DIELECTRIC SURFACE FLASHOVER IN A SIMULATED
LOW EARTH ORBIT ENVIRONMENT

by

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ABSTRACT

Virtually all concepts for the use of electrical energy at high voltages (for commercial, scientific or military applications) must utilize solid dielectrics as insulators. In general, surface flashover on insulators sets the limit on the applicable voltage of the system. For practical applications, scaling laws (i.e., empirical curves relating the flashover voltage to the gap distance) were formulated which describe the simplest cases in ideal geometrical configurations only. The design of high voltage systems is usually based on unnecessarily high safety factors with severe limitations on high voltage amplitudes and power densities in a system. Understanding the mechanisms of surface flashover in the space environment is critical in increasing the dielectric flashover voltage by applying, for example, electric and magnetic shielding techniques.

For this investigation, an experimental apparatus was designed and constructed as a coaxial system in order to operate electrical and optical sensors with high temporal resolution. Current, voltage, and soft x-ray emission are recorded by highly sensitive sensors which have a risetime on the order of one nanosecond. The plasma is generated by an electron cyclotron resonance plasma source and the ultra violet radiation originates from a UV enhanced Xenon arc lamp.

This experiment is the first to investigate the early phase of dielectric breakdown in a simulated low earth orbit environment. The results show that the breakdown mechanisms are drastically altered with a plasma and UV environment, compared to the “pure” vacuum case. Dielectric breakdown with a plasma background shows a lower breakdown voltage and a different current amplification mechanism in the early phase of flashover, compared to measurements in vacuum without plasma. With UV illumination, the dielectric flashover voltage amplitude decreases and the pre-flashover current increases at a slower rate, compared to results without UV. Low amplitude magnetic fields were applied and several magnetic insulation or shielding techniques were tested. Increases of the breakdown voltage amplitude of up to a factor of four were found with magnetic insulation for the UV case. With a plasma background, the duration of an applied voltage pulse can be increased by a factor of 2 without causing flashover compared to the case without external magnetic fields.

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CHAPTER I

INTRODUCTION

Insulators between high voltage conductors are essential in electrical systems for structural support or as interfaces between different dielectric materials (e.g., vacuum and liquids). Surface flashover across these insulators limits the power density transferable through high voltage systems (i.e., surface flashover typically occurs at an electric field amplitude of 10% to 50% of the volume breakdown electric field). The physical mechanisms leading to the breakdown are poorly understood. Therefore, in high voltage operating systems, the distance between high voltage components is designed with a large safety factor which increases weight and dimensions of the system. For space applications, for example, where weight is an important factor, the insulator technology has to be improved.

In recent years, the demand for a higher surface flashover potential in a low earth orbit (LEO) environment has increased. The LEO environment consists of the earth's upper atmosphere which extends from roughly 100 to 1000 km altitude. Typical LEO missions take place at an altitude of 400 to 500 km, where the atmosphere is mainly atomic oxygen. At this altitude, plasma densities of $5 \cdot 10^4$ to 10^6 cm^{-3} with electron temperatures of 0.1 to 0.2 eV at a neutral gas background pressure of 10^{-7} torr are found [1, 2]. In addition, the environment includes UV photons from the solar radiation.

Numerous methods have been developed to increase the flashover voltage of insulators for terrestrial conditions, such as the choice of insulator and electrode geometries, choice of materials, and the application of surface coatings. None of these techniques have been proven to work for space conditions. Furthermore, the plasma background and UV radiation are likely to change some of the breakdown processes, compared to a pure vacuum insulator environment.

It is essential to study the physical mechanisms involved in the pre-flashover process in a LEO environment in real time (e.g., with nanosecond temporal resolutions) in order to design new insulation techniques. This research simulates the plasma and UV environment of the LEO, and it measures the pre-flashover current, voltage, and x-ray emission for the first time. Magnetic shielding techniques are used to significantly improve the performance of an electrically stressed insulator.

Chapter II provides a short overview of different dielectric surface flashover models and provides a more detailed description of the most common model, the saturated secondary electron emission avalanche model (SSEEA), including the influence of an external magnetic field. Furthermore, the effects of a plasma and UV environment on the insulator are discussed. The experimental apparatus is introduced in Chapter III, with its vacuum and high voltage system,

plasma and UV radiation sources, diagnostic sensors, and the data acquisition system. Chapter IV presents the dielectric breakdown measurements and discusses the results. This chapter is separated in two parts: dc and pulsed insulator flashover. A summary of this work is given in Chapter V. In the appendix, the listing of a computer program used for this investigation is given.

CHAPTER II

BACKGROUND

2.1. Overview of the Models of Dielectric Surface Flashover in Vacuum

Many models have been proposed to describe the complex mechanisms of dielectric surface flashover in vacuum [3-10]. These models can be categorized into three main groups and their subsets:

above surface

- ionization of gas which is adsorbed on the insulator surface
- secondary electron emission avalanche leading directly to flashover
- saturated secondary electron emission avalanche
 - thermal desorption of surface gas
 - electron induced desorption of gas molecules at the insulator surface

- below surface

collisional ionization

- thermal runaway

- transitions of below and above surface models.

During recent years, the saturated secondary electron emission avalanche (SSEEA) model with electron induced gas desorption has been recognized by most scientists, although a few researchers [11, 12] are currently working with a below surface model with electron induced gas desorption. In the following sections, the SSEEA model is introduced and a few remarks are given on the current research on below surface models.

2.1.1. Saturated secondary electron emission avalanche model with electron induced gas desorption

The SSEEA model was first proposed by Boersch et al. in 1963 [3] and expanded by Anderson and Brainard in 1978 and 1980 [4, 5] who added the electron induced desorption of gas molecules to the model. A visualization of the saturated secondary electron emission avalanche is given in Figure 2.1. The surface breakdown is initiated by electrons which are field emitted at the triple point, the area where cathode, dielectric, and vacuum are in close proximity. Some of these electrons strike the surface of the insulator. Electrons with an energy larger than A_1 (see Figure 2.2) are able to emit secondary electrons from the dielectric. The secondary electrons which

are emitted with an average energy on the order of 1 eV, are accelerated by the parallel applied electric field and if they strike the surface are capable of producing additional electrons from the insulator (see Figure 2.1a). The emission of secondary electrons produces a positive surface charge on the insulator surface and an electric field perpendicular to the surface is developed. The positive surface charge is increased until the average impact energy of the electrons is A_1 , and the surface current saturates. Most of the emitted electrons are part of this surface current: a small fraction of the electrons are accelerated longer in the applied electric field and have an energy larger than A_1 . Electrons which strike the insulator surface desorb gas molecules, and the gas drifts away from the insulator with thermal velocity. It is assumed that after the gas has drifted above the saturated surface current, it is ionized by the more energetic electrons, and the final discharge occurs.

(a)

(b)

(c)

Fig. 2.1. Schematic description of the dielectric surface flashover by the SSEEA model: (a) secondary electron emission avalanche, (b) saturation of the secondary electron emission current and electron induced desorption of gas at the insulator surface, and (c) development of the final discharge in the desorbed gas.

Fig. 2.2. Generic curve of the secondary emission yield as a function of the electron impact energy. This curve does not represent a specific material. [3]

2.1.2. Below surface models

Sudarshan et al. [9, 11] and Le Gressus [8, 12] have proposed dielectric breakdown models which are based on collisional ionization in a sublayer just underneath the surface of the dielectric. In 1988, Jaitly and Sudarshan [9] proposed that

Electrons in the surface sublayer, produced either by field emptying of traps (or defect sites) or by injection at the cathode triple junction, cause positive charge generation by internal ionization processes. The positive charges drift toward the cathode aiding further electron emission due to the increased local stress. This process becomes regenerative until a threshold level is reached at which a highly conducting plasma is developed along the solid/vacuum surface interface causing breakdown. (p. 3418)

Recently, Sudarshan et al. [13] included electron induced gas desorption as the final stage in their model. In 1994, Asokan and Sudarshan [14] suggested “that the lattice or crystallographic defects that are usually identified in the form of discrete energy states (e.g., traps), located within the forbidden gap of the insulator, may be responsible for the initiation of surface flashover” (p. 97). Their theory was based on measurements they performed mostly on silicon oxide and alumina (Al_2O_3) samples. At the Conference on Electrical Insulation and Dielectric Phenomena (1994 CEIDP), Li and Sudarshan reported light emission from the pre-flashover on alumina and PMMA. They propose that the pre-flashover light emission may be attributed to electroluminescence on the dielectric surface which is related to the processes of trapping and detrapping of electrons at trap centers in the surface region of the dielectric. Gressus [12] stated that

... theoretical works and experiments have supported the idea that breakdown is related to charge detrapping. More precisely, the mechanical energy released during polarization relaxation is the motive

force of catastrophic damage induced by any type of stress: electrical, mechanical, ionizing radiation. (pp. 625-626)

In 1992, Hegeler et al. [15, 16] showed that with an external magnetic field of 260 mT, the current amplification mechanism is significantly altered (see Figure 4.3 in section 4.1). In a collisional ionization dominated process, an external magnetic field influences the ionization mechanism only if the collision frequency is on the order of the electron cyclotron frequency. It was shown that the threshold of the magnetic field required to influence the collisional ionization was at least several Tesla. Therefore, it is believed that a below surface model is not adequate to describe the insulator surface flashover in vacuum.

2.2. Parameters of the Dielectric Surface Breakdown

This section estimates some parameters of the SSEEA. Since the surface charge distribution and density, gas desorption coefficient and other important variables have not been determined, the calculations below can only give a rough estimation of the expected processes triggering the dielectric surface flashover in vacuum.

2.2.1. The saturated electron surface current with electron induced gas desorption

The SSEEA model assumes a positive surface charge on the dielectric surface at unity secondary electron emission yield. The electric field is then given by $E = \{-E_x, E_y, 0\}$ where E_x is the applied field component in the test gap of the insulator and E_y results from the surface charge of the dielectric. Figure 2.3 shows the trajectory of an electron on the insulator surface in the electric field. For this calculation, the applied electric field parallel to the surface is assumed to be constant over the entire gap. The effects of a non-constant electric field will be discussed at a later point.

Fig. 2.3. Trajectory of an electron on the insulator during saturation of the surface current.

The motion of the field emitted electrons is described by the Lorentz force

$$\mathbf{F} = q[\mathbf{E} + (\mathbf{v} \times \mathbf{B})] , \quad (2.1)$$

where $\mathbf{F}$ is the force, q is the electron charge, and $\mathbf{B}$ is the magnetic flux density. Without an external magnetic field, the equation of motion simplifies to

$$m \frac{d\mathbf{v}}{dt} = q \mathbf{E} \quad (2.2)$$

where m is the electron mass. Integrating the above equation, the velocity and trajectory of the electrons are found:

$$\begin{aligned} v_x &= \frac{e}{m} E_x t \\ v_y &= v_0 - \frac{e}{m} E_y t \\ s_x &= \frac{e}{m} E_x \frac{t^2}{2} \\ s_y &= v_0 t - \frac{e}{m} E_y \frac{t^2}{2} , \end{aligned} \quad (2.3)$$

with $E_z = 0$ and the initial conditions $\mathbf{v}(0) = \{0, v_0, 0\}$ and $\mathbf{s}(0) = \{0, 0, 0\}$. The electron impacts the surface after

$$t_1 = \frac{2 m v_0}{e E_y} , \quad (2.4)$$

with an energy, A_i , of

$$A_i = \frac{m}{2} v_0^2 \left[1 + 4 \frac{E_x^2}{E_y^2} \right] . \quad (2.5)$$

Taking into account the cosine law distribution [3] in the direction of emission, the average value of the electron impact, A_1 , becomes

$$A_1 = \frac{m}{2} v_0^2 \left[1 + 2 \frac{E_x^2}{E_y^2} \right] . \quad (2.6)$$

With the electron emission energy

$$A_0 = \frac{m}{2} v_0^2 , \quad (2.7)$$

the electric field due to the surface charge is given by

$$E_y = E_x \sqrt{\frac{2 A_0}{A_1 - A_0}} . \quad (2.8)$$

The positive surface charge can be written as

$$\sigma_+ = 2 \epsilon_0 E_y , \quad (2.9)$$

where ϵ_0 is the electrical permittivity in free space. With the assumption that the electron charge density σ_- is equal to the positive charge density on the dielectric surface, the saturated surface current per unit channel width is

$$I_x = \sigma_- v_e = 2 \epsilon_0 E_y v_e = 2 \epsilon_0 v_0 E_x . \quad (2.10)$$

The average electron velocity in x-direction

$$v_e = v_x(t)_{average} = \frac{v_x(t_1)}{2} = v_0 \frac{E_x}{E_y} = \sqrt{\frac{A_1 - A_0}{m}} . \quad (2.11)$$

and the electron current density incident on the dielectric surface is given by

$$J_y = \frac{I_x}{s_{x_{average}}} = \frac{2 \epsilon_0 v_0 e E_x^2}{A_1 - A_0} . \quad (2.12)$$

The density of desorbed gas molecules is estimated by Pillai-Hackam [17] as

$$n = \frac{\gamma J_y}{e v_{th}} , \quad (2.13)$$

with the average thermal velocity of the desorbed gas

$$v_{th} = \sqrt{\frac{8 R T}{\pi M}} , \quad (2.14)$$

where γ is the desorption coefficient (desorbed gas molecules per electron), R is the molar gas constant, T is the temperature, and M is the molar mass.

The SSEEA model assumes that the final breakdown occurs in the desorbed gas above the surface. Several delay times are involved in this final phase of breakdown (i.e., the gas above the surface must have a sufficient density for ionization and the gas molecules must be ionized prior to breakdown). These delay times are highly dependent on each other, and they can not easily be

estimated since the profile of the desorbed gas above the surface is not known. In the desorbed gas, the mean free path length, λ , of the electron above the surface is a function of the density and the momentum transfer cross section, σ_e . The gas desorption delay time, τ_g , is here estimated as the time for the gas density to reach one electron mean free path length, λ ,

$$\tau_g = \frac{\lambda}{v_{th}} = \frac{1}{n \sigma_e v_{th}} . \quad (2.15)$$

Note that the breakdown is likely to occur more quickly since ionization of the gas might start at lower gas densities.

The probability that a desorbed gas molecule is ionized while drifting through the saturated secondary electron emission avalanche is [17]

$$P = \frac{\sigma_i I_x}{e v_{th}} , \quad (2.16)$$

where σ_i is the effective ionization cross section of the desorbed gas.

The parameters of a dielectric surface flashover on Lexan at a gap distance of $d_g = 1$ cm and an applied electric field of $E_x = 20$ kV/cm have been estimated in Table 2.1. For the calculations, an average electron emission energy of $A_0 = 1$ eV is assumed. The average impact electron energy, A_1 , of 45 eV for Lexan was measured by Adamson [18] with an accuracy of 20%. The gas molecule desorption coefficient, γ , is the variable of the SSEEA model with the largest uncertainty (i.e., estimates ranges from 0.1 to 200 [5, 17, 19]). For the parameters given in Table 2.1, a desorption coefficient of $\gamma = 100$ has been used. The momentum transfer cross section $\sigma_e = 10^{-16}$ cm² and the effective ionization cross section, σ_i , is on the order of 10^{-17} cm² [20].

2.2.2. The influence of an external magnetic field on the trajectory of the electrons

The influence of external magnetic fields on the dielectric surface flashover voltage in vacuum has been investigated by Lehr and Korzekwa [21]. With the proper orientation of the magnetic field, increases in the breakdown voltage of up to a factor of 3 with a magnetic flux density of 700 mT have been observed. The first results on the magnetic field influence on the pre-flashover current were published by Hegeler et al. [15] (see Figure 4.3 in section 4.1).

