface of the target. In George's thesis, it was shown that the electrons preferentially scatter about the direction satisfying an optical Snell's law. Because this observation was not confirmed in this thesis, a pure random emission process is assumed with George's observation in mind. Consequently, a geometrical argument may be used to determine the secondary electron emission loss based on this random probability argument. The diameter of the detector is 45 mm and outside diameter of the drift tube is 3 mm. The distance between the detector and the testing sample is 2.54 cm. Figure 4.5 shows the area covered by the detector.

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versus the vacuum chamber. From Figure 4.5, one can calculate the area where the secondary electrons captured by the detector,

$$\int_{\phi_1}^{\phi_2} \int_{r=r_1}^{r=r_2} r^2 \sin \theta d\theta d\phi |_{r=R} = 2\pi R^2 (\cos \theta_1 - \cos \theta_2)$$  \hspace{1cm} (4.8)

where $R = 22.5$ mm is the radius of the detector, $\theta_1$ and $\theta_2$ can be calculated from the dimension shown, numerically $\theta_1 = 3.38^\circ$ and $\theta_2 = 41.5^\circ$. Therefore, the fraction of the hemispherical area covered by the detector, $\Psi$, is

$$\Psi = \frac{\text{cone}}{\text{hemisphere}} = \frac{2\pi R^2 (\cos \theta_1 - \cos \theta_2)}{2\pi R^2} = (\cos \theta_1 - \cos \theta_2)$$  \hspace{1cm} (4.9)

or numerically, 0.2493 of the total secondary electrons will be captured by the detector. Therefore, the secondary electron current resulting in loss just before the grid is

$$I_{\text{LossSEE}} = (1 - \Psi)I_{\text{SEE_{target}}}$$  \hspace{1cm} (4.10)

Consequently, the secondary electron emission current just before the grid is

$$I_{\text{SEE_{grid}}} = SEY \times (I_{PB} - I_{\text{lossPB}}) - (1 - \Psi) \times SEY \times (I_{PB} - I_{\text{lossPB}})$$

$$= \Psi \times SEY \times (I_{PB} - I_{\text{lossPB}})$$  \hspace{1cm} (4.11)

The detector assembly consists of a controlling grid providing a drift region for the primary and secondary electrons between the grid and target material, and a microchannel plate (MCP) that amplifies the electron signal for detection by the detector. As shown in Chapter 2, the controlling grid just in front of the detector has an estimated 82% coverage of the detector. Also calculated in Chapter 2, 52% of the MCP's area is blocked by material. Let the fraction of loss relative to the incident secondary electrons at both the grid and MCP be defined respectively as GridLoss = 0.82 and MCPLoss = 0.52. Incorporating these losses into both Eqs. 4.6 and 4.11 yields the secondary electron emission as measured on the surface of the anode detector grid, respectively,
\[ I_{\text{SEEanode}} = (SEY \times (I_{PB} - I_{\text{lossPB}}) - I_{\text{lossSEE}})(1 - \text{GridLoss})(1 - \text{MCPLoss}) \]  
\[ I_{\text{SEEanode}} = \Psi \times SEY \times (I_{PB} - I_{\text{lossPB}})(1 - \text{GridLoss})(1 - \text{MCPLoss}) \]

Since the current measured from the Faraday cup is the primary beam current that has passed through the drift tube and mesh grid, and the beam is captured by the Faraday cup so there is no primary beam loss to wall, therefore, this measured current can be treated as the primary beam current, \( I_{PB} \), implying that \( I_{\text{lossPB}} = 0 \).

Table 4.2 shows the current measurements of the Faraday cup, sample, tube and grid. The plots of the measurements are shown in Figure 4.6 to 4.8. The measurements show that the mean primary beam current is 2.203 nA, and the mean sample current is 0.96875 nA. From Eq. 4.5, the SEY can be calculated as 0.56. Upon substituting this value into Eq. 4.11 yields the following secondary electron current that reaches the grid, \( I_{\text{SEEgrid}} = 0.308 \) nA where \( \Psi = 0.2493 \). Using Eq. (4.12b), the secondary electron current on the delay line anode is \( I_{\text{SEEanode}} = 26.6 \) pA. The mean current measured at the grid while the primary electron beam is colliding with the sample is 0.26263 nA, so the measured percent grid loss is \( 0.26263/0.308 = 85\% \). From Figure 2.47 and Eq. 2.45, the percentage grid loss based on the past experimental data was calculated as \( 82\% \). The difference between these two percentages is due to the fact that there was a potential of 100 V applied to the grid at the time when the data was recording. The potential on the grid will accelerate the electrons allowing some of the electrons to pass through the grid openings without being attracted to the grid wires by image charge effects (sometimes denoted as mirror effects). Because of the positive grid potential, those electrons passing very close to the grid wires are attracted and lost to the grid.
4.2 Discussions of Experimental Results

A discussion of experimental and theoretical data is presented. Anomalies in the data will be pointed out and possible sources of error will be alluded to. Because the detector is limited on the number of electrons it can process and record in a fixed time duration, it will be determined if the detector has been saturated and what primary beam currents are required to amend this effect.