The motion of the free electrons above the insulator surface is described by the Lorentz force, equation (2.1). Considering a uniform electric field $\mathbf{E} = \{-E_x, E_y, 0\}$ and a homogeneous magnetic flux density $\mathbf{B} = \{0, 0, B_z\}$, the components of the particle acceleration are given by

$$\begin{aligned}\frac{dv_x}{dt} &= \frac{e}{m} (E_x - v_y B_z) \\ \frac{dv_y}{dt} &= -\frac{e}{m} (E_y - v_x B_z),\end{aligned}\tag{2.17}$$

Table 2.1. Surface flashover parameters for Lexan with a gap distance of 1 cm and an applied breakdown field of 20 kV/cm.

ratio of the electric fields	$(E_y/E_x) = 0.21$
lateral range of the electron trajectory (average)	$s_x = 22 \mu\text{m}$
height of the electron trajectory	$s_y = 2 \mu\text{m}$
charge density	$\sigma_+ = \sigma_- = 7.6 \cdot 10^{-10} \text{ A s/cm}^2$
saturated surface current per unit channel width	$I_x = 0.2 \text{ A/cm}$
average electron velocity in x-direction	$v_e = 2.8 \cdot 10^8 \text{ cm/s}$
electron current density incident on the surface	$J_y = 95 \text{ A/cm}^2$
density of desorbed gas molecules	$n = 6 \cdot 10^{17} \text{ cm}^{-3}$ (p = 20 torr)
average thermal velocity of the desorbed gas (N ₂)	$v_{th} = 480 \text{ m/s}$
ionization probability of the gas while drifting through the saturated surface current	$P = 3 \cdot 10^{-4}$
drift time of the gas molecules (maximum)	$\tau_g = 300 \text{ ns}$
electron transit time through the gap	$\tau_e = d_g/v_e = 3.6 \text{ ns}$

using the rectangular coordinate system shown in Figure 2.3. With the boundary conditions given in equation (2.3), the velocity and trajectory of the electrons are given by

$$\begin{aligned}v_x &= -\frac{E_y}{B_z} \cos(\omega t) - \left[v_0 - \frac{E_x}{B_z} \right] \sin(\omega t) + \frac{E_y}{B_z} \\ v_y &= \left[v_0 - \frac{E_x}{B_z} \right] \cos(\omega t) - \frac{E_y}{B_z} \sin(\omega t) + \frac{E_x}{B_z} \\ s_x &= -\frac{E_y}{\omega B_z} \sin(\omega t) + \frac{1}{\omega} \left[v_0 - \frac{E_x}{B_z} \right] (\cos(\omega t) - 1) + \frac{E_y}{B_z} t \\ s_y &= \frac{1}{\omega} \left[v_0 - \frac{E_x}{B_z} \right] \sin(\omega t) + \frac{E_y}{\omega B_z} (\cos(\omega t) - 1) + \frac{E_x}{B_z} t,\end{aligned}\tag{2.18}$$

with the electron cyclotron frequency

$$\omega = \frac{e B_z}{m} . \quad (2.19)$$

Bergeron [22] calculated the critical magnetic flux density, B_c , required to lift off the saturated avalanche from the dielectric surface:

$$B_c = \frac{1.6 \cdot v_0}{v_1^2} E_x , \quad (2.20)$$

where v_0 and v_1 are the velocities associated with the average electron emission energy, A_0 , and the average electron impact energy A_1 , respectively. The magnetic flashover inhibition concept is shown in Figure 2.4. In Bergeron's equation, the space charge due to the electron avalanche was included and an isotropic distribution of the emission was taken into account. For an applied electric field of $E_x = 20$ kV/cm, an electron emission energy of $A_0 = 1$ eV, and an impact electron energy of $A_1 = 45$ eV, the critical magnetic flux density is 120 mT.

Fig. 2.4. Trajectory of an electron on the insulator: (a) $B_z < B_c$ and (b) $B_z > B_c$ [22].

Lehr and Korzekwa also investigated the case in which the $E \times B$ vector points into the surface. For small magnetic field strengths (on the order of 100 mT), the flashover decreases compared with the breakdown voltage at $B_z = 0$. Since it can be assumed that the number of electrons which strike the insulator surface is increased, the number of electrons necessary to start a breakdown is reached at a lower flashover voltage. When the magnetic flux density is further increased (up to 700 mT), the breakdown voltage increases again, but it never reaches voltage amplitudes comparable to the case where the $E \times B$ vector points away from the surface. A strong $E \times B$ drift into the surface can cause a decrease in the mean free path length of the electrons, and thus, a decrease of the following items: the impact energy of the electron striking the dielectric

surface, the secondary emission of electrons, and the probability of ionization of the desorbed surface gas.

2.3. Limitation of the SSEEA Model

The SSEEA model is a very simple zero-dimensional model (e.g., in the formulation of Pillai and Hackam [17], without a dependence on the coordinate between anode and cathode) which can be used to describe the dielectric surface flashover results quantitatively. The model could be improved by considering the following points:

1. Nonuniform surface charge density: The proposed starting mechanism of electron field emission at the cathode, as well as the processes in the developing avalanche head [23], are expected to lead to a nonuniform surface charge density. On the time scale of several tens to a few hundreds of nanoseconds, during which the discharge develops, the positive surface charge consists mainly of immobile ions. For the saturated avalanche, a surface charge density, fixed in time but dependent on the coordinate between cathode and anode, should be considered. Furthermore, the influence of the electron volume charge density above the surface is expected to produce modifications of the saturated avalanche parameters, as discussed by Bergeron [22] in relation to magnetic field effects. Comparing his computer simulations with a self-consistent electron density above the surface with Pillai-Hackam's approximation of a localized electron density above the surface, he found differences in the critical magnetic field amplitude of a factor of two. Since the emerging two-dimensional model cannot be treated analytically, a two-dimensional computer simulation is suggested.
2. Unknown secondary emission parameters: The parameters A_0 and A_1 , as well as the energy and angular distribution of emitted secondary electrons, are virtually unknown, especially their variation as a function of material. More detailed measurements of these parameters would help to understand the build-up of the saturated avalanche more quantitatively.
3. Gas desorption: It is generally accepted that the final discharge develops in the gas desorbed from the insulator surface. Discrepancies in the electron induced desorption rate cover two orders of magnitude. Some detailed measurements of the desorption process, such as high resolution momentum measurements or a direct time resolved measurement of the gas density above the surface, would be essential to further understanding of this process.

2.3.1. The effects of an inhomogeneous electric field in the dielectric gap

In many applications, the electric breakdown field throughout the gap is not constant. This experiment uses two cathode shapes, a “field enhanced” and a “smooth” electrode (described in section 3.2.3). In order to simplify the estimation of the electric field along the centerline of the dielectric gap, the electrodes are replaced by two solid spheres with a diameter of 0.5" and 0.02" for the “smooth” and “field enhanced” electrode, respectively. A program which is listed in the appendix is used to plot the electric field. The electric field was normalized and plotted as $E(x)/E_{avg}$, where $E_{avg} = V_{applied}/d_g$ (see Figure 2.5).

Fig. 2.5. Estimation of the electric field along the centerline of the dielectric gap. The normalized gap distance is measured from the cathode to the anode. The cathode consists of (a) a “field enhanced” electrode and (b) a “smooth” electrode. For both cases, a “smooth” electrode is used for the anode, with a gap distance of 2 cm. The geometric field enhancement due to the dielectric was not taken into account.

With the field enhanced cathode, the electric field amplitude varies by more than two orders of magnitude throughout the gap (see Figure 2.5a). At the cathode, the field enhancement factor is on the order of 70 (i.e., not including the microstructure of the electrode which may lead to enhancement factors of several hundreds [24]). The minimum electric field amplitude of approximately 6% of the average electric field occurs at a normalized gap distance of 62% away from the cathode, and more than 75% of the gap has an electric field amplitude of less than 20% of the average field. It can be assumed that the surface charge amplitude is not constant along the centerline of the gap. Near the cathode, where the electric field amplitude is much larger than the average electric field, it is likely to find the highest positive charge density on the dielectric surface. Following the centerline from the cathode towards the middle of the gap, the positive surface charge should decrease. It is presumed that the surface of the dielectric will also be charged

negatively at low breakdown voltages in the area of the gap where the minimum electric field is located. At an average electric field of 10 kV/cm, the electrons have to be accelerated for 800 μm in order to gain 50 eV (i.e., the required impact energy for secondary electron emission is roughly 45 eV). Since the lateral hopping distance is very large and the electron impact energy is relatively small at low electric fields, it is estimated that the existence of a negative charge density is more likely than a positive surface charge. In the region close to the anode, the surface of the insulator can be either positively or negatively charged (i.e., it is not known to the author if the electrons will gain sufficient energies to produce secondary electrons at low breakdown electric fields).

By using smooth electrodes (see Figure 2.5b), it is possible to obtain a positive charge density on the dielectric surface throughout the gap. Although the amplitude of the surface charge will not be constant throughout the gap, it is believed that electrons have adequate energy to produce secondary electrons in the middle of the gap, and thus, positive surface charge on the insulator.

2.4. Ultraviolet-Induced Dielectric Surface Flashover

Enloe and Gilgenbach [7] have investigated UV-laser-induced dielectric surface flashover on several polymers. The dielectric was illuminated by a 60 ns UV radiation pulse from an excimer laser (KrF) with a wavelength of 249 nm and a fluence of 10 to 150 mJ/cm^2 (0.4 to 6 MW/cm^2). They measured the UV induced breakdown on insulators with an angle of $+45^\circ$ and -45° (see Figure 2.6). Note that the flashover strength is at a minimum for the planar insulator ($\phi = 0^\circ$) and has two maxima at $\phi = \pm 45^\circ$ [25]. The flashover potential in vacuum is typically greater for an insulator angle of $+45^\circ$, compared to $\phi = -45^\circ$.

Fig. 2.6. Insulator geometry with angles ϕ of: (a) 0° , (b) $+45^\circ$, and (c) -45° .

They measured UV induced electron emission from the insulator and hypothesized that the photoelectron emission is a two-step photoionization process. The bandgap energy is approximately 10 eV for most polymers, and photons with a wavelength of 249 nm have an energy

of 5 eV. Therefore, any photoelectron emission must take place via a multiphoton interaction. Enloe and Gilgenbach [7] concluded that

Ultraviolet-induced flashover over polymeric insulators in vacuum depends on the ultraviolet fluence incident on the insulator surface. The negative (unconventional) configuration is superior in ultraviolet tolerance to the positive-angle (conventional) configuration by approximately a factor of 2 in fluence. Insulating materials with high dielectric constants and low secondary electron emission coefficients exhibit superior ultraviolet tolerance. A model of ultraviolet-induced insulator flashover based on induced charging of the insulator surface is sufficient to explain the observed phenomena. The ultra-violet fluences required to initiate flashover are sufficiently low that the contribution of neutral particle emission to the initiation of flashover may be disregarded, except perhaps at very low field stress (10 kV/cm) where the critical fluences required to initiate flashover are correspondingly higher. (p. 388)

UV induced electron emission from an insulator is not well understood. Photoelectron emission from the dielectric surface might also be related to impurities and surface states of the insulator [26] instead of a two-photon ionization process.

2.4.1. Estimation of the UV induced electron space charge above the insulator

Independent of the electron emission process, it is certain that electrons are emitted from the dielectric surface by UV photons. A schematic illustration of the expected processes is shown in Figure 2.7. Electrons, emitted by UV photons, will drift away from the surface with an initial velocity, $v(y_0)$. Without an external potential, an electron cloud should be formed above the surface at a distance, y_1 . Measurements of the photoemission current (see section 4.2.1) showed that at first a significant electron current is released from the surface which, after some time, is drastically reduced. This effect indicates that the supply of photoelectrons from the dielectric surface is limited (i.e., for UV photons with energies on the order of 3 to 6 eV). When electrons are photoemitted from the insulator, an electric field normal to the surface is built up due to the positive surface charge and the electron space charge (see Figure 2.7). Newly photoemitted electrons are decelerated by this electric field and they are more likely to fall back onto the insulator. Electrons which hit the surface can be reemitted by UV photons.

In order to estimate the distance of the electron space charge from the dielectric surface, the steady state photoemission of the electrons is simplified. All electrons are emitted perpendicular to the surface with a constant energy, eV_0 . The space charge is formed at a distance, y_1 , where the electrons have zero velocity. The result of this space charge limitation is that the electric field at the distance, y_1 , is zero.

Fig. 2.7. Schematic illustration of the UV induced electron emission from a insulator.

The system can be described by Poisson's equation

$$\frac{d^2 V(y)}{dy^2} = -\frac{\rho(y)}{\epsilon_0} \quad (2.21)$$

and with the boundary conditions of

$$\begin{aligned} V(y_0) &= V_0 \\ V(y_1) &= 0 \\ E(y_1) &= -\left. \frac{dV(y)}{dy} \right|_{y=y_1} = 0, \end{aligned} \quad (2.22)$$

where $V(y)$ is the potential, $E(y)$ is the electric field, $\rho(y)$ is the particle charge, and ϵ_0 is the permittivity for vacuum. The kinetic energy of the electrons is given by

$$\frac{1}{2} m v(y)^2 = e V(y), \quad (2.23)$$

and the steady state current density, J , of the photoelectrons can be written as

$$J = \rho(y) v(y), \quad (2.24)$$

with the electron velocity, $v(y)$, and the electron mass, m . With equations (2.23) and (2.24), the equation 2.21 can be rewritten as

$$\frac{d^2 V(y)}{dy^2} = -\frac{J}{\epsilon_0} \sqrt{\frac{m}{2eV(y)}}. \quad (2.25)$$

By a double integration and with the boundary conditions given in equation (2.22), the potential, $V(y)$, is given by

$$V(y) = \left(-\frac{3}{2} \sqrt{\frac{J}{\epsilon_0}} \sqrt{\frac{m}{2e}} y + (V_0)^{\frac{3}{4}} \right)^{\frac{4}{3}}, \quad (2.26)$$

and the space charge distance, y_1 , is found as:

$$y_1 = \frac{2}{3} \sqrt{\frac{\epsilon_0}{J}} \sqrt{\frac{2e}{m}} (V_0)^{\frac{3}{4}}. \quad (2.27)$$

A photoemission current from copper of approximately 200 nA was measured (see section 3.3.2) for the solar simulator used in the experimental setup. The irradiated area had a diameter on the order of 5 mm, which lead to a current density of 10^{-2} A/m^2 . In order to estimate the distance, y_1 , in equation (2.27), it is assumed electrons are emitted from the surface with an energy of 1 eV, at a steady state current density of $J = 10^{-2} \text{ A/m}^2$. For this case, the electron space charge is located approximately 1.5 cm above the surface.

In reality, the photoemission of electrons is more complex. Electrons will be emitted with a distribution of velocity and angles to the surface, and the current density is a function of the distance normal to the surface (compare equation (2.24)). In addition, in the experimental test chamber, some photoelectrons will be collected by the electrodes or by the grounded coaxial outer conductor which is placed at a distance of either 14 or 3.8 cm from the test sample (see section 4.2.7). Therefore, it is expected that the electron space charge density above the dielectric surface is significantly lower than the positive charge density on the surface. These effects will decrease the space charge distance, y_1 , in equation (2.27). It is more likely that the electron space charge will be on the order of one millimeter above the surface.

2.4.2. Electron trajectory for the UV induced insulator flashover with an external magnetic field

It is expected that the positive charge density on the dielectric surface is enhanced when the insulator is irradiated with UV. Therefore, during the secondary electron avalanche, the electric field normal to the surface, E_y , should increase compared to the case without UV (see equation 2.8). The expected electron trajectory near the cathode (area of UV radiation) with and without an external magnetic field is shown in Figure 2.8. The values of the electric and the magnetic field are similar to the cases used for the measurements which are shown in section 4.2.6. At an electric field of 4.6 kV/cm, a magnetic flux density of only 26 mT (i.e., $B_c = 27 \text{ mT}$, from equation 2.20) should be sufficient to lift up the electrons, and therefore, eliminate the surface flashover at this gap voltage (see Figure 2.8a). It is assumed that UV irradiation increases the electric field, E_y , from 21% of E_x (from Table 2.1) to 23% of E_x . Under these conditions, a magnetic field of $B = 30 \text{ mT}$ will not be adequate to prevent the electrons from hitting the surface (see Figure 2.8c). With UV irradiation and without any magnetic fields, the electrons should gain an impact energy of 40 eV, close to the threshold energy to emit secondary electrons from the insulator. With an $E \times B$

drift away from the surface, electrons have an impact energy of 110 eV which is reduced to 27 eV with an $E \times B$ drift into the surface. Measurements with UV illumination near or on the cathode (see section 4.2.6) showed no major change with an $E \times B$ drift away from the surface, compared to the case with $B = 0$, but the flashover potential increased significantly for the case with an $E \times B$ drift into the surface. Although the surface charge density during the saturated secondary electron emission avalanche has not been measured, the measurements with an external magnetic field suggests that the positive surface charge amplitude is slightly increased (i.e., otherwise, the electrons are lifted off the surface with $B = 30$ mT).

Fig. 2.8. Estimated electron trajectory near the cathode for the UV induced insulator surface flashover. The electron is emitted perpendicular to the surface with an energy of 1 eV, and the electric field parallel to the surface is $E_x = 4.6$ kV/cm (i.e., average electric field of 2 kV/cm with a field enhancement factor of 2.3). The electric field normal to the surface is 21% of E_x (without UV) and 23% of E_x (with UV, assumed): (a) without UV and with an $E \times B$ drift away from the surface ($B = 26$ mT), (b) with UV at $B = 0$, (c) with UV and an $E \times B$ drift away from the surface ($B = 30$ mT), and (d) with UV and an $E \times B$ drift into the surface ($B = 30$ mT).

2.5. Plasma-Induced Dielectric Surface Flashover

In recent years, surface flashover on insulators in a space plasma has been investigated. The SPEAR (Space Power Experiments Aboard Rockets) project [27] was the largest research program with emphasis of the low earth orbit environment. For this research project, some experimental surface flashover tests were performed and computer simulations were written in order to predict the plasma sheath current in relation to the applied voltage of the experimental apparatus. Although the low earth orbit plasma is quasineutral, a charged particle model (ions and electrons) was used for the computer code (i.e., with an applied voltage, no quasineutral plasma exists near the experimental apparatus).

It was expected that voltage hold-off time at the dielectric surface is inversely proportional to the plasma current (i.e., if the plasma induced discharge resulted from electric field modification by plasma charge collected on the dielectric surface). It was found that [27]

High-voltage standoff capability of insulators improved with conditioning. The conditioning process is understood qualitatively as resulting from changes in the surface properties, such as removal of surface contaminants and gas desorption. The theory developed for the SPEAR program relates high-voltage standoff to surface desorption coefficients, and conditioning leakage currents to quantity of desorbed gas. (p. 9-25)

2.5.1. Estimation of the plasma drift velocity from the ECR plasma source into the test chamber

Argon plasma with a density of approximately 10^{12} cm^{-3} is produced in a stainless steel tube. Part of the plasma drifts along the magnetic fields lines toward the electric test chamber (i.e., the electrical test chamber is the volume inside of the outer conductor mesh). The plasma stream diffuses and most of the plasma is collected by the walls of the tube and by the chamber (i.e., near the test sample, a “plasma” density on the order of 10^6 cm^{-3} was measured as shown in section 3.3.1). The electron plasma temperature is roughly 5 eV. The plasma source is turned on at least 10 minutes before any voltage is applied in the test chamber (i.e., all conductors are grounded).

The dielectric surface flashover normally occurs within 200 ns after the voltage pulse is applied to the test gap. Electrons, which are located in the electrical test chamber, will drift towards the positive electrodes within a few nanoseconds. The plasma expansion velocity at the outer conductor mesh should be in the order of the ion thermal velocity. Computer simulations of the plasma expansion into a vacuum showed a plasma drift velocity, v_p , of [28]

$$v_p = 3 \sqrt{\frac{kT}{m_i}} , \quad (2.28)$$

where kT is the thermal energy and m_i is the mass of the ion. Assuming an ion temperature similar to the temperature of the electrons (worst case), the plasma will expand with an average velocity on the order of 10^4 m/s. Consequently, no electrons outside the electrical test chamber should influence the insulator breakdown when a gap voltage is applied, since they will not drift through the outer conductor mesh, towards the test sample, within 200 ns. Since the vacuum chamber wall and the outer conductor mesh of the electrical test chamber are grounded, the plasma is not accelerated by an external electric field outside of the electrical chamber.

2.5.2. Electron trajectory for the plasma induced insulator flashover

As for the case with UV irradiation, an external magnetic field is used to alter the electron trajectory during the dielectric breakdown initiation with a plasma background. Figure 2.9 shows the expected electron trajectory during the saturated electron avalanche at an average electric field of 18 kV/cm. It is assumed that during the saturated electron avalanche the amplitude of the electric field, E_y , normal to the surface is slightly lower for the case with a plasma background. The “plasma” electrons have a higher drift velocity than the “plasma” ions, and the dielectric might have more negative charge than positive charge on its surface prior to the electron avalanche. Therefore, it takes more time to generate a “homogeneous” positive surface charge throughout the gap. Dielectric surface breakdown measurements with an $E \times B$ drift away from the surface showed a higher insulation effect with a plasma background compared to the case without plasma. The effect of the $E \times B$ drift away from the surface is enhanced, for example, if the charge density of the surface is less positive compared to the surface charge during a surface flashover without plasma.

For the calculations of the electron trajectories (see equation 2.18), an electric field of $E_y = 21\%$ of E_x (from equation 2.8) is used for the case without a plasma. With a plasma background, an electric field of $E_y = 17\%$ of E_x is assumed. For all four cases, the electron impact energy is at least 45 eV (see Figures 2.9a-d). With an $E \times B$ drift away from the surface, the lateral hopping distance is increased. Measurements showed that the $E \times B$ drift delays the exponential current rise (i.e., the current is still rising linearly). The exponential current rise is associated with discharge development in the desorbed gas. If the lateral hopping distance is increased, gas desorption at the dielectric surface might be reduced which would delay the final breakdown.

(a)

(b)

(c)

(d)

Fig. 2.9. Estimated electron trajectory for the plasma induced insulator surface flashover. The electron is emitted perpendicular to the surface with an energy of 1 eV, and the electric field parallel to the surface is $E_x = 18$ kV/cm. The electric field normal to the surface is 21% of E_x (without UV) and 19% of E_x (with plasma, assumed): (a) without plasma at $B = 0$, (b) without plasma and with an $E \times B$ drift away from the surface ($B = 30$ mT), (c) with plasma and an $E \times B$ drift away from the surface ($B = 30$ mT), and (d) with plasma and an $E \times B$ drift into the surface ($B = 30$ mT).

CHAPTER III

EXPERIMENTAL APPARATUS AND DIAGNOSTIC SENSORS

The purpose of this experiment is to get a better understanding of the mechanisms and processes involved in the initiation of the dielectric breakdown in a plasma and UV radiation environment. Consequently, it is of special interest to investigate the early phase of the dielectric breakdown with high temporal and high amplitude resolution. Therefore, this research requires a low inductance electrical test apparatus combined with fast and sensitive electrical sensors. This chapter outlines the major subsystems of the experimental apparatus and explains the diagnostic sensors used in obtaining the experimental results.

3.1. High-Voltage Electrical System

In order to achieve a system with low stray reactance, the experimental apparatus has been designed and constructed as a coaxial system with a closely matched impedance (see Figure 3.1). Two modes, a dc-charged mode and a pulse charged mode, are used with this system.

In the dc-charged mode, an RG-19 transmission line with an impedance of $52\ \Omega$ and one-way transit time of approximately 135 ns is charged by a 100 kV dc-voltage supply through a high-voltage resistor, R_c , of $200\ M\Omega$. This charging cable is directly connected to the anode of the dielectric test gap. The voltage is manually increased in small increments until a current with an amplitude of more than 30 mA is detected on the load line which will trigger the single-shot data acquisition system.

In the pulse-charge mode, a transmission line with a one-way transit time of approximately 100 ns is dc-charged through a resistor of $500\ M\Omega$ to voltages of up to 70 kV. During the cable charging, a Physics International (PI) 670 spark gap with an electrode separation of 1 cm is pressurized to 50 psi with nitrogen or with a combination of nitrogen and sulfur hexafluoride (SF_6). The spark gap, which has been built into the coaxial geometry, operates in a pressure-triggered self-breakdown mode, e.g., the spark gap switch closes when the applied gas pressure is released. The voltage switching range of the spark gap was increased by venting the spark gap gas into a 17 liter chamber which was evacuated to a pressure of less than 1 Torr. The spark gap generated a voltage pulse with a risetime of 20 ns at 20 kV and 6 ns at 70 kV. A typical rise of a voltage pulse is shown in Figure 3.2. A $200\ M\Omega$ resistor, R_b , is connected between the spark gap and ground to insure reliable triggering of the spark gap and to safely drain residual charge from the intermediate coaxial line. A voltage pulse of 200 ns duration with an amplitude of half the charge voltage is generated by closing the spark gap. The pulse travels through a transmission line with a one-way transit time of approximately 135 ns to the test gap. The voltage amplitude doubles at the

test gap until flashover occurs. The system is terminated in a shorted transmission line with a one-way transit time of 145 ns. The pulsed-charged mode is necessary when a plasma environment is applied to the test chamber.

Fig. 3.1. Experimental apparatus with its coaxial geometry showing both modes of operation: (a) dc-charged mode and (b) pulse-charged mode.

Fig. 3.2. Risetime of the voltage pulse which is generated by the spark gap with a charge voltage of 50 kV. The voltage pulse produced has a duration of approximately 200 ns and an amplitude of 25 kV.

3.2. Test Configuration

This section provides an overview of the vacuum system, the electrical test chamber, the electrode arrangement on the test sample, and the external magnetic field implementation. In addition, the preparation of the dielectric sample is described.

3.2.1. Vacuum chamber and pumping system

A stainless steel bell jar, with a 50 cm base diameter and a height of 75 cm is utilized as an experimental vacuum chamber. It has six 4" ports and two 6" ports which are used for windows, optical diagnostics, UV illumination, high voltage feedthroughs, and connection to the plasma source. The base of the bell jar contains twelve additional 1³/₈" ports which are used in part for the vacuum gauges, a backfill gas valve, and electrical feedthroughs. The pump system uses a compact Sargent Welch roughing pump, model number 8851, with a free air displacement of 510 liters/minute to an ultimate pressure of $6 \cdot 10^{-4}$ Torr, and a Sargent Welch turbo-molecular high vacuum pump, model number 3106S, with a pumping speed of 400 liters/second for nitrogen and an ultimate pressure of 10^{-8} Torr. The vacuum chamber can be separated from the vacuum pump by a 160 ISO-F pneumatic gate valve. The system pressure is monitored using standard sensors: two thermocouple gauges, one cold cathode gauge, and one hot filament ion gauge (hot cathode).

3.2.2. Electrical test chamber

The test chamber has been constructed with a coaxial geometry. The inner conductor consists of a brass or copper rod, and a copper mesh with 50% transmittance is utilized as an outer conductor. An impedance of 52Ω throughout the test chamber is desired; on the other hand, the electrical test chamber should have the biggest possible volume to assure a presence of a large number of charged particle (from the plasma) near the test sample (i.e., the outer conductor is grounded at all times). The outer conductor has a diameter of 11.75" and a length of 13.5", and the inner conductor is identical for the high voltage charging side and for the load side. The internal inductance of the test chamber is on the order of 100 nH. This inductance will limit the breakdown current to a maximum rise of 100 A/ns, for a breakdown voltage of 10 kV.

3.2.3. Electrode and insulator arrangement

This experiment uses planar dielectric samples which have the advantage of a relatively localized arc channel when breakdown occurs. The test sample holder with the electrode arrangements is shown in Figure 3.3. Measurements are taken with two cathodes: a "smooth" semi-spherical electrode with a radius of 0.25" and a "field enhanced" electrode with a 0.02" wide tip at the front. A "smooth" electrode is used as the anode in both cases. All electrodes have an

angular cut of 2° to assure good dielectric surface contact at the tip of the electrode. In addition, the dielectric sample is pressed underneath the electrodes by Nylon screws. A threaded G-10 rod is used to accurately set the gap distance in the range from 0.5 to 2 cm.

Fig. 3.3. Electrode arrangement on the test sample with (a) the complete test sample holder, (b) “smooth” electrode, and (c) “field enhanced” electrode.

3.2.4. Dielectric test sample preparation

The samples have been cleaned with deionized (DI) water or with methanol and then treated in an ultrasonic cleaner. The surface area of the samples is 3" by 2" and they are $\frac{1}{8}$ " and $\frac{1}{4}$ " thick for Pyrex and Lexan, respectively. All samples have been kept at a pressure of less than 10^{-5} Torr for at least 18 hours prior to breakdown testing.

Lexan: The paper is removed from the surface and the sample is cleaned with DI water. The surface is then treated with wet 600 grit silicon carbide sandpaper, using DI water, in order to clean any the glue from the surface. After this procedure, the sample is placed in an ultrasonic cleaner with DI water for 15 minutes.

Pyrex: The Pyrex sample is cleaned with methanol and is also treated in an ultrasonic cleaner with DI water for 15 minutes.

3.2.5. Magnetic field arrangement

Rare earth Neodymium magnets are implanted into the dielectric test sample as shown in Figure 3.4. On the backside of the Lexan test sample, two parallel slots are machined across the entire width of the sample. The grooves are 1" apart, measured between the centerlines of the

slots, and each groove is 0.18" wide and 0.15" deep. The 35 NE magnets have the form of a cube with a side length of 0.175". An array of 5 rare earth magnets are mounted with Super Glue in each of the two slots below the cathode. This arrangement produces a homogeneous magnetic field of approximately 30 mT parallel to the surface and perpendicular to the electric field which is applied between the two electrodes on the test sample. The magnetic flux density in relation to the sample surface is given in Table 3.1. The maximum magnetic field of $B = 40$ mT is found inside of the insulator at a normal distance of $z = -3$ mm to the surface.

Fig. 3.4. Dielectric test sample with implanted rare earth magnets: (a) side view and (b) top view of the sample.

Table 3.1. The magnetic flux density in relation to the sample surface, measured normal to the surface at the centerline of the test gap.

Distance normal to the surface [mm]	-3	0	2	5	7.5	10
Magnetic flux density [mT]	40	30	26	15	6.5	2

3.3. Low Earth Orbit Environment Simulator

Plasma and UV illumination is used to simulate the space environment. The plasma is generated by an Electron Cyclotron Resonance (ECR) plasma source and the UV radiation originates from a UV enhanced Xenon arc lamp. The operation and limitations of both systems are described in the following sections.