The current generated from the charges that reach the delay line anode based on theoretical calculation was 26.6 pA. Therefore, the number of charges impinging on the delay line in 0.1 s is (26.6 pA) \times (0.1 s)/(1.6e-19) = 1.66e7 electrons under the assumption that the emitted electrons are randomly emitted with no external force present. The data acquisition board, TDC8PCI2, is programmed to record one count per 34.4 μs, so for a 0.1 second beam pulse, the maximum electron count is 0.1/(34.4e-6) = 2907 according to the LeCroy chip data specifications. The maximum electron count is orders of magnitude smaller than the total number of electrons calculated based on the theoretical study employing experimental measurements. This is an indication that the detector is being saturated with electrons. Consequently, one should expect that the number of counts recorded in experiment is the maximum count. If one takes into consideration of observations made in a previous work [25], a large population of backscattered electrons will be directed satisfying a Snell’s law for electromagnetic waves. The experimental setup for the data evaluated in this thesis has the beam impinging on the sample at 30° from the normal to the surface. Using Fig. 4.9 and simple geometry, the specular electrons strike the detector 15 mm from the axis [25]. This implies that the number of
electrons colliding with the detector using an equal random probability of electron scattering is low. Hence, detector saturation is further enhanced.

Table 4.1 provides seven experimental data sets that have been carefully evaluated. It is noted that three of the seven data sets studied exceed the maximum number of counts that can be recorded by the detector in 0.1 s. The detector recording duration is longer than the duration of the electron beam pulse. Outside of detector failure, one must conclude that a second source of electrons may exist adding to the total count of electrons during the time that the detector was recording or the electron beam pulse duration is greater than 0.1 s. The beam pulse duration was controlled by a pulse generator; the pulse width was set at 100 ms for the previous SEE tests. Upon testing the repeatability of the pulse generator, the pulse width observed from the oscilloscope varies from 101.6 ms to 102.4 ms, this corresponds to the maximum count of 2953 to 2977 respectively. Working backwards from the number of counts recorded, assuming that maximum of one count per 34.4 ps can be recorded, the electron pulse durations varies from 53.22 ms to 169.52 ms as obtained from extreme count values listed in Table 4.1. The average beam pulse generated from the pulser is 102 ms, so three out of seven analyzed IMF data has beam pulse within +/- 20% of the average pulse. This tends to indicate that a possible alternative source of detected electrons may exist in the experiment. Upon examining the spatial distribution of recorded hits graphically, no one region appears to have unusually high count population. This seems to imply that discharge breakdown effects from sharp edges may not be a dominant source of charge. Breakdown might be emanating from dust particles. RoentDek seems to think that field emission from dust particles may generate a corona in the large potential difference. The random nature of the corona will
result in a random spatial distribution of charge than results in no apparent pattern in the graphical display of charge recorded. Since timestamp data is not meaningful, no record exists on how long the detector was on. Other counts appear to have a low count number compared to the maximum count for a 0.1 s beam pulse. Because timestamps are not meaningful, one can not determine just how long the detector is actually recording data. These data sets suggest that the anode delay line did not experience the high volume of charge count possibly because the MCP may have saturated with charge. This loading effect may affect charge acceleration through the MCP pores limiting the size of the signal imposed on the delay lines. It is noted that a definite spatial pattern does exist in graphical plots that have been related to the experiment and verified with a Monte Carlo code. It is also noted that a 0.1 s pulse duration in earlier experiments was chosen since the number of counts recorded was too few for lower current values. Once the detector has been repaired, further investigations in light of this thesis and earlier works are warranted.

Since the theoretical number of hits exceeds the maximum count, the detector appears to be saturated. To prevent saturation, the primary beam current needs to be reduced. Assuming 1 count in 34.4 μs, the maximum number of hits that can be recorded in a 0.1 s time duration is 2907. This implies that the maximum uniform SEE current impinging on the delay line anode is \( [2907 \times 1.6e-19 / 0.1 =] \) 4.65 fA. Using Eq. 4.12b and the 4.65 fA incident SEE delay line anode current, the primary beam current leaving the beam drift tube is about 0.39 pA. Higher primary beam currents, within the validity of this theory, will saturate the detector. This current is within the noise level range and therefore, it will be difficult to distinguish the primary beam current measured with a Faraday cup.
To increase the primary beam current but not saturate the detector, one can increase the maximum count by programming TDC8PCI2 to record 16 counts per channel. The dead time, in this case, is 11.4 μs. Therefore, the maximum count for a 0.1 s pulse is \((0.1\text{s}) \times (16 \text{ counts})/(32 + 11.4 \, \text{μs}) = 36866 \text{ counts}\). This implies that the maximum uniform SEE current impinging on the delay line anode is 59 fA. Therefore, the maximum primary beam current measured at the Faraday cup is 4.9 pA in order that the detector does not saturate. This number may be an upper estimate value of the primary current required in order to prevent the detector saturation. If the secondary electrons is not equally distributed, (e.g., a Snell’s like law for electron emission is valid and the specular beam is directed towards the detector), then the percentage of secondary electrons impinging on the anode delay line would be larger (e.g., specular beam directed to detector) or smaller (e.g., specular beam directed away from detector). Also, a small negative potential applied to grid can be used to repel and hence control the number of electrons that pass to the anode delay line. Consequently, the primary beam current may be increased. As a result, the primary beam current that prevents the detector saturation can be higher than 4.9 pA.
Figure 4.1 Each timestamp from an Imf file represent one electron hit, the scatter plot shows the data was time stamped in a group of a few millisecond. The gap in between two groups of data is about 40 ms.
Figure 4.2 The electron counts in each 2 ms to 8 ms time block.
Figure 4.3 The dcf file is the graphical file that shows the distribution of the electron hits that were captured by the detector.