3.3.1. Plasma source

The ECR Argon plasma source is seen in Figure 3.5. A 2M137-M14 Magnetron, operating at a frequency of 2.46 GHz and an r-f output power up to 1.2 kW, is used as a microwave source. Four solenoid magnets provide the required magnetic flux density of 0.0875 Tesla for which the electron cyclotron frequency roughly equals the microwave frequency. Argon gas with a pressure

of $5 \cdot 10^{-4}$ torr is released into the chamber. Argon plasma with a density of approximately 10^{12} cm^{-3} is produced and drifts through a 1 m long, 10 cm diameter, stainless steel tube into the test chamber. At the test gap, the plasma electron temperature and density has been measured with a Langmuir probe and found to be approximately 3 to 5 eV and 10^4 to 10^6 cm^{-3} , depending on the applied microwave power. The magnetic field from the solenoid magnets is attenuated outside of the ECR plasma source with steel endplates and shorting rods in order to minimize the magnetic flux density in the test chamber. At the test gap, the magnetic field is found to be 10^{-3} Tesla.

Fig. 3.5. The electron cyclotron resonance plasma source.

Parameters of the plasma: The electron cyclotron frequency is given by

$$f_c = \frac{|q| B}{2 \pi m_e} , \quad (3.1)$$

where q is the electron charge, B is the magnetic flux density, and m_e is the electron mass. The electron cyclotron frequency is 2.45 GHz for a magnetic flux density of 87.5 mT and is reduced to approximately 28 MHz near the test sample (where $B = 1 \text{ mT}$).

The gyro radius can be written as

$$r_L = \frac{m v_e}{|q| B} , \quad (3.2)$$

with the electron thermal velocity, v_e , which can be expressed as

$$v_e = \sqrt{\frac{T_e}{m}}, \quad (3.3)$$

where T_e is the thermal energy of the electron. In the test chamber, near the dielectric test sample, electrons with an energy of 5 eV have a gyro radius of 5 mm. Assuming that the ions have the same temperature as the electrons, their radius would be more than 1 m. The Debye length of the 5 eV plasma near the test sample is on the order of 2 to 20 cm for a plasma density of 10^6 cm^{-3} and 10^4 cm^{-3} , respectively.

Limitations of the plasma: The plasma data show that the gyroradius of the ions is larger than the vacuum chamber and that the Debye length is on the same order as the electrode gap on the dielectric sample. Therefore, near the test sample, no “quasineutral” plasma exists, but a collective of charged particles, electrons and ions, are found.

3.3.2. Solar simulator

An Oriel 150 W dc Xenon arc lamp is used to illuminate the dielectric test sample with UV irradiation. The main components of the solar simulator are the lamp power supply, the lamp housing with a fused silica lens and a rear reflector, and the 150 W Xenon, UV enhanced, arc lamp, model number 6254. The lamp has an irradiance of $0.1 \mu\text{W cm}^{-2} \text{ nm}^{-1}$ at a wavelength of 200 nm and $0.8 \mu\text{W cm}^{-2} \text{ nm}^{-1}$ at 300 nm, measured at a distance of 50 cm without focusing lenses [29]. For a comparison, the power density, the photon flux, and photon energy of the solar spectrum is given in Table 3.2.

Table 3.2 The power density, the photon flux, and photon energy of the solar spectrum for wavelengths of 200, 250, and 300 nm [30].

Wavelength [nm]	Solar power density [$\mu\text{W cm}^{-2} \text{ nm}^{-1}$]	Photon flux [photons $\text{cm}^{-2} \text{ s}^{-1} \text{ nm}^{-1}$]	Photon energy [eV]
200	2	$2 \cdot 10^{12}$	6.20
250	5.5	$7 \cdot 10^{12}$	5.97
300	66	10^{14}	4.14

Testing of the UV lamp: Indirect photon flux measurements of the solar simulator have been performed. In the experimental setup, the test area is illuminated from two directions: (a) through a side port of the vacuum chamber directly onto the sample, and (b) through a top port of the

chamber with an additional fused silica lens and an Al and MgF_2 coated mirror with 80% reflectance at 200 nm. In both cases, a $\frac{1}{8}$ " thick quartz plate with a diameter of 3" is used as the port window. Figure 3.6 shows the geometry of the test sample which was irradiated with UV. One electrode is connected to the copper plate which has a negative potential under normal operation (i.e., it then acts as an electron emission source). The other electrode is insulated from the Cu plate by a $\frac{5}{1000}$ " Mylar foil. This electrode is connected to a current meter, Keithley 610C, which is then grounded. The gap distance between the two electrodes is 2 cm. Three UV irradiation patterns are tested and the positions of the estimated focal point are also shown in Figure 3.6. The results of the UV illumination test measurements are given in the Figure 3.7

Fig. 3.6. Configuration of the test sample for the UV irradiation measurements with the three UV illumination patterns: (I) near the cathode, (II) between the two brass electrodes, and (III) at the anode.

A maximum electron emission current of 300 nA is found when UV illumination is applied from the side port of the vacuum chamber. The photo current is reduced to approximately 30% when the test sample is irradiated from the top port. This result is expected since the UV light is attenuated by the additional fused silica lens and the mirror. Not only the amplitude of the UV irradiation is attenuated, but also fewer short-wavelength photons hit the test sample when UV illumination is applied from the top port. This effect can be seen from the photo emission current which saturates at lower voltages (shown in Figure 3.7a) compared to the case when UV is applied from the side port (seen in Figure 3.7b). Photons with a wavelength of less than 290 nm are able to release electrons from the Cu plate. With an estimated UV irradiation area of $\frac{1}{2} \text{ cm}^2$ and an assumed photon emission efficiency of 10%, an electron current of 300 nA results from a photon flux of $4 \cdot 10^{13} \text{ photons cm}^{-2} \text{ s}^{-1} \text{ nm}^{-1}$, which is approximately on the same order of magnitude as the solar radiation.

Fig. 3.7. Photo emission current from the Cu plate: (a) UV illumination from the top port, (b) and (c) UV irradiation from the side port. (a) and (b) operate with the UV lamp at 150 W and irradiates the sample from all three positions (see Figure 3.6). (c) UV illumination near the cathode, position I, at 40 W, 80 W, 120 W, and 150 W (lamp input power) for i, ii, iii, and iv, respectively. A negative photo emission current indicates electron emission from the Cu plate.

Experimental limitations with the solar simulator: UV illumination from the side port of the vacuum chamber indicates a good simulation of the condition in the LEO. Tests have shown that the number of photoelectrons is maximized when the sample is placed perpendicular to incoming UV photons. The position of the sample allows dielectric breakdown measurements with and without an external magnetic field. Measurements with a plasma background or with an x-ray sensor could not be performed under this sample angle due to the limited number of access ports of the vacuum chamber. The sample back plate may shield the incoming plasma stream and the solid angle of the x-ray sensor is drastically reduced. In order to measure x-ray emission and to use an additional plasma environment, the sample must be illuminated from the top port.

3.4. Diagnostic Sensors and the Data Acquisition System

This experimental apparatus has been designed and constructed with a coaxial geometry in order to utilize current and voltage sensors with high temporal resolution. For this setup, three current probes, three capacitive voltage dividers, one x-ray sensor and one Langmuir probe have been designed and constructed. A unique trigger system is used to correlate the sensor signals which are recorded with four 1 GHz oscilloscopes.

3.4.1. Current sensor

Current measurements are obtained with a transmission line type current sensor [31, 32]. It has a sensitivity of 0.1 V/A and a risetime of less than one nanosecond. A description of this sensor is found in reference 33; therefore, this sensor is only briefly described below. A schematic of the current probe is given in Figure 3.8. The sensor reproduces the primary current with insignificant waveform distortion, i.e., there are negligible limitations of the amplitude transfer function such as high or low frequency cutoffs. The current probe has a two-way transit time of 310 ns in which the sensor output is proportional to the primary current input. In general, the transit time is approximately inversely proportional to the output sensitivity. After the two-way transit time, internal reflections of the probe output signal are seen. Dispersion on the output of an un-optimized current probe causes ringing on the trailing edge of the probe output [32]. Minimum dispersion is achieved by [32]

$$\frac{r_s}{r_c} = \sqrt{e} \cong 1.65 \quad (3.4)$$

where r_s is the minor radius of the conductor shield and r_c is the minor radius of the coil. Table 3.3 shows the typical parameters of the current sensors used in this experiment.

Type A current sensors are located on both sides of the test gap. The more sensitive type B current probe, placed at the load side of the test gap, is used as a trigger pick-off for measurements in the dc-charging mode. The conductor shield of the current sensor is part of the coaxial outer conductor of the experimental apparatus. The type A current probe provides a signal with an amplitude of up to 2 A, corresponding to 100 V with a 50 Ω load, for dielectric breakdown voltages of 50 kV. When the pre-flashover current is investigated, a parallel stack of two 1N4151 switching diodes are used to limit the amplitude of the signal. This technique protects the highly sensitive vertical amplifiers of the oscilloscopes. The capacitive load of the switching diodes is 2 pF and the risetime of the current probe increases to 0.6 ns with the clipping circuit.

Fig. 3.8. Schematic illustration of the transmission line type current sensor with removable clipping diodes.

Table 3.3 Major parameters of the two types of transmission line current sensors used with the experimental apparatus. The characteristic impedance was computed from the measured inductance and capacitance value.

Description	Type A	Type B
Number of turns	495	246
Minor radius of the conductor shield	1.65 cm	1.65 cm
Minor radius of the coil	1 cm	1 cm
Inductance	515 μH	129 μH
Capacitance	65 pF	69 pF
Characteristic impedance	2810 Ω	1370 Ω
Wire resistance	8.4 Ω	2.6 Ω
Risetime (without clipping diodes)	0.5 ns	0.4 ns
Two-way transit time	310 ns	160 ns
Sensitivity (into 50 Ω)	0.1 V/A	0.2 V/A

3.4.2. Voltage sensor

A standard capacitive voltage divider with coaxial geometry is used as a voltage probe . It has a capacitance ratio of approximately 800:1 and a RC-time constant of about 50 ns. The RC-time constant of the probe is further increased by adding a 900 Ω resistor between the sensor output and the oscilloscope input. This method reduces the sensitivity of the voltage probe since the 900 Ω resistor becomes part of a resistive voltage divider with the 50 Ω load of the scope.

Three voltage probes are used with the experimental setup and their capacitances range from 1.1 to 2.4 nF.

3.4.3. X-ray sensor

Soft x-ray emission is measured with an Amperex XP 2020 photomultiplier tube (PMT), operated at 2.4 kV, in conjunction with an NE 102 plastic scintillator. A 10 μm aluminum foil absorbs the visible light emitted by the discharge, and the transmission characteristic of this foil is given in Figure 3.9. The PMT has a propagation delay of 33 ns and a risetime of 3 ns. Its response is linear for output amplitudes of several volts and has a maximum output voltage of 50 V when the PMT current saturates with respect to the input luminosity power. The scintillator, with a diameter of 2", is placed 17" above the test sample.

Fig. 3.9. Transmission characteristic of the 10 μm aluminum foil as a function of the photon energy [34].

During the dielectric breakdown process, x-rays are most likely produced by electrons above the insulator surface. These free electrons have been accelerated in the electrical breakdown field and then hit the positive electrode where they produce x-ray photons. Therefore, the sensitivity of the x-ray sensor is defined as the PMT output voltage versus the x-ray producing electron current. The parameters used to calculate the x-ray sensitivity are given in Table 3.4. The sensitivity of the sensor can be written as

$$\frac{V_{out}}{I_{x-ray}} = Z_o \frac{T_e}{2 \cdot T_p} T_e \delta \Omega_{sc} \eta_{mesh} \eta_{ste} \eta_{fe} \eta_{oe} \Omega_{sc-pmt} \alpha \eta_{pe} \quad (3.5)$$

$$\frac{V_{out}}{I_{x-ray}} = 3 \cdot 10^{-8} T_e^2 \eta_{ste} \left[\frac{V}{A (eV)^2} \right] \quad (3.6)$$

where V_{out} is the output voltage of the PMT into the 50 Ω load of the oscilloscope and I_{x-ray} is the x-ray producing electron current. The x-ray photons have a wide energy spectrum which ranges from tens of eV to the maximum energy of the impacting electrons. An average photon energy of $0.5 \cdot T_e$ is used in this estimation. The sensitivity of the x-ray probe is estimated in Figure 3.10 which shows the voltage output of the PMT versus the impact energy of a 10 mA x-ray producing electron beam. The estimation of the x-ray sensitivity is within one order of magnitude .

Table 3.4. Parameters of the x-ray sensor.

	Description	Value
T_e	impact electron energy at the anode	varies
δ	energy conversion efficiency (for Bremsstrahlung)	$2.9 \cdot 10^{-8} \cdot T_e$
Ω_{sc}	solid angle of the scintillator to the test gap	0.01 sr
η_{mesh}	transfer efficiency of the copper mesh (coaxial outer conductor)	0.5
η_{ste}	spectral transfer efficiency of the 10 μm Al foil	see Figure 3.9
η_{fe}	fluorescence efficiency of the scintillator	0.02
T_p	visible photon energy in the scintillator (after x-ray conversion)	4 eV
η_{oe}	output efficiency of the scintillator due to internal total reflections	0.11
Ω_{sc-pmt}	solid angle of the PMT to the scintillator	0.016 sr
α	PMT amplification	10^7
η_{pe}	PMT quantum efficiency	0.1
Z_o	load of the PMT output	50 Ω

3.4.4 Langmuir probe

A Langmuir probe has been designed to measure the plasma electron temperature and density. This probe is 27" long and consists of a $3/16$ " copper rod, a brass ball with a diameter of $3/4$ ", and an Al tube with an outer diameter of $3/8$ ". Polyethylene is used inside the Al tube to

insulate the Cu rod and epoxy is utilized as a vacuum seal. The brass ball is placed 4" away from the Al tubing and, in this section, the Cu rod is covered with a thin heat shrink hose.

Fig. 3.10. Sensitivity of the x-ray sensor which is defined as the PMT output voltage versus the impact energy of the x-ray producing electron current. This graph is normalized for a 10 mA electron beam.

Fig 3.11. A schematic of the Langmuir probe.

Voltage was applied to the brass ball and the Al tubing was grounded at all times. The potential is swept from -30 V to +30 V and the measured current, which is amplified by a factor of 1000, is recorded with an X-Y plotter. The measurements show the saturated ion current and the linear electron current rise, but only a weak saturation of the electron current is found. The electron temperature of the "plasma" was estimated and found to be on the order of 3 to 5 eV.

This result is comparable to the expected output of the ECR plasma source. For an applied microwave power of 100 W and 300 W, a plasma density of 10^4 and 10^6 cm^{-3} has been estimated, respectively.

3.4.4. Trigger system

The trigger circuit is shown in Figure 3.12. It consists of a high speed differential comparator, NE521, with a typical propagation delay of 7 ns. The TTL-output signal of the comparator is applied to a 2N2222 transistor which is biased in an avalanche mode. For input voltages below 5 mV, the output voltage level of the comparator is at logic low, which is on the order of 0.4 V. In this case, the transistor is in the cut-off region and the output voltage is approximately 0 mV. When the input potential increases to an amplitude of above 5 mV, the comparator output changes to logic high, typically 3.4 V, and the transistor is turned on. The collector of the transistor is at 225 V and is connected to a charge line, RG-223, with a length of 1.2 m. The potential between the collector and the base of the transistor is sufficient to produce an avalanche-multiplication of carriers due to impact ionization in the lattice. A pulse with sub-nanosecond risetime and an amplitude of 50 V is measured at the output. The duration of the pulse is equivalent to the two-way transit time of the charge line.

Fig. 3.12. Trigger circuit with sub-nanosecond risetime and a typical propagation delay of 7 ns with resistors R_1 , R_2 , R_3 , and R_4 , of 49.9 Ω , 51 Ω , 510 Ω , 100 k Ω , respectively, 1N4151 diodes, an NE521 comparator, and a 2N2222 transistor. The comparator operates at ± 5 V and $V_c = 450$ V.

3.4.5. Data acquisition system

The output of the two current probes, the capacitive voltage divider, and the x-ray sensor is displayed by four Tektronix (TEK) 7104 oscilloscopes which have a bandwidth of 1 GHz. Each scope is equipped with a 7A29 vertical amplifier and a 7B10 or 7B15 time base. The pulse from the trigger circuit is divided into four signals, with a Bishop Instruments five port splitter, which then trigger the oscilloscopes. The traces of the TEK scopes are recorded with TEK C1001 or C1002 digitizing cameras, interfaced with a 486/33 MHz PC, using software supplied with the camera system. The data acquisition system has been calibrated with a pulse with a duration of 200 ns and 0.2 ns risetime, produced by a TEK pulse generator, type 110. This calibration pulse has been supplied to the signal cables of each sensor and to the trigger circuit in order to correlate the signals. The signals are estimated to be simultaneous within 1 ns. Andrew 84147/LFL4-50A and 84147/LFL2-50A coaxial cables with a bandwidth of several GHz are used for signal and delay lines.

CHAPTER IV

RESULTS AND DISCUSSION

4.1. Previous Work

Dielectric surface flashover has been investigated over the last thirty years [3-12]. In recent years, some researchers [11, 13, 35-40] have investigated the mechanisms of flashover by measuring the pre-flashover phase of the dielectric breakdown. In 1991, for the first time, high resolution early phase current measurements of the dielectric surface breakdown were published by Hegeler et al. [41]. A small test chamber with a coaxial geometry was used for these measurements, similar to the LEO setup shown in chapter III. The test chamber was constructed and built for a pure vacuum environment and had a diameter of 3" and a length of 10".

Between 1990 and 1992, different dielectric materials (alumina, boron-nitride, Celcon, G-10, Lexan, PMMA, and Pyrex) were tested in the small chamber. Between 8 to 10 shots (dielectric breakdowns) were taken for each sample and the measurements started with new samples. For all materials, two distinct phases for the early stage of breakdown were found: a linearly rising current with a duration of several nanoseconds to several tens of nanoseconds (I), followed by an exponential current rise (II). Amplitudes at the transition from linear to exponential current rise were a few amperes. Soft x-ray emission started simultaneously with the current and stopped at the transition from linear to exponential current rise. An x-ray producing electron current of several tens of milliamperes was estimated to be equivalent to approximately 1% of the pre-breakdown current measured during phase I. Typical results for Pyrex, as an example, are shown in Figure 4.1. The average flashover voltage on Pyrex, with an electrode gap of 0.5 cm, varied from 5 kV for the first shot to 20 kV for the tenth shot. The current amplitude at the transition from phase I to phase II varied between 1 and 8 A, depending on the flashover voltage. A comparison of the two parameters characterizing the current, the slope of the linearly rising current and the amplitude at the transition from linear to exponential rise, is given in Figure 4.2.

In addition, the above-surface charge carrier amplification processes have been observed by Masten et al. [40] with a laser deflection sensor and a streak camera. Laser deflection measurements confirmed a rapid development of a plasma, above the insulator surface, during the early phase of the discharge, with electron number densities in the range of 10^{17} to 10^{18} cm⁻³. Streak camera measurements verified the formation of an intense visible emission 25 to 50 μ m in diameter just above the dielectric surface during the formation of the discharge.

The influence of an external magnetic field on the early phase of flashover was explored using Pyrex as a test material. The magnetic field was parallel to the dielectric surface and perpendicular to the applied electric field in the flashover gap. The pole faces of the electromagnet

or the permanent magnets were placed outside the test chamber at a distance of 4" which was large enough not to produce any electric field distortions in the gap. Two polarizations for the magnetic field have been used, with an $E \times B$ drift away from the insulator surface or into the surface. Significant changes in the waveforms for current, luminosity, and x-ray emission were observed for the case with the $E \times B$ drift away from the surface (see Figure 4.3). Flashover voltage increases of up to 50% were found with an applied magnetic flux density of 260 mT. A plateau formation for the pre-breakdown current was detected combined with a decrease of the x-ray emission and luminosity. With the $E \times B$ drift into the surface, a small decrease of the breakdown voltage was observed with $B = 260$ mT, and no significant changes in current, luminosity, or soft x-ray emission signals were detected.

Fig. 4.1. Current, luminosity and x-ray emission for the early phase of flashover on Pyrex with an electrode separation of 5 mm: (a) dielectric surface breakdown voltage, V_b , of 9 kV, shot number, n_s , of 3, (b) $V_b = 7$ kV, $n_s = 1$, and (c) $V_b = 7.5$ kV, $n_s = 2$.

4.2. DC Dielectric Breakdown Measurements

Two dielectric materials, Lexan and Pyrex, were used to investigate the insulator breakdown with and without UV illumination at a pressure of 10^{-6} torr. The discharge energy per shot ranged from 5 mJ for $V_b = 2$ kV to 3 J for $V_b = 50$ kV. The dielectric flashover is analyzed in relation to the electrode gap distances, using a smooth or field enhanced electrode, and with an external electric shield or magnetic field. A summary of the dc results with UV illumination is given at the end of this section.

Fig. 4.2. Parameters characterizing the early phase breakdown current: (a) Slope of the linearly rising part of the current in the early phase of flashover, as a function of the flashover voltage for different materials. (b) Current amplitude at the transition from linear (phase I) to exponential rise (phase II), as a function of the breakdown voltage for several dielectric materials. The gap distance was 5 mm in all measurements.

4.2.1. The dielectric test sample under UV illumination

Before dielectric breakdown measurements with UV illumination were performed, Lexan was tested for the emission of electrons by photons with energies of less than 6 eV. When the insulator was placed under UV irradiation, a short current pulse was detected. The analog current meter, Keithley 610C, was too slow to detect the current amplitude accurately, but the current measurements indicated that photons from the UV spectrum of the Xenon arc lamp can emit electrons from the surface of the dielectric. Since the band gap energy of dielectrics is on the order of 10 eV [26], the photoemission may only be produced at the surface of the insulator [26]. The precise cause of the photoemission at these low energies is unknown.

In general, the lowest dielectric flashover voltage has been detected when the sample is irradiated with UV illumination near the cathode (i.e., the UV focal point has a diameter of approximately 0.5 cm with its center at the triple point where cathode, dielectric, and vacuum are

in close proximity). It is estimated that on the order of 10 electrons per nanosecond are emitted due to UV irradiation which is applied from a top port of the vacuum chamber (see also Figure 3.7a). For the above estimation, the solar simulator is operated at its maximum input power level of 150 W. When the sample and electrode are irradiated from the side port of the vacuum chamber, the emission of electrons increases by a factor of 4.

Fig. 4.3. The pre-flashover current and luminosity with an applied $E \times B$ drift away from the surface for Pyrex, with an electrode gap of 5 mm: (a) no external magnetic fields, $V_b = 8$ kV, and $n_s = 2$, (b) $B = 100$ mT, $V_b = 8$ kV, and $n_s = 2$, and (c) $B = 260$ mT, $V_b = 9$ kV, and $n_s = 1$.

When the sample is illuminated with UV irradiation in the middle of the gap (i.e., the electrodes are not irradiated), the dielectric flashover voltage amplitude increases by approximately 10% compared to the case where no UV illumination is applied. In addition, an increase of the breakdown voltage is also found when the entire gap of the sample is illuminated with a UV irradiation pulse with a duration of several minutes prior to breakdown (i.e., the Xenon arc source was turned off approximately 2 minutes before a dc voltage was applied to the test sample). For all measurements with UV irradiation, the dielectric sample is actually irradiated with the entire spectrum of the Xenon arc lamp with wavelengths ranging from 200 nm to a few micrometers.

Dielectric breakdown measurements have been performed without the UV spectrum of the arc lamp. When the sample is illuminated by the Xenon arc lamp without its UV spectrum (i.e., the UV part is blocked by a low pass filter with a cutoff wavelength of 390 nm), the dielectric breakdown voltage generally increases by 5 to 10% compared to the case where the sample is not illuminated.

A pressure increase in the vacuum chamber of approximately 8% is found when most of the UV irradiation hits the dielectric sample. In this case, the previous background pressure was 10^{-6} torr. When the UV light is blocked with the low pass filter, a pressure increase of only 4% is detected.

4.2.2. Overview of the dielectric surface flashover with and without UV illumination

Figure 4.4 shows the typical current, voltage, and x-ray emission measurements during the dielectric surface breakdown. The first waveform reflections are detected at approximately 270 ns after the breakdown when the current and voltage amplitude falls drastically. These waveform reflections are produced by the transmission line at the source side which is terminated with a 500 M Ω resistor. At 290 ns after the breakdown, the reflections from the shorted load line are seen; the current amplitude roughly reaches its original amplitude again. The current sensor shows internal signal reflections after 300 ns and the voltage probe has an RC-time constant of roughly 900 ns. A short x-ray emission pulse is measured prior to breakdown, and it stops a few nanoseconds before the final discharge occurs. It is postulated that the x-ray emission is produced by free electrons above the surface which have a free path length on the order of the gap distance (i.e., the electrons have been accelerated in the electrical field over the entire gap when they strike the anode). The x-ray emission stops when adsorbed surface gas leaves the insulator surface and reduces the free path length of the electrons above the surface.

A second x-ray emission signal is detected about 290 ns after the dielectric surface discharge took place. In this time period, the gap voltage changed its polarity. It is not likely that the second x-ray signal is produced by electrons striking the positive gap electrode since the energy of the electrons in the plasma discharge is not adequate to generate x-ray photons. Some electrons will be accelerated toward the outer conductor and they are likely to produce x-ray photons, because the gas above the insulator should be still within a few hundred micrometer of the dielectric surface if the gas expands with thermal velocity into the vacuum.

Figure 4.5 compares the duration of the surface breakdown development on Pyrex to Lexan. The duration of breakdown is here defined as the time the breakdown current increases from 30 mA to 50% of its final breakdown amplitude. In general, the breakdown develops within a

shorter time period if the average applied electric field is increased. The dielectric surface flashover occurs faster on Pyrex at lower voltage amplitudes compared to Lexan. The reason for the fast breakdown development at low voltages has not been clarified.

Fig. 4.4. Typical current, voltage, and x-ray emission measurements for a dc dielectric breakdown. The output of the x-ray PMT is normalized in both cases. (a) Dielectric material: Lexan, without UV irradiation, gap distance $d_g = 10$ mm, breakdown voltage $V_b = 17.5$ kV, shot number $n_s = 9$. The maximum amplitude of the x-ray emission measurement is 0.6 V. (b) Pyrex with UV illumination from the top port of the vacuum chamber, $d_g = 15$ mm, $V_b = 8.5$ kV, $n_s = 11$, and a maximum x-ray emission amplitude of 21 mV.

When the triple point of the dielectric gap is illuminated with UV irradiation, then the breakdown voltage is decreased (dependent on the power density of the UV irradiation). Figure 4.6 shows the effect of weak UV illumination onto the cathode and part of the dielectric surface. The UV illumination causes an increase in the duration of breakdown, although additional electrons are produced (i.e., photoemission mostly from the electrode). Note that the breakdown voltage amplitude in Figure 4.6b is greater than in Figure 4.6a. When the breakdown voltage on Pyrex at an electrode separation of 2 cm is compared for each surface breakdown, weak UV irradiation causes a slight decrease in the voltage amplitude (see section 4.2.3, Figure 4.10d). It is assumed that the delay of breakdown by UV irradiation is produced by gas desorption prior to breakdown and by the initial positive surface charge on the insulator. An explanation of these effects is given in section 4.2.9.

Previous measurements showed a linear rising current in the early phase of breakdown (see Figure 4.1c). This linear pre-flashover current is also observed in the LEO setup with a faster current rise at higher breakdown voltages as shown in Figure 4.7. A linear current rise can be associated with a constant current density (i.e., an electron avalanche saturation is expected from the SSEE model) which diffuses/expands in width and/or height over time.

Fig. 4.5. The duration of the dielectric surface flashover in vacuum for various dielectric materials. (a) Pyrex, $d_g = 5$ mm, $V_b = 4.2$ kV, $n_s = 6$, (b) Lexan, $d_g = 5$ mm, $V_b = 7$ kV, $n_s = 5$, (c) Pyrex, $d_g = 15$ mm, $V_b = 5$ kV, $n_s = 6$, and (d) Lexan, $d_g = 15$ mm, $V_b = 10.3$ kV, $n_s = 6$.

Fig. 4.6. Dielectric surface breakdown with and without UV illumination: (a) Pyrex, without UV irradiation, $d_g = 20$ mm, $V_b = 6.3$ kV, $n_s = 6$, and (b) Pyrex with UV illumination from the top port of the vacuum chamber, $d_g = 20$ mm, $V_b = 8.5$ kV, $n_s = 9$.

Fig. 4.7. The pre-flashover current of the dielectric surface on Pyrex at $d_g = 20$ mm in vacuum: (a) $V_b = 5$ kV, $n_s = 5$, (b) $V_b = 6.3$ kV, $n_s = 6$, and (c) $V_b = 7.7$ kV, $n_s = 7$.

The breakdown voltage amplitude normally increases with each surface flashover; an effect which is known as conditioning of the dielectric sample. A discharge on the insulator surface will desorb gas, create a charge density, and may chemically alter the surface composition of the insulator. On Pyrex, a trace mark of the final arc channel can be easily detected. It has a width between 1 and 2 mm. It can be anticipated that the pre-flashover current is altered if the initiation of the breakdown starts along a surface area on which a previous discharge occurred, compared to a dielectric surface flashover initiation on a virgin surface area. Figure 4.8 shows the early phase flashover current on two consecutive discharges which took place at the same breakdown voltage amplitude. It is assumed that the second discharge developed in part on a conditioned surface area. Since the width of the current channel on the insulator surface expands towards the anode, the initial electron channel at the cathode might start on an unconditioned surface area and then expands into a conditioned area of the dielectric. The surface charge of a conditioned area is likely to be positive [42]. Therefore, the electron avalanche on the dielectric surface could be reduced due to recombination and/or by decrease of the secondary electron yield.

The early phase of surface flashover on Lexan often showed a constant current with amplitudes on the order of a few tens of milliamperes for a duration of 10 to 30 ns as shown in Figures 4.8c, 4.8d, and 4.9. This effect has not been observed on Pyrex. The constant current is normally detected after a few discharges have occurred on the dielectric surface. The reason for this effect is not known but it can be speculated that the positive charge density on the insulator might be responsible for this effect. The surface of Lexan was treated with 600 grit sandpaper whereas the surface of Pyrex is smooth. On Lexan, the electric field normal to the dielectric surface will have some areas with large field enhancement factors along the gap (i.e., the microstructure of a rough surface contains mountains/tips and valleys. Positive charge density on a tip will produce an electric field enhancement). Electrons which drift above those tips are likely

to recombine. In addition, it is likely that Lexan and Pyrex have different secondary electron emission yields; the charge distribution on the insulator surface and the electron avalanche amplification rate might differ for the two materials.

Fig. 4.8. Deviation in the pre-flashover current rise with similar breakdown voltages. Pyrex with UV illumination from the top port at $V_b = 2.8$ kV: (a) $n_s = 3$, and (b) $n_s = 4$. Lexan, without UV irradiation at $V_b = 7.8$ kV: (c) $n_s = 4$, and (d) $n_s = 5$. The test samples have an electrode separation of $d_g = 15$ mm for all cases.