Figure 4.4 Generic dependence of the secondary emission coefficient (δ) on the impact kinetic energy (K) [31].

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Figure 4.5 The distance between the detector and the sample, the outside diameter of the tube and the radius of the detector are shown in order to calculate the angle $\theta_1$ and $\theta_2$. So the percentage of the secondary electron captured by the detector can be determined.
Figure 4.6 Sample current vs. the primary beam current at 1 keV.
Figure 4.7 Tube current measured while the beam is captured by the Faraday cup (red line) and the beam is bombarding the sample (blue line) at 1 keV.
Figure 4.8 Grid current measured while the beam is captured by the Faraday cup (red line) and the beam is bombarding the sample (blue line) at 1 keV.
Figure 4.9 Sketch showing specular reflection from an inclined surface [25]
Table 4.1 The Imf files that are studied in detail. The numbers of times of long durations are observed are in [ ].

<table>
<thead>
<tr>
<th>Data Set / Date</th>
<th>Total Time Duration of Data Set (s)</th>
<th>Total No. of Counts (#)</th>
<th>Typical Time Durations in which Data is Time Stamped (ms)</th>
<th>Typical Time Durations between Bursts of Time Stamped Data (ms)</th>
<th>Unusually long Time Durations Betw. Bursts of Time Stamped Data (ms [approx. no. #])</th>
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<td>1401.lmf/ May 5</td>
<td>0.656</td>
<td>2704</td>
<td>4~7 ms</td>
<td>40 ~ 43 ms</td>
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<td>4928</td>
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<td>51 ~ 53 ms</td>
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Table 4.2 The current measured from Faraday cup, sample, tube and grid while the primary beam is captured by Faraday cup and the beam is bombarding the sample.

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<th>Filament current (A)</th>
<th>Emission current (uA)</th>
<th>Cup current (nA)</th>
<th>Sample current (nA)</th>
<th>Tube current (pA)</th>
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CHAPTER 5

FUTURE SUGGESTIONS

5.1 Future Suggestions

A unique experimental apparatus was designed and set up to study the conservation of charge of the secondary electron emission test stand. Several hours of pumping time was require to achieve the ultra high vacuum pressure from the atmospheric level. To reduce the pump down time, a gate valve was added to the physical structure of the vacuum system. This addition has reduced the pump down time to less than 3 hours. The system may be modified more depends on the future application. The usage of microwave to heat the sample described in Chapter 3 may be the next application.

For the continuation of the current study, the detector assembly is still under testing. The grid in front of the MCP may be placed in an ultrasound bath to remove dust that might lead to the field emission when the high voltages are applied. The MCP stack may be removed from the detector assembly and order interchanged. If the problems still exist then the detector assembly may be shipped back to RoentDek for testing. The MCP stack may be replaced if it is indeed damaged. The current data acquisition card, TDC8PCI2 does not create a reliable time stamp, so the time stamp is meaningless. To obtain the real time stamp of the electron hits, a different data acquisition card will be needed. The new data acquisition card TDC8HP produces the time stamp on the card and transfers it to the
PC. Therefore, the time stamp is very precise. But the PC will also need to be upgraded with the motherboard features fast RAM and a high quality chipset that handles the IO-data transfer. A cylindrical cage with mesh wall which encloses the detector and the testing sample is under construction. It will be placed inside the chamber for testing upon completion. The function of this cage is to capture those secondary electrons normally directed toward the chamber wall will be monitored allowing for a complete experimental verification of conservation of charge in the UNLV Secondary Electron Emission Test Stand to be conducted.

The calculations performed in Chapter 4 has shown that 4.9 pA may be an upper estimate value of the primary beam current required in order to prevent the detector saturation. But the noisy environment is difficult for measuring small current even though the electrometer is capable of small current measurement. The triaxial cable connected to the Keithley electrometer provides a good shielding and may prevent the noise interfering the measurements. Another option is to turn the cryo pump off while taking the measurements to further reduce the microphonic effects.

Numerical modeling is to be conducted to verify experiment. MAGIC is the code of choice to model the experiments and compare with the actual measurement once the difficulties with the detector have been resolved.
BIBLIOGRAPHY


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