4.2.3. UV irradiation of the dielectric test sample in relation to the electrode gap distances

A series of sixteen measurements have been performed on Pyrex and Lexan with electrode gap distances of 0.5, 1.0, 1.5, and 2.0 cm. For these measurements, a “smooth” electrode is used as an anode and the cathode consists of a “field enhanced” electrode. The sample is irradiated with UV at the triple point. The UV irradiation is applied from a top port of the vacuum chamber as described in section 3.3.2. Figures 4.10 and 4.11 show the breakdown voltage of the test sample for the first nine discharges.

(a)

(b)

Fig. 4.9. Saturated early phase breakdown current on Lexan: (a) UV illumination from the top port, $d_g = 5$ mm, $V_b = 5.5$ kV, $n_s = 6$, and (b) no UV, $d_g = 15$ mm, $V_b = 10.3$ kV, $n_s = 6$.

(a)

(b)

(c)

(d)

Fig. 4.10. Dielectric flashover on Lexan and Pyrex with an electrode separation of: (a) 0.5 cm, (b) 1.0 cm, (c) 1.5 cm, and (d) 2.0 cm. Lexan and Pyrex are abbreviated with L and P, respectively. The extension, UV, indicates that the sample is illuminated with UV from a top port of the vacuum chamber. The Xenon arc lamp is operated at its maximum input power of 150 W.

Fig. 4.11. Dielectric flashover on Lexan and Pyrex at a gap distance of 5, 10, 15, and 20 mm: (a) Lexan, (b) Lexan under UV illumination, (c) Pyrex, and (d) Pyrex under UV irradiation.

This series of measurements uses only one sample for each configuration and since consistency is important in order to compare the results, different measurements with slightly altered configurations are not combined in Figures 4.10 and 4.11. In all measurements, surface flashover on Lexan occurred at higher voltage amplitudes compared to Pyrex. The breakdown voltage on Lexan with a gap distance of 20 mm appears to be abnormally high since other measurements at this gap distance show lower breakdown voltages (see Figure 4.12).

Figures 4.10 and 4.11 show that the dielectric breakdown voltage is not significantly decreased by weak UV irradiation. When the dielectric sample is illuminated with UV from the side port of the vacuum chamber (i.e., in this configuration, the photoemission increases by a factor of 4), the breakdown voltage is drastically reduced compared to the pure vacuum case (see Figure 4.12). This result suggests that there is a minimum or critical number of electrons needed to initiate the surface flashover. With UV illumination from the top port, with an additional lens and a reflecting mirror, the photoemission at the cathode should be near or just below the threshold for

the breakdown initiation. The effects of stronger UV irradiation on the sample is described in the sections below.

Fig. 4.12. Dielectric flashover on Lexan at a gap distance of 20 mm. The UV irradiation was applied from the side port of the vacuum chamber. The dc breakdown voltage was computed from the average of at least three measurements. The standard deviation of the breakdown voltage is within 25% (no UV) and 5% (UV) from its amplitude.

4.2.4. DC breakdown using the smooth and the field enhanced electrode

In the experiment, two cathode shapes, a “field enhanced” and a “smooth” electrode, were used as shown in Figure 4.13. The field enhanced cathode was originally intended to lower the dc breakdown voltage and to localize the arc channel on the dielectric surface. At the cathode tip, electric field enhancement factors of 70 and 2.2 have been estimated for the field enhanced and the smooth electrode, respectively (see section 2.3.1). The dielectric surface flashover amplitude for the two electrode configurations is compared in Figure 4.14. It shows that the breakdown voltage is not always lower with the field enhanced cathode, compared to the case with a smooth electrode. Possible reasons are:

- With the field enhanced cathode, a large region of the gap is significantly below the applied average electric field (see Figure 2.5a). Low gap voltages might be sufficient to field emit electrons from the cathode, but no breakdown will occur if the electron avalanche stops (i.e., when it reaches the area in the gap with a very low electric field amplitude). This point is further described in section 4.2.8.
- The samples have been inspected for the locations of the arc channels. Figure 4.14 shows that the arc channels on the sample with the field enhanced cathode are more localized compared to the case with the smooth electrode. Therefore, the sample with the field enhanced electrode will condition at a faster rate, and the breakdown voltage will increase more rapidly with each discharge.

- The electron field emission might be caused by micro electric field enhancement due to surface roughness with field enhancement factors of up to 300 [24].

Fig. 4.13. Approximate position of the discharge arc channels on the Pyrex sample with a field enhanced and a smooth cathode.

Fig. 4.14. Dielectric surface flashover in vacuum on Lexan at $d_g = 10$ mm: (a) and (b) with a smooth cathode, (c) with a field enhanced cathode.

4.2.5. The influence of the electrode surface contact on the dielectric breakdown voltage

In all of the regular dielectric surface breakdown measurements, the electrodes were firmly pressed onto the insulator surface with nylon screws to insure a good contact with the dielectric surface (see Figure 3.3). The effect of a poor electrode/surface contact on the dc breakdown voltage has been investigated and the results are shown in Figure 4.15. When only the cathode is lifted off the dielectric surface, the breakdown voltage is increased by a factor of 2 to 3 compared to the case with a proper electron/surface contact (see Figure 4.14). The breakdown voltage

increases even further, when the anode is also slightly lifted off from the surface. The current, voltage and x-ray emission signals during breakdown are shown in Figure 4.16.

Fig. 4.15. Dielectric surface flashover in vacuum on Lexan at $d_g = 10$ mm: (a) with a smooth cathode which floats approximately 0.5 mm above the dielectric surface, and (b) with a field enhanced cathode, neither anode or cathode touch the surface of the insulator.

Fig. 4.16. Typical current, voltage, and x-ray emission measurements for a dc dielectric breakdown in vacuum with improper electrode/surface contact. The output of the x-ray PMT is normalized. Lexan at $d_g = 10$ mm, $V_b = 23$ kV, shot number $n_s = 5$: (a) the maximum amplitude of the x-ray emission signal is 1.1 V, and (b) linear rise of the current in the initial phase of breakdown, approximately 80 ns prior to the final discharge.

When the cathode is lifted up from the dielectric surface, the triple point for the field emission is eliminated (i.e., the electron emission region at the cathode does not have the geometric field enhancement from the dielectric/vacuum interface). Without the geometric field enhancement, fewer electrons might be emitted from the cathode. X-ray emission measurement showed that a larger fraction of the emitted electrons strike the anode without hitting the dielectric compared to the case when both electrodes have a good contact with the dielectric surface. Electrons which do

not strike the surface will not start the secondary electron avalanche and desorb gas from the surface. Therefore, the dc breakdown voltage will increase. This effect is well-known from the research of dielectric surface flashover with angled insulator (see Figure 2.6). Figure 4.15b shows a breakdown voltage of 29 kV for the first discharge when both electrodes are raised off the insulator surface compared to $V_b = 16$ kV at $n_s = 2$. Before the first discharge is initiated, no significant positive surface charge should exist on the insulator. Since both electrodes are raised off the surface, only a small fraction of the electrons will strike the insulator surface in the early phase of breakdown. For this electrode setup, a relatively high breakdown voltage is anticipated. After the first discharge, the insulator will have a positive surface charge in some regions of the gap. This positive surface charge will pull more electrons onto the surface during the initiation of the second discharge. Consequently, the breakdown voltage is lower at the second shot.

By comparing the duration of breakdown to the case with proper electrode contact (compare Figure 4.16a to 4.4a) it is found that the duration of breakdown is longer for the case with a poor electrode/surface contact. The initial current rises very fast (see Figure 4.16b) but takes a longer time until the final discharge occurs (i.e., with proper electrode/surface contact, the final discharge occurs between 30 and 50 ns earlier). Electrons, field emitted from the cathode, will strike the insulator for the first time 1 mm away from the cathode if a homogeneous electric field of 20 kV/cm parallel and 10 kV/cm normal to the surface is assumed. The electron emission center is located 0.5 mm above the surface. It is likely that the electric field normal to the surface is not constant throughout the gap. Near the cathode, a large positive charge density is expected because electrons which hit the surface should have a high impact energy there. If an electric field normal to the surface of 20 kV/cm is created (i.e., if it has the same amplitude as the electric field parallel to the surface), the electrons will strike the insulator 500 μ m away from the cathode. It is likely that close to the cathode no gas is desorbed from the dielectric since the electron avalanche will start further away from the cathode. The discharge might be delayed until the desorbed gas expands toward the cathode.

4.2.6. UV illumination of the insulator with external magnetic fields

The influence of external magnetic fields have been investigated on Lexan with an electrode separation of 20 mm. Previous measurements [35] with a magnetic flux density of $B = 260$ mT showed magnetic insulation effects at electric field amplitudes of up to 25 kV/cm. A magnetic field of $B = 30$ mT should be sufficient to alter the electron trajectory above the insulator surface at electric field amplitudes below 3 kV/cm. The experimental setup with smooth gap electrodes and with the magnet arrangement underneath the dielectric sample is described in section 3.2.5. UV irradiation has been applied from the side port from the vacuum chamber in order to produce a

photon flux comparable to the solar radiation in the lower earth orbit region. The results of the experiment are shown in Figure 4.17.

Fig. 4.17. The effect of external magnetic fields on the dc dielectric flashover voltage amplitude with applied UV illumination on Lexan at a gap distance of 20 mm. The sample was illuminated with UV from the side port of the vacuum chamber: (a) without UV, (b) to (d) with UV irradiation. (c) with an $E \times B$ drift away from the surface, and (d) with an $E \times B$ drift into the surface (30 mT was applied at the cathode region). The standard deviation of the breakdown voltage is within 25%, 5%, 10%, and 20% from its amplitude for the curves (a) to (d), respectively.

The Xenon arc source is operated at its maximum input power of 150 W and the sample is irradiated at the triple point. Without UV irradiation, a “normal” conditioning of the sample is seen, whereas with UV illumination the breakdown voltage is only slightly increased with the shot number. A breakdown develops at an average electric field strength of 1.5 to 2 kV/cm. With an $E \times B$ drift away from the surface (i.e., the charged particle drift has two components, one perpendicular and one parallel to the dielectric surface), no significant increase in the breakdown voltage amplitude is seen. With an $E \times B$ drift into the dielectric surface, the breakdown voltage increases by up to a factor of 3 compared to the case with $B = 0$. Explanations for the dielectric surface breakdown results with external magnetic fields are given in section 4.2.9.

During the dielectric breakdown measurements with an external magnetic field, only a charging and load line with a two-way transit time of 100 ns each was available. The breakdown voltage amplitude could be accurately measured, but the current and voltage waveforms showed reflections after 100 ns. The duration of breakdown with “strong” UV irradiation (compared to the case when UV illumination is applied from the top port of the vacuum chamber) was on the order of 1 to 2 μ s. It is speculated that this long duration of breakdown might be partially caused by the strong positive charge density and by the gas reduction on the dielectric surface.

4.2.7. UV irradiation of the dielectric sample with an external electrical shield

Previous dielectric surface flashover measurements in vacuum [35] showed that the breakdown voltage is substantially increased if the breakdown initiating electrons above the dielectric are prevented from striking the dielectric surface. UV irradiation will emit electrons from the surface, and these electrons might initiate the breakdown. Some of these electrons could be collected by an electric shield prior to breakdown.

In the LEO setup, the grounded coaxial outer mesh is placed at a distance of approximately 5.5" from the test sample. It was difficult to add an external shield in the LEO test chamber, therefore, a smaller test chamber is used for the measurements. The test chamber has a coaxial outer conductor with a radius of 1.5" which has been grounded. UV irradiation is applied directly from a side port of the vacuum chamber. It is estimated that the UV photon flux density in this setup is increased by a factor of 2 compared to the case when the dielectric sample is irradiated with UV from the side port of the LEO chamber. The electrodes with a diameter of 0.25" are 50% smaller than in the LEO setup. Therefore, a larger dielectric surface area is irradiated with UV compared to the LEO setup.

The dc breakdown voltage of Lexan with a gap distance of 2 cm was extremely high with this new setup; the first discharges on the sample occurred at a flashover voltage of roughly 30 kV. The sample conditioned quickly to a breakdown voltage above 50 kV after the third or fourth discharge. The high flashover voltage might partially result from the presence of the outer conductor which acts as an electron collector. The results will be discussed in detail in section 4.2.9.

4.2.8. Anomalies of the early phase breakdown current

The oscilloscopes, which record the current, voltage, and x-ray signals, have been triggered by a highly sensitive trigger system as described in section 3.4.4. The scopes are usually triggered when the current rises above an amplitude of 20 to 30 mA at the load side of the breakdown gap (i.e., the final breakdown current is 200 A for $V_b = 20$ kV). It is not known that any previous researcher recorded the pre-flashover current in this early stage for a dc insulator surface flashover. Figure 4.18 shows current signals which occurred when the current, voltage and x-ray signals showed no indication of a dielectric surface breakdown within a time frame of 500 ns. The amplitude of these current signals never exceeded 50 mA. The current decreased to zero and stayed unchanged for the rest of the time window (i.e., not counting the reflections from the load and source side). This type of current signals are found on both dielectric materials, although, it occurred more often on Lexan (usually once or twice during ten discharges). The pulse duration of the current is approximately 50 ns as shown in Figure 4.18b. A few of these current signals have a

longer pulse duration (see Figure 4.18a). The “no breakdown” current signal is seen more often in cases where the field enhanced cathode is used (compared to the smooth electrode), a low average electric field on the order of 0.5 to 2 kV/cm is applied, the sample is illuminated with UV, and an external magnetic field with an $E \times B$ drift into the dielectric surface is used in addition to the UV irradiation. Figure 4.19 shows current waveforms with an initial current pulse similar to Figure 4.18 but with breakdown occurring within the time frame of 500 ns, or shortly after 500 ns (i.e., the current, voltage and x-ray signals indicate that a dielectric surface breakdown occurs).

Fig. 4.18. Measured current signals for the case when the current, voltage and x-ray signals showed no indication of a dielectric surface breakdown within a time frame of 500 ns. (a) Pyrex with UV illumination from the top port of the vacuum chamber, $d_g = 5$ mm, $V_{\text{applied}} = 1$ kV, and (b) Lexan without UV irradiation, $d_g = 10$ mm, $V_{\text{applied}} = 5$ kV.

Possible reasons for a current signal to decrease to zero as shown in Figure 4.18b are:

- The electron emission at the cathode stops. At low average electric fields, a relative high electric field enhancement at the cathode is required to emit electrons. A sharp “micro” tip which has a field enhancement factor of several hundred [24] will erode during emission, the field enhancement might decrease and the electron emission stops.
- The electric field parallel to the surface is not constant throughout the gap. Especially with the field enhanced cathode, the electric field amplitude drops significantly near the middle of the gap. Electrons which are emitted from the cathode might start a large secondary electron avalanche near the cathode. This avalanche will move towards the anode. When it reaches the region with a low electric field parallel to the surface, the electrons might not gain sufficient energies to generate secondary electrons. This effect could be also caused by an external magnetic field with an $E \times B$ drift into the dielectric surface.

- A positive charge density on the insulator surface could decrease the electron avalanche significantly. If the electron emission at the cathode decreases in addition, the initial “breakdown” current might stop.

Fig. 4.19. Anomalies of the pre-flashover current prior to the breakdown which occurs within 500 ns: (a) Lexan without UV illumination, $d_g = 21$ mm, $V_b = 2$ kV, and (b) Lexan with UV irradiation from the top port of the vacuum chamber, $d_g = 10$ mm, $V_b = 2.8$ kV.

4.2.9. Summary of the UV induced dc insulator surface flashover measurements

Numerous elementary processes associated with UV illumination are not known quantitatively. The only well known process is photoelectron production from metals (here: from the cathode) which produces an electron cloud above the surface. Photoelectron emission from the insulator is probably related to impurities and surface states in this experiment (two-photon ionization can be excluded for these experimental data), and a very weak photo current originating from the insulator surface has been observed (see section 4.2.1). Also, the mechanism of UV induced gas desorption is virtually unknown. It can be speculated that UV illumination breaks the van-der-Waals-type bonds of adsorbed gas molecules (with binding energies in the sub-eV region) which leads to an effective removal of adsorbed molecules. Emission velocities are expected to be on the order of thermal velocities, as in the case of electron induced desorption.

In view of these effects, the following mechanisms might play a role in the case of UV irradiation -- either enhancing or reducing the flashover voltage:

- Gas desorption: It is expected that UV illumination effectively reduces the amount of gas on the insulator surface prior to breakdown. Desorption velocities are on the order of several 100 m/s.
- Photoelectrons: UV irradiation generates an electron cloud above the surface, before any voltage is applied to the gap. The electron density profile is not known.

- Positive charge density on the insulator surface: Photoelectrons are emitted from the insulator. Therefore, a positive surface charge is produced on the dielectric.
- Change of the surface composition of the insulator: On Lexan, the insulator surface changed its color where it was exposed to UV irradiation. It is assumed that the surface is chemically altered by UV illumination. UV photons might break some molecule bonds at the dielectric surface. Electrons which hit the surface could be chemically absorbed by the broken molecule bonds; the dielectric material will be transformed/modified, and electrons are lost at the surface. A chemically altered surface might have different parameters (the secondary electron emission coefficient, for example) which directly or indirectly influences surface flashover.

The UV induced dc surface flashover measurements showed the following trend: UV illumination on the insulator enhances the flashover voltage, whereas UV irradiation on the cathode decreases the surface breakdown potential. A summary of the dc breakdown measurements is given below. Possible flashover processes with UV illumination are used to explain the enhanced or reduced flashover voltage compared to the case without UV irradiation. During measurements, the dc voltage in the gap is slowly increased (i.e., the RC charging time constant is approximately 1 s, and the voltage is increased every few seconds in steps of 0.5 to 1 kV until breakdown occurs). In order to describe the complex, dynamic UV induced flashover mechanisms, the dielectric surface breakdown process is examined at t_0 (before a voltage is applied to the gap), t_1 (when the gap voltage amplitude is several 10 V), t_2 (the electric field at the cathode is sufficient to emit electrons), and t_3 (breakdown occurs).

1. Strong UV illumination in the middle of the dielectric gap (electrodes are not irradiated):
 - t_0 : Gas has been desorbed by UV photons, a positive charge density is generated at the surface, and photoelectrons are above the insulator.
 - t_1 : Photoelectrons will drift towards the anode. They will strike the anode directly, or they will hit the dielectric surface. If they strike the surface near the anode, where no UV is applied, a negative surface charge will be produced (i.e., the electrons have a maximum impact energy of only a few eV). Electrons, which hit the surface in the middle of the gap, recombine with the positive charge density. These electrons can be reemitted by UV photons. It is expected that, after some time, the UV irradiated surface area has a positive charge density and photoemission stops. Near the anode, a negative charge density should be found on the surface.
 - t_2 : Some electrons will be emitted from the cathode. Their energy is not adequate to start an electron avalanche throughout the gap (i.e., some electrons are emitted from "micro" tips at the cathode, although the average electric field in the gap is too low

to start a surface flashover). When these electrons drift above the positive surface charge in the middle of the gap, they are likely to recombine with the positive surface charge and then be emitted by UV photons again. At low electric fields, the negative charge density at the surface region near the anode (without UV illumination) might increase.

- t_3 : The initiation of the breakdown is not fully understood. It can be postulated that breakdown occurs when: a sufficient number of electrons are field emitted from the cathode, electrons gain enough energy in the electric field parallel to the surface to emit secondary electrons from the surface, the electron avalanche is self-sustaining, and a sufficient gas density can be built up for the final discharge channel.

Measurements showed that the flashover voltage is enhanced and the breakdown develops slower when the middle of the insulator is illuminated with UV.

2. Strong UV illumination on the cathode (a small area of the insulator near the cathode is also irradiated):

t_0 : Gas desorption and a positive surface charge is found only near the cathode. The electron density above the surface should be higher compared to the above case 1.

t_1 : Same as in case 1. Continuous photoemission will generate surface regions with a high positive and negative charge density as shown in Figure 4.20.

t_2 : In addition to the field emitted electrons, photoelectrons are generated continuously from the cathode. Therefore, near the cathode, the electron density above the surface is higher compared to case 1. At low average electric fields, the surface charging along the gap (positive or negative) and other mechanisms (electron induced gas desorption, etc.) are not fully understood for the case when a high electron cloud exists near the cathode

t_3 : Same as in case 1.

Measurements showed that the flashover voltage is drastically decreased and the breakdown develops slower. Most of the UV photons strike the cathode and produce photoelectrons. Gas desorption prior to breakdown and the initial positive surface charge due to photoionization is limited to a small region of the gap.

3. Weak UV illumination at the triple point (a field enhanced electrode is used; therefore, a large area of the insulator near the cathode is irradiated):

t_0 : Same as in case 2.

Fig. 4.20. Illustration of the expected charge density at the surface with UV irradiation at the triple point when the amplitude of the applied electric field parallel to the surface is on the order of the electric field normal to the surface.

t_1 : Similar to the second case, but less electrons are emitted from the cathode (i.e., a smaller cathode area is exposed to UV photons, and the UV photon flux is considerably decreased compared to the case 2). A negative surface charge in the gap is expected (see Figure 4.20), but with a smaller amplitude compared to second case.

t_2 : Combination between case 1 and case 2.

t_3 : Same as in case 1.

With UV illumination from the top port of the LEO setup, the flashover voltage is only slightly decreased (see Figure 4.10) and the breakdown develops slower compared to the surface flashover without UV irradiation.

4. “Very” strong UV illumination at the triple point and with a copper mesh 1.5" above the surface (a small electrode is used, a large insulator area at the cathode is irradiated):

t_0 : Similar to case 2. In addition, the copper mesh might collect photoelectrons.

t_1 : Similar to the third case. Furthermore, it is expected that the “hard” UV irradiation will chemically alter the dielectric surface.

t_2 : Similar to case 2.

t_3 : Same as in case 1.

With UV illumination from the side port of the small vacuum chamber (see section 4.2.7), the flashover voltage is increased. The results should not be compared with the previous cases since the “hard” UV irradiation might have changed the material composition at the surface significantly.

External magnetic fields at the cathode region will alter the trajectory of the electrons. With strong UV irradiation at the triple point (see case 2), a positive surface charge is expected near the cathode (see Figure 4.20). With an $E \times B$ drift away from the dielectric surface ($B = 30$ mT), no significant increase of the flashover voltage is seen as shown in Figure 4.17. From the results it can be assumed, that the electrons are not lifted up from the surface with an applied magnetic flux density of 30 mT. Note that for a dielectric surface breakdown without UV irradiation 30 mT is sufficient to lift up the electrons from the insulator (at the same gap voltage). The critical magnetic field to lift up the electrons is influenced by the UV induced positive surface charge (i.e., a larger magnetic flux density is required if the positive charge density on the insulator increases).

With an $E \times B$ drift into the surface, the flashover potential increases by a factor of 3 to 4 after several discharges occurred on the sample (see Figure 4.17). Plots of the electrons trajectory showed a decrease in the lateral hopping distance on the surface by a factor of 1.5 to 2, compared to the case when $B = 0$. Possible reasons for the increase are:

- The sample conditioned faster. The electron induced gas desorption will be more efficient if the electrons have a short lateral hopping distance.
- The impact energy of the electrons is reduced by a factor of 1.5 to 2. A higher electric field parallel to the surface is required for the electrons to gain enough energy for the secondary electron emission.

The dielectric surface flashover measurements with UV illumination indicate that the breakdown voltage decreases only if the electrode is irradiated with UV. UV illumination of the dielectric generally slightly enhances the flashover potential, compared to the case without UV. In order to prevent the dielectric surface flashover in the low earth orbit environment, it is proposed that the electrodes or metal be coated with a thin dielectric material. This technique will only marginally increase the weight of the system. For dc and pulsed high voltage systems with a risetime of less than 1 kV/ns, the photoelectrons from the dielectric will not initiate the dielectric breakdown. In addition, solar irradiation will initially desorb gas from the insulator surface, which should improve the surface breakdown characteristics on the dielectric.

During the solar radiation simulations, the insulator was exposed to UV for a duration of up to 90 minutes. Within this time, the surface composition of the dielectric already changed. It is very likely that the surface breakdown mechanisms are altered over time due to the UV induced insulator aging. The aging influence on the surface flashover mechanisms is poorly understood and needs to be investigated in order to predict surface flashover system failures in the low earth orbit.

4.3. Pulsed Dielectric Breakdown Measurements

Insulator flashover measurements on Lexan and Pyrex have been performed with and without a plasma background. A voltage pulse with a duration of 200 ns is applied to the test gap (see section 3.1) and current, voltage, and x-ray emission are measured. Figure 4.21 shows the voltage and current signals of a dielectric surface flashover in vacuum for a duration of 300 ns. Note that the source-side voltage almost doubles, reaching a value close to the charge voltage V_{applied} , until the discharge occurs on the test sample. The source-side current rises as the pulse reaches the current sensor, then falls as the pulse reflects from the open test gap, then rises again as the sample flashes over.

Fig. 4.21. Voltage and current waveforms occurring during dielectric surface breakdown in vacuum. Voltage and current are abbreviated with V and I, the subscripts S and L indicate source and load side of the test gap. Current waveforms are shown inverted for clarity. $V_{\text{applied}} = 38$ kV, $d_g = 7$ mm, with the field enhanced cathode. Material: Pyrex.

4.3.1. Insulator flashover with and without plasma, using the field enhanced cathode

Measurements were initially taken using the field enhanced cathode, described above, due to the assumption that a pulsed breakdown system would require higher electric field amplitudes than an equivalent dc charge system. The applied voltages ranged from 35 to 60 kV for a gap distance of 7 mm. The typical dielectric flashover signals, with and without plasma, are shown in Figure 4.22. No major changes in the voltage and current waveforms for vacuum and plasma are seen. The delay time of breakdown decreased slightly from approximately 20 ns at 35 kV to 15 ns at 60 kV. The time of breakdown is defined here as the difference in time between 50% of the applied voltage reaching the test gap and the actual breakdown (i.e., when the current amplitude reaches 50% of its expected breakdown amplitude which is on the order of 150 to 300 A). In order to discern the effect of an ambient plasma on surface flashover, it is necessary to apply an electric field whose amplitude is near the breakdown threshold in vacuum for a 200 ns voltage pulse.

However, a fast breakdown always occurred in measurements with a field enhanced cathode at a gap voltage of 25 kV and above (i.e., note that the spark gap sets the range of the applicable voltage, a minimum of 20 kV at atmospheric pressure), and a relatively large amount of electrode material was found on the test sample, near the cathode. It is assumed that the high electric field at the cathode causes material erosion which generate a high electron density at the cathode. The electron cloud, due to erosion, might have a significantly larger density than the plasma background. Therefore, it was decided that the smooth electrode should be used in subsequent measurements.

Fig. 4.22. Typical results for Pyrex with and without a plasma background, at $d_g = 7$ mm, and with the field enhanced cathode. The measurements were performed on the same test sample on two consecutive discharges. Current waveforms are shown inverted for clarity: (a) without plasma, $V_{\text{applied}} = 36.5$ kV, and (b) with plasma, $V_{\text{applied}} = 35.5$ kV.

4.3.2. Pulsed dielectric surface flashover on Pyrex

The test sample is “conditioned” with a few discharges before a plasma background is applied. Figure 4.23 shows the current, voltage, and x-ray emission signals for the second and fifth discharge. In general, the breakdown delay increases with each discharge until flashover no longer occurs within the pulse duration when the applied gap voltage is the same for each discharge. Note that no breakdown develops within 200 ns does not mean that no discharge occurred on the sample. Since the voltage pulse reflects at the test gap and the charging resistor, the applied voltage pulse could develop a discharge at a later time (i.e., the charging line is drained with a RC time constant of 0.3 s). A noise signal is seen on the current signal (see Figures 4.23b and 4.23d) which is generated by the spark gap. In later measurements, the shielding around the spark gap was improved which decreased the noise level.

The plasma background is added after the breakdown delay increases above 100 ns for the surface flashover in vacuum. The first discharge with plasma always shows a decrease in the

breakdown delay as seen in Figure 4.24. In addition, the x-ray emission increased with a plasma background. For both environments, the linear rise of the current from 1 to 6 A is seen, although the current rises faster with a plasma background. The initial rise and fall of the current signal (see Figures 4.24b and 4.24d) is associated with the displacement current which charges the gap capacitance.

Fig. 4.23. Typical current, voltage, and x-ray emission measurements for a pulsed insulator flashover in vacuum on Pyrex at $d_g = 10$ mm: (a) and (b) $V_{\text{applied}} = 28$ kV, $n_s = 2$, and (c) and (d) $V_{\text{applied}} = 24$ kV, $n_s = 5$. The current signal in (b) and (d) picked up noise which was generated from the spark gap.

The decrease of the breakdown delay can be understood as:

- The actual dc breakdown voltage is lower with a plasma background.
- The insulator flashover is initiated more rapidly with a plasma.

Both interpretation would explain the decrease of the breakdown delay and the increase of the current slope in the early phase of flashover. The increase of the x-ray emission with plasma indicates that more electrons strike the anode with high impact energies (i.e., electrons which might not hit the insulator surface).

Even though the breakdown delay with a plasma background is always shorter for the first discharge compared to the case without plasma, measurements showed that the test sample conditioned faster with a plasma. The influence of the surface charging due to the plasma and other plasma effects will be discussed later in the chapter.

Fig. 4.24. Dielectric breakdown with and without plasma, on Pyrex at $d_g = 10$ mm: (a) and (b) without plasma at $V_{\text{applied}} = 28$ kV, $n_s = 6$, and (c) and (d) with plasma background at $V_{\text{applied}} = 28$ kV, $n_s = 7$. Measurements are taken on the same sample. The current signal in (b) and (d) was partially restored from the noise.

4.3.3. Insulator flashover on Lexan, with and without a plasma, and the influence of the external magnetic field on the plasma induced breakdown

Lexan has been tested at several gap distances in order to find the “optimum” breakdown delay for this experimental setup (i.e., a breakdown which occurs within 200 ns at a given gap voltage, with and without plasma). The dielectric sample was first tested with an electrode separation of 20 mm because it was assumed that the influence of the plasma background on the dielectric breakdown is increased at large gap distances. At this distance, a breakdown occurred within 200 ns at gap voltages of 30 to 40 kV for the first few discharges. The breakdown voltage later increased to 50 kV at which a partial discharge developed between the inner- and outer-

conductor of the coaxial test chamber (with a plasma background). Since these partial discharges are not desired for the investigation of the insulator surface flashover, a gap distance of 10 mm was chosen with a charging voltage of approximately 17 kV for the first discharge. Pulsed dielectric breakdown measurements showed that the results are reproducible (i.e., the below indicated trends are always seen). Therefore, this section shows one presentative measurement result for each case, with and without plasma, and with the influence of an external magnetic field. The surface flashover signals in vacuum on Lexan are shown in Figure 4.25. It shows a breakdown delay of 70 ns for the first discharge at $V_{\text{applied}} = 17$ kV. At this voltage level, measurements showed an approximate 10% standard deviation in the breakdown level.

Fig. 4.25. Surface flashover in vacuum on Lexan at $d_g = 10$ mm: (a) and (b) $V_{\text{applied}} = 17$ kV, $n_s = 1$.

With a plasma background, the breakdown delay is decreased by approximately 10 ns for the first discharge at $V_{\text{applied}} = 17$ kV, as shown in Figure 4.26. This decrease is smaller than for the case when the test sample is first conditioned without plasma for several discharges (see Figure 4.24). This effect is discussed in section 4.3.4. In addition, an increase of the pre-flashover current rise and the x-ray emission is seen for the case with plasma.

When an external magnetic field of $B = 30$ mT is applied perpendicular to the applied electric field, a significant change in the breakdown development is seen (with a plasma background). With an $E \times B$ drift away from the dielectric surface, x-ray emission increased by more than 200%, the current rise in the early phase of breakdown is substantially decreased, and the delay of breakdown is increased by a factor of 2 to 2.5 for the first discharge (see Figure 4.27). With an $E \times B$ drift into the surface (see Figure 4.28), no major change in the breakdown delay is seen compared to the case with $B = 0$, but the x-ray emission shows a decrease in amplitude. The early phase current shows some difference in the rise which is more obvious after a few discharges on the test sample (see Figure 4.29).

Fig. 4.26. Dielectric breakdown with a plasma background, on Lexan at $d_g = 10$ mm: (a) and (b) $V_{\text{applied}} = 17$ kV, $n_s = 1$.

Fig. 4.27. Insulator breakdown with a plasma background and an external magnetic field, on Lexan at $d_g = 10$ mm: (a) and (b) $V_{\text{applied}} = 18$ kV, $n_s = 1$, with an $E \times B$ drift away from the dielectric surface ($B = 30$ mT).

Fig. 4.28. Dielectric flashover with a plasma background and an external magnetic field, on Lexan at $d_g = 10$ mm: (a) and (b) $V_{\text{applied}} = 16$ kV, $n_s = 1$, with an $E \times B$ drift into the dielectric surface ($B = 30$ mT).

An external magnetic field of 30 mT also had a noticeable effect on the pulsed insulator breakdown in vacuum (see Figure 4.30). An external $E \times B$ drift away from the dielectric surface causes an increase in x-ray emission and the breakdown delay time and a decrease in the current risetime in the early phase of breakdown compared to the case with $B = 0$. Note that the $E \times B$ drift with a plasma background (see Figure 4.27) has a longer breakdown delay and a smaller pre-flashover current rise compared to the case without a plasma. For an average electric field of 18 kV/cm, the critical magnetic field to lift up the electrons from the surface should be on the order of 100 mT (see equation 2.20).

Fig. 4.29. Dielectric flashover on Lexan with a plasma background with $d_g = 10$ mm: (a) $V_{\text{applied}} = 18$ kV, $n_s = 2$, ($B = 0$), and (b) $V_{\text{applied}} = 16$ kV, $n_s = 2$, with an $E \times B$ drift into the dielectric surface ($B = 30$ mT).

Fig. 4.30. Insulator surface flashover in vacuum and an external magnetic field, on Lexan at $d_g = 10$ mm: (a) and (b) $V_{\text{applied}} = 18$ kV, $n_s = 1$, with an $E \times B$ drift away from the dielectric surface ($B = 30$ mT).

4.3.4. Summary of the plasma induced insulator flashover measurements

The following results have been found for the pulsed dielectric breakdown:

- i. The test sample conditioned faster with a plasma background compared to the case without plasma.
- ii. X-ray emission is increased with plasma.
- iii. For the first discharge with plasma, the delay of breakdown is reduced (i.e., the delay time is compared to the previous vacuum discharge if the sample was conditioned prior to the plasma discharge as shown in Figure 4.24).
- iv. With an $E \times B$ drift away from the dielectric surface, the breakdown delay and the x-ray emission increases, and the current rise in the early phase of breakdown decreases for both cases, with and without plasma compared to measurements with $B = 0$.
- v. The effect of the $E \times B$ drift away from the surface is enhanced in a plasma background compared to the case without plasma.
- vi. With plasma, and with an $E \times B$ drift into the surface, the x-ray emission is drastically reduced, but the delay time of breakdown is similar to the $B = 0$ case. The pre-flashover current often shows a “smoother” transition from the slow current rise (at amplitudes below 1 A) to the fast current increase just prior to breakdown (at a current amplitude of several amperes) as shown in Figure 4.29.

The effects of a plasma background on the insulator surface flashover mechanisms are not known quantitatively. For this experiment, near the test sample, no “quasineutral” plasma exists, but a collective of charged particles, electrons and ions, will influence the dielectric breakdown. Possible effects of the charged particles are described below. As for the case with UV irradiation, the complex plasma induced insulator flashover is examined at three discrete times: t_0 (before the voltage pulse is applied), t_1 (the gap voltage is on the order of 1 kV), and t_2 (the breakdown is initiated).

- t_0 : -- Gas desorption prior to breakdown: It is assumed that the “plasma” electrons and ions will strike the dielectric surface and induce gas desorption. The gas desorption efficiency is not known. It is expected that gas desorption velocity is on the order of several 100 m/s (thermal velocity of the gas molecule).
- Surface charging: Electrons and ions which hit the dielectric, will not emit secondary electrons from the surface since their impact energy is too low (i.e., by one order of magnitude smaller than the energy, A_1 , at which the secondary electron emission yield is one). They will produce a surface charge of unknown density and distribution along the gap.

- Electron emission from the electrodes: The temperature of the “plasma” electrons should be on the order of 5 eV. This temperature is just above the threshold energy for electron emission from the electrodes (i.e., for copper, the work function is 4.3 eV). Note that the electron temperature is only 0.1 to 0.5 eV in the lower earth orbit.
 - “Free” electrons and ions above the dielectric surface.
- t₁: -- The “plasma” electrons will drift towards the anode, and most of the free electrons within the test chamber will be collected (i.e., electrons have an average velocity of 10^7 m/s for a gap voltage of 1 kV). Note that most of the initial electrons will produce very soft x-ray emission when they hit the anode. These soft x-ray photons can not be detected with the x-ray sensor (see Figure 3.10). Some of the “plasma” electrons might hit the insulator surface. They will neutralize part of an existing positive surface charge or generate a negative surface charge. In addition, if their impact energy is high, they can produce secondary electrons on the surface.
- Most ions will still be in the test chamber since their drift velocity is several orders of magnitude lower compared to the velocity of the electrons. Within 10 ns, the ions just above the dielectric surface could have traveled a distance of 10 μ m (with an electrode separation of 1 cm and a constant gap voltage of 1 kV). Therefore, at the cathode, impacting ions will not produce any secondary processes (electron emission, for example) since their maximum impact energy is 1 eV. Ions, which are further away from the surface, will be nearly stationary (i.e., in this region, the electric field strength is smaller compared to the field in the insulator gap).
- t₂: -- The plasma continuously drifts into the test chamber with a velocity on the order of 10^3 to 10^4 m/s (see section 2.5.1). Consequently, it is expected that no significant number of electrons or ions will drift into the test chamber during the initiation of breakdown.
- The “plasma” ions will strike the cathode with higher impact energies which should be sufficient to emit secondary electrons from the electrode (i.e., ions which are accelerated in a gap field of 15 kV/cm for 10 ns will gain more than 200 eV).
 - Again, the initiation of the breakdown is not fully understood (see section 4.2.9).

The above described plasma effects can be used to explain some of the results which have been summarized at the beginning of this section to:

- i. The faster conditioning of the sample might be partially due to the plasma induced gas desorption prior to breakdown. Furthermore, the arc channel width could be bigger with the plasma background; a larger surface area can be conditioned during one discharge.
- ii. The increase of the x-ray emission with plasma could relate to the ion induced electron emission at the cathode.
- iii. For the case when the sample was conditioned prior to the plasma discharge: The plasma will alter the existing charge density on the surface. A previous positive surface charge might be neutralized by the plasma electrons.
- iv. With an $E \times B$ drift away from the surface, the trajectories of the breakdown initiating electrons are altered. This effect could delay a breakdown (i.e., the lateral hopping distance on the surface is increased, less electrons strike the surface at a time, and the electron induced gas desorption is delayed). Electrons have been accelerated in the electric field for a longer time when they strike the anode (x-ray emission increases).
- v. The effect of the $E \times B$ drift from the surface is enhanced if the charge density of the surface is more negative compared to the surface charge during a surface flashover without plasma (see section 2.5.2).
- vi. An $E \times B$ drift into the surface will decrease the impact energy of the breakdown initiating electrons. On the other hand, more of the “plasma” electrons could strike the dielectric surface during the time t_1 (i.e., the electron current in the very early phase of breakdown might be higher compared to the case with $B = 0$).

With an external magnetic field, the trajectory of the charged particles are altered when a voltage is applied to the gap. The magnetic field will also change the trajectories of the electrons and ions without a gap voltage because an electric field between the electrons and the ions exists.

Argon with a pressure of $5 \cdot 10^{-4}$ torr is used as a fill gas for the plasma generation. The insulator breakdown was measured with Argon gas but without plasma and these measurements show that the Argon will not significantly change the breakdown mechanisms compared to a surface breakdown in vacuum at 10^{-6} torr. Nevertheless, the dielectric surface will absorb the Argon gas which might change the electron induced gas desorption coefficient.

CHAPTER V

CONCLUSIONS

Some of the basic breakdown processes have been investigated which govern the charge carrier amplification and transport mechanisms in the early phase of the dielectric flashover under a simulated LEO environment. The results indicate that the breakdown mechanisms are altered with plasma and UV compared to the pure vacuum case. UV irradiation desorbs gas from the surface, produces photoelectrons above the surface, generates a positive surface charge on the insulator, and changes the surface composition of the material. It is assumed that plasma causes gas desorption on the insulator surface as well, and adds negative charges to the dielectric surface.

UV illumination of the dielectric increases the flashover potential. UV irradiation of the cathode reduces the breakdown electrical field compared to the case without UV. When the insulator is exposed to UV, the breakdown develops at a slower rate.

An external magnetic field of 30 mT influences the dielectric breakdown. With an $E \times B$ drift into the surface, the breakdown voltage increases significantly with each discharge compared to the case at $B = 0$. The $E \times B$ drift will decrease the lateral hopping distance for the electrons on the surface. This effect could enhance the surface conditioning (i.e., due to an increase of the electron induced gas desorption). Furthermore, a higher breakdown voltage is required if electrons do not gain enough energy to generate secondary electron emission.

For the dc surface flashover, with an $E \times B$ drift away from the surface, no major changes in the breakdown current and voltage are seen. Under vacuum surface flashover conditions (without a plasma or UV), the drift should have been sufficient to lift up the initiating from the surface at the applied breakdown potential. Since the “weak” $E \times B$ drift away from the surface does not influence the breakdown process, it can be postulated that UV irradiation produces a positive charge with a higher amplitude at the surface during the secondary electron avalanche compared to the case without UV.

Two trends have been seen for the pulsed dielectric breakdown results with a plasma background: (1) when the sample is conditioned before plasma is added to the test chamber, the breakdown always occurred faster for the first discharge, and (2) the sample conditions faster with plasma on consecutive discharges compared to the case without plasma. Plasma electrons can neutralize a positive surface charge which was generated from the previous discharge. This effect should decrease the breakdown voltage. On the other hand, the plasma will induce gas desorption prior to breakdown which should enhance the flashover potential.

For the pulsed insulator flashover, no major changes in the breakdown process are seen with a weak $E \times B$ drift into the surface, but an $E \times B$ drift away from the surface increases the breakdown

delay by a factor of 2 to 2.5 compared to the case at $B = 0$. The effect is seen with and without plasma, although with plasma the magnetic insulation is more effective. This is another indication that the plasma will add more negative charges onto the surface. With an $E \times B$ drift away from the surface, the current rises linearly to amplitudes of more than 7 A, whereas for the case with $B = 0$, an exponential rise of the current is found after a current amplitude on the order of 1 A. In addition, the duration of the linear current rise is longer compared to the case with $B = 0$. The $E \times B$ drift will alter the trajectory of the electrons (e.g., increase the lateral hopping distance on the surface), which most likely decreases the electron induced gas desorption on the dielectric. It takes more time to reach a sufficient gas density above the surface for the final discharge, therefore, the breakdown delay is increased.

The dielectric surface flashover voltage can be drastically increased in a low earth orbit environment if the electrodes/metals are coated with a thin insulator material. This coating is appropriate in cases where breakdown occurs by UV irradiation since photoelectrons from the dielectric will not initiate the dc surface flashover. Critical areas of the insulator can be protected from plasma impact by permanent magnets positioned away from these areas (see Figure 3.4). External magnetic fields will divert the plasma from these sensitive areas, and the plasma will then strike the insulator near the areas where the magnetic poles are located. Furthermore, the magnetic field which produces an $E \times B$ drift away from the surface causes a significant increase in the breakdown delay; the applied voltage pulse can be increased by a factor of 2 without causing flashover.

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APPENDIX

PROGRAM: NORMALIZED ELECTRIC FIELD BETWEEN 2 SPHERES

```

10 REM *VERSION FEB-10-95*
20 REM *by F. HEGELER (modified from a program written by M. GIESSELMANN)*
30 CLEAR
35 DEFDBL A-Z
40 CLS
50 PRINT "***** Normalized Electric Field between 2 Spheres *****"
55 PRINT
60 INPUT "Radius of Sphere1, [mm] : "; R1
70 INPUT "Radius of Sphere2, [mm] : "; R2
80 INPUT "Sep.    of Spheres, [mm] : "; D
90 NC = 200                                     'number of image charges
100 NG = 200                                    'number of gap intervals
110 DIM Q1(NC), Q2(NC), X1(NC), X2(NC), E(NG)
200 A = D + R1 + R2: C = R1 * R2 / (R1 + R2)
300 Q1(0) = 1: Q2(0) = 1
310 FOR I = 1 TO NC
320 Q2(I) = (Q1(I - 1) * R2) / (A - X1(I - 1))
330 X2(I) = R2 ^ 2 / (A - X1(I - 1))
340 Q1(I) = (Q2(I - 1) * R1) / (A - X2(I - 1))
350 X1(I) = R1 ^ 2 / (A - X2(I - 1))
360 NEXT I
390 X = 0
400 FOR K = 0 TO NG
405 E(K) = 0
410 FOR I = 0 TO NC
420 E1 = Q1(I) / (R1 + X - X1(I)) ^ 2
430 E2 = Q2(I) / (A - R1 - X - X2(I)) ^ 2
440 E(K) = E(K) + E1 + E2
450 NEXT I
455 X = X + (D / NG)
460 NEXT K
500 ESUM = 0
510 FOR L = 0 TO (NG - 1)
520 ESUM = ESUM + (E(L) + E(L + 1)) / 2
525 NEXT L
530 EAVG = ESUM / NG
535 PRINT "Normalized E-Field"
540 FOR M = 0 TO NG STEP 20
560 PRINT "E("; M; ")="; E(M) * D * C
570 NEXT M
580 PRINT
590 PRINT D * C * EAVG
600 OPEN "C:\E-FIELD.dat" FOR OUTPUT AS #1
610 FOR L = 0 TO NG
620 PRINT #1, USING "##.#####"; E(L) * D * C
630 NEXT L
640 CLOSE

